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LASL Hot Dry Rock Geothermal Project

July 1, 1975—June 30, 1976

Compiled by

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LASL HOT DRY ROCK GEOTHERMAL PROJECT

ANNUAL REPORT

JULY 1, 1975 -- JUNE 30, 1976

Compiled by

A. G. Blair, J. W. Tester, and J. J. Mortensen

1. SUMMARY AND HIGHLIGHTS

The Hot Dry Rock (HDR) Geothermal Energy Development Project is conducted by the Los Alamos Scientific Laboratory (LASL) under the sponsorship of the Energy Research and Development Administration (ERDA), Division of Geothermal Energy. The primary goals of the Project are (a) to investigate and develop methods of thermal energy extraction from naturally hot rock in the Earth's crust by manmade underground circulation systems, (b) to demonstrate the commercial feasibility of such systems, and (c) to encourage and assist further industrial development and widespread application of this new technology. At this time, the only large-scale HDR field experiment in the nation is conducted under this project.

The magnitude of the hot dry rock resource in this country is sufficiently large that the development of economic extraction and utilization methods could have a significant impact. The U. S. Geological Survey's estimate of the accessible dry hot rock resource base of the USA (comprised of the crystallized parts and hot margins of only the 48 best known hot igneous systems) is 48 000 quads (12×10^{21} cal), about 15 times the total estimated heat content of all tabulated hydrothermal systems.¹ Furthermore, the potential environmental effects associated with the development and operation of hot dry rock geothermal power-production systems appear to be minimal.^{2,3}

The heat extraction concept being investigated requires drilling two holes into hot crystalline rock, connecting them at depth through a large hydraulic fracture or fractures, and then circulating pressurized water through this closed connected system to recover heat from the rock. Following a field resource investigation and subsequent drilling of a slim test borehole, GT-1 (granite test-1), in the New Mexico Jemez plateau, a deep hole, GT-2, was drilled about 2.5 km from GT-1. The initial plan was to use GT-2 as an experimental laboratory, and to drill two new holes, EE-1 (energy extraction-1) and EE-2 for a 100-MW(t) heat extraction experiment. Such a circulation system would have energy extraction properties and fluid behavior similar to those that would be encountered in the operation of a 10-MW electric generating plant, approximately the size needed to provide electric power to a city of 10 000 inhabitants. However, funding and technical considerations have led to the decision to use GT-2 as one of the two boreholes for a more modest experiment, to drill only one additional hole, EE-1, and to establish a downhole circulation connection between these two boreholes.

In May 1975 drilling began on EE-1 about 75 m (250 ft) from GT-2. The planned procedure was to drill EE-1 in such a direction as to intersect a hydraulically produced target fracture formed near the bottom of GT-2. The connected system was then to be used in a fluid circulation loop that would extract 10 - 20 MW of thermal energy using an air-cooled heat exchanger at the surface. The desired intersection was not made, but a connection between EE-1 and GT-2 by a downhole hydraulically produced fracture system was established. At this time, the impedance to fluid flow in this downhole system results in a pressure drop that is too high to permit fluid flow rates that would support a 10- to 20-MW(t) heat extraction experiment. Although the exact reasons for the failure to achieve the desired simple intersection have not been established, two primary contributing factors are clear. First, there was considerable uncertainty concerning the relative locations of the two boreholes near full depth, because conventional borehole surveys provided ambiguous results and borehole ranging techniques had not yet been sufficiently developed. Second, the orientation, linear extent, and general shape of the target fracture were poorly known when EE-1 was being drilled. Present plans call for attempts to reduce the flow impedance of this system to permit the 10- to 20-MW (thermal) heat extraction experiment to be carried out.

In the course of the work outlined above, many diagnostic and analytic techniques have been developed. Instrumentation and equipment capable of performing

necessary measurements at downhole temperatures up to 200°C (390°F) and pressures up to 400 bar (6000 psi) have been developed. A list of major technical achievements follows.

1. Successful drilling into hard crystalline rock was accomplished to depths of about 3 km (10 000 ft) and bottomhole temperatures of about 200°C (390°F).

2. Hydraulic fractures in the crystalline rock with radii as large as 150 m (500 ft) were successfully produced in open-hole sections and through casing perforations, at temperatures up to 200°C.

3. Values of in situ permeability of the Fenton Hill granite were measured, and are in the low microdarcy range. The permeability shows a strong dependence on pore fluid pressure, in agreement with laboratory permeability measurements on core specimens.

4. Directional drilling at depths of up to 3 km was successfully accomplished.

5. At least 90-95% of water injected into fractured regions was recovered.

6. A connection was established between two deep boreholes through a fractured region of hot granite for the first time. The flow impedance of this connection had an initial value of about 1320 bar/liter/s (1200 psi/gpm), and has now decreased to about 30 bar/liter/s (27 psi/gpm).

7. Instruments were developed to operate for several hours under the high-temperature (200°C) and high-pressure (400 bar) downhole conditions. Included were acoustic detectors, a mechanical acoustic source, temperature probes, self-potential (SP) and induced potential (IP) probes, and water samplers.

8. The compressional and shear (P and S) components of seismic signals produced by fracture extension and inflation were detected downhole. Analyses of particle motion at the P-wave arrival provide a map of what is believed to be the main fracture originating near the bottom of GT-2, as well as a preliminary map of the bottomhole EE-1 fracture.

9. Acoustic ranging has generally identified the relative positions of GT-2 and EE-1 at several depths.

10. SP and IP techniques have determined vertical fracture lengths at the borehole, as well as fluid-injection points and precise casing location.

11. Pressure-flow and fluid residence time distribution studies have measured certain properties of the downhole system, such as the product of the effective fracture surface area and the square root of the permeability, and the effective fracture volume for circulating fluid.

12. Core sample studies have provided physical and chemical data that will aid in predicting and analyzing fracture initiation and growth, in predicting downhole heat transfer rates, in altering reservoir rock permeability, and in predicting and controlling scaling and corrosion problems.

13. Techniques were developed to examine reservoir performance by modeling fluid flow and heat transfer in hydraulic fractures and wellbores of specified geometries.

14. A geothermal power-production system model was formulated that bases the total capital investment for a power plant on the costs of production and reinjection wells and major equipment.

To accomplish these results, industrial participation was obtained in many areas. Private firms were engaged under contract for the drilling of GT-2 and EE-1, for workover operations in GT-2, and for activities closely associated with the drilling. In addition, subcontracts were arranged for downhole instrumentation development, including acoustic sources and detectors, borehole logging equipment, and acoustic data analysis.

Many of the techniques, equipment, and instruments required for creating and characterizing a hot dry rock reservoir at a depth of 3 km and a temperature of 200°C were not available at the start of this project. Although considerable progress has since been made in developing these tools, the task continues to be formidable. Theoretical and laboratory studies, while valuable aids, cannot by themselves produce methods and equipment that are certain to work satisfactorily in the field. Only after deep boreholes became available could capabilities be developed through field experiments. For example, in the development of fracture-mapping methods, several field techniques, such as monitoring of surface seismic signals during downhole fracturing, the use of surface and near-surface active sources combined with downhole acoustic detectors, and use of a borehole televiewer, were tried before it was determined that downhole acoustic detection was required. At that time, suitable equipment had to be designed and built, and appropriate data analysis methods had to be developed. These methods and equipment will have to be upgraded and new tools developed, as reservoirs are created at greater depths and higher temperatures.

During the next few months, additional field experiments and modeling studies will be conducted to better characterize the downhole reservoir system. It is anticipated that an attempt will be made to reduce the flow impedance by chemical leaching, fracture propping with particles, or fracture extension. If the

impedance can be sufficiently reduced, the 10- to 20-MW(t) circulation loop experiment will then be conducted. If it cannot, present plans call for redrilling the bottom portion of either EE-1 or GT-2 to intersect a known fracture in GT-2 or EE-1, to create a connection of the kind initially attempted. Provided this new connection has sufficiently low impedance, the 10- to 20-MW(t) circulation loop experiment will then be conducted.

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2. INTRODUCTION

Geothermal energy is the natural heat contained in the rocks, metallic alloys, fluids, gravels, and soils that constitute the Earth's interior. Because of the insulating effect of its outer crust, the rate at which geothermal heat escapes from the Earth's interior is low and temperatures at depth are very high—in general at or near the melting temperatures of the rocks. Therefore, as holes are dug or drilled downward from the surface, continuously increasing temperatures are normally encountered; the average rate of increase with depth (i.e., the geothermal gradient) is about $30^{\circ}\text{C}/\text{km}$ ($90^{\circ}\text{F}/\text{mi}$). There are, however, local differences in crustal structure and geologic history so that this gradient actually varies widely from place to place, as does the way in which the Earth's heat is stored.

The sedimentary and volcanic formations at and near the Earth's surface are often sufficiently permeable so that groundwater from rain and melting snow circulates freely through them. Where these conditions exist, the normal hydrologic situation is cool water migrating through the permeable formations over the cooled upper surface of a low-permeability basement rock. However, where the circulation is impeded locally by some structural discontinuity, a large convective cell may form within the permeable rock. In this case the cooler water descends and extracts heat from the surface of the basement rock. The hot water or steam rises and carries the heat upward toward the Earth's surface, establishing a hydrothermal reservoir. Temperature is nearly constant and if temperature and permeability are sufficiently high, commercially useful hot water or steam may be extracted through a drilled hole.

The permeabilities of most basement rocks and of some massive sedimentary and volcanic formations are not sufficient to permit geothermal fluids to be produced from them at useful rates, even though the temperatures of the rock and fluid within may be usefully high. In this case the geothermal reservoir is said to be "dry" even if it actually contains a significant amount of water—in the same sense that an oil well is described as dry if it does not achieve a commercial production rate, even though it may in fact produce some oil, gas, or water.

2.1. Historical Background of LASL HDR Project

In 1970, during a study of a new drilling technique potentially useful for penetrating very hot rock, LASL attention was drawn to geothermal energy, to the probable existence of many large, dry geothermal reservoirs at drillable depths, and to the enormous thermal energy content of the hot, dry rock constituting these reservoirs. A concept for extracting heat from them was developed based, in one form, on drilling two holes into the hot rock, connecting them at depth through a very large crack produced by hydraulic pressurization, and then circulating pressurized water through this connected system to recover heat from the rock. (See Fig. 2-1.)

In 1971, a field investigation was undertaken to determine whether a location accessible to the Laboratory could be found at which the geothermal gradient, geology, and hydrology indicated the probable existence of a usefully hot, dry geothermal reservoir at an economical drilling depth. Temperature-gradient measurements made in a series of holes drilled to depths of about 30 m and the available geological, geophysical, and hydrological information suggested that such a reservoir might exist beneath the Jemez Plateau. Additional field studies produced further encouraging evidence,¹ including heat-flow measurements in holes drilled 200 - 300 m, which confirmed heat flow values of about 5 heat flow units (HFU)* on the west side of the caldera.

2.1.1. Geologic Setting of the Fenton Hill Test Site. The selected test site, shown in Fig. 2-2, is about 32 km west of Los Alamos, NM, adjacent to New Mexico Highway 126. The site, Fenton Hill, is within a large burned area of the Santa Fe National Forest. It is situated on the Jemez Plateau about 1.5 km west of the outermost ring fault of the Valles Caldera and about 13 km west of the center of the caldera. The caldera, in turn, sits astride the western edge of the Rio Grande Rift (see Fig. 2-3).

The site is within a large coherent block bounded by faults and capped by the Bandelier Tuff, a welded ash flow. The closest fault with surface expression is the ring fault east of the site. About 20 km west of the drill site is the major north-south striking Nacimiento fault.

*1 HFU = 10^{-6} cal/cm²·s. The worldwide average heat flow is 1.5 HFU.

Fig. 2-1.
Conceptual diagram of manmade
geothermal heat extraction system.

Fig. 2-3.
Location of test site.

Fig. 2-2.
Aerial view of Fenton Hill site showing
GT-2 on left and EE-1 in center.

About 0.73 km of Cenozoic and Paleozoic rocks overlie the Precambrian at the site. The predominantly volcanic Cenozoic rocks consist of the Bandelier Tuff, the Paliza Canyon Formation, and the Abiquiu Tuff. The Paleozoic rocks are mainly shales (Abo Formation) and limestones (Magdalena Group).

Smith, Bailey, and Ross² of the United States Geological Survey and others^{3,4} have examined the region around the Valles Caldera in considerable detail. Their work should be consulted for additional information.

2.1.2. Drilling and Testing. To investigate the feasibility of the LASL energy extraction concept and to verify the existence of a dry geothermal reservoir under the Jemez Plateau, a slim exploratory geothermal test hole (GT-1) was drilled in Barley Canyon at the Fenton Hill site in 1972 to a final depth of 785 m (2576 ft). It penetrated about 150 m (500 ft) into the basement granite and reached a temperature of 100°C. The initial permeability of the hot basement rock was very low, so that it appeared capable of containing a pressurized-water circulation system, and of being fractured hydraulically at moderate pumping pressures to create such a system.

Subsequently, a "Dry Hot Rock Geothermal Energy Project" was established at LASL. It is the first project to investigate the feasibility of extracting geothermal energy from nonmolten hot rock in regions where the geothermal gradient is above normal but where neither natural steam nor hot water can be produced at economically useful rates from wells drilled into the geothermal reservoir. Funding for the project was received from the AEC during FY73 from the Division of Physical Research and was expended largely in fracturing and hydrologic studies in hole GT-1, and in investigations of its physical and geologic environment. A Geothermal Energy Group was established March 1, 1973, and was given primary responsibility for the engineering aspects of the project, with scientific and engineering support to be provided by other Laboratory groups.

To initiate large-scale field investigations of hot dry rock energy systems, AEC's Division of Applied Technology provided operating funds in FY74, and drilling of a second exploratory hole (GT-2) was begun in February about 2.5 km south of GT-1. Many difficulties were encountered in drilling, cementing, and logging the hole; furthermore, it was necessary to drill the hole considerably deeper than originally anticipated to reach the target temperature of 200°C.

The drilling of GT-2 was completed during FY75 to a final depth of 2929 m (9610 ft), with a bottom temperature of 197°C. Two heat flow values were obtained in GT-2 and GT-1. A heat flow of about 5 HFU was observed in the volcanic and sedimentary rocks; in the Precambrian rocks a value of 3.7 HFU was obtained. The difference apparently resulted from the flow of hot water along the Precambrian unconformity.

Attention was then focused on a long series of pressurization, hydraulic fracture formation and extension, and hydrology experiments in GT-2, on analysis of data from such experiments, and on development of equipment, instrumentation, and techniques required for these experiments and for future work.

With the establishment of ERDA in January 1975, Headquarters responsibility for the Hot Dry Rock Project was assumed by the ERDA Division of Geothermal Energy (DGE).

Drilling of the second deep hole, EE-1 (Energy Extraction), was begun in May at a distance of about 75 m (at the surface) from GT-2. In addition, a workover rig was brought in during the last quarter of FY75 and a very encouraging set of experiments were conducted in hole GT-2. These experiments continued into FY76.

2.2. Preview of Report

In the following section the FY75 and 76 hot dry rock field program is summarized. The development of fracture-mapping and borehole-ranging concepts, instrumentation, and techniques is discussed in Sec. 4, together with their application to the connected system involving GT-2, EE-1, and the hydraulic fractures between them. Experiments conducted to investigate the characteristics and behavior of this system and of its physical and geochemical environment are described and analyzed, and physical and mathematical models of the system and its behavior are discussed in Secs. 5 and 6. Economic factors influencing hot dry rock development are also discussed in Sec. 6. The large effort devoted to drilling and downhole instrumentation and equipment development and use during the year is summarized in Sec. 7. The involvement in these and other project activities of industrial organizations is outlined in Sec. 8. Finally, in Sec. 9 the major achievements of the project during 1976 are outlined, the major problem areas and critical issues that remain are reviewed, and recommendations and plans for future activities are presented.

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3. SUMMARY OF FIELD PROGRAM

This section outlines the important events in the field program conducted at the geothermal energy site on Fenton Hill, from July 1, 1974 through June 30, 1976. Prior activities were discussed briefly in Sec. 2. For background, the most relevant event is the start of drilling of GT-2 on February 17, 1974. By June 30 the drilling had reached a depth of 1774 m (5821 ft).

In this report, several reference points are used for depth measurements in GT-2 and EE-1. During drilling operations depths are normally measured from the top of the Kelly bushing on the drilling platform, and associated records and reports are based on this reference point. If a workover rig is brought in later (as was done in the case of GT-2), depths are measured from the rotary table of that rig. Finally, after installation of a wellhead (Christmas tree) assembly, depth measurements are usually made from the top of the assembly, but occasionally, for convenience, the casing flange is used as a reference. Although all depth measurements in this report could have been converted to a single reference point, some confusion would occasionally result from comparisons with earlier records and reports. Therefore, Table 3-1 is offered to show the relationship among these several reference points. Unless otherwise noted, all depths in this report are measured along the borehole from the top of the wellhead of the respective borehole. Note, however, that for many depth measurements, uncertainties of a meter or more are common (e.g., because of unknown cable stretch due to weight and temperature effects).

3.1. FY75*

From July 1 to September 8, 1974, drilling continued in GT-2 from 1774 to 2042 m (5821 to 6700 ft). This phase of the drilling operation was interrupted periodically for hydrologic testing, temperature and other geophysical logging, coring, and hole-orientation surveys. In addition, surface seismic stations were installed and tested.

* In Sec. 3.1, depths are measured along the borehole from the top of the Kelly bushing on the Calvert Western drilling platform (GT-2) or the Signal drilling platform (EE-1).

TABLE 3-I

RELATIONSHIPS AMONG BOREHOLE-MEASUREMENT REFERENCE POINTS

Reference Point	Elevation above Sea Level			
	GT-2		EE-1	
	(m)	(ft)	(m)	(ft)
Kelly bushings				
(Signal rig)			2655.2	8711.3
(Calvert Western rig)	2652.2	8701.5		
Rotary table top				
(workover rig)	2651.0	8697.5		
Top of wellhead				
(Christmas tree)	2650.5	8696.0	2652.8	8703.5
Lower casing flange				
(near ground level)	2648.3	8688.6	2650.6	8696.3

The hydrologic tests conducted were only of limited success, primarily because of leakage around various packers used to isolate sections of the hole or leakage in the drill pipe string itself. Packer failure was attributed mainly to inadequate temperature capability of the packer-component elastomers and to inadequate packer design for open-hole operation. Geophysical logging consisting of 3-arm caliper, 3-D sonic, gamma, density, temperature, and neutron logs were run at a hole depth of 1935 m (6350 ft). Of these only the neutron log failed because of temperature (about 137°C at TD). JOIDES core recoveries taken at intervals of 1823 - 1825 m (5980 - 5986 ft), 1874 - 1876 m (6150 - 6156 ft), 1876 - 1878 m (6156 - 6162 ft), and 1933 - 1935 m (6344 - 6350 ft) varied from 17 to 100%. The rock type was generally a mafic schist or gneiss.

Drilling of GT-2 was interrupted at 2042 m (6700 ft) where the rock temperature was 146°C, for a series of pressurization and fracture experiments. These experiments revealed that below about 1100 m (3600 ft) the permeability of the granitic basement rock was extremely low and apparently competent of containing pressurized water with acceptably low leak-off rates. Hydraulic fractures produced at pumping pressures of about 170 bar (2500 psi) appeared to be nearly vertical, essentially planar, and oriented about 35° east of north. The largest fracture produced had a calculated radius of about 210 m (700 ft) and, when vented after propping, returned about 90% of the water previously injected to inflate it.

Cores, logs, and drilling rates during deepening of the hole to 2932 m (9619 ft) indicated that throughout at least the bottom 330 m (1100 ft) of GT-2 the

granitic rock was extremely uniform in structure and properties. Improved bits and drilling procedures increased bit life to about 70 h and progressively increased drilling rates in this type of rock to about 2.4 - 2.7 m (8 - 9 ft/h) when the bit was turning on bottom. Slight modifications to the JOIDES-type coring bit also significantly improved its performance. Over this drilling interval bottomhole temperature increased to 197°C, geothermal gradient increased to about 60°C/km, and hole deviation from the vertical decreased to about 2°.

GT-2 was completed on December 9, 1974, at a total depth of 2932 m (9619 ft). (See Fig. 3-1.) The hole was logged to its full depth and a 185-m-long (608-ft) section of 19.4-cm-diam (7-5/8-in.) steel casing was cemented in place as a liner (scab) with its lower end 12 m (38 ft) above the bottom of the hole. An Otis casing packer with a removable plug-type valve intended to be installed near the bottom of this liner was seated instead near the center of the liner because of a constriction in the pipe. The top of the liner was closed with a polished-bore seal penetrated by 10.3-cm-i.d. min. (4-in.) steel tubing leading to the surface. On December 20, 1974, after the liner, seal, and tubing had been pressure tested, the drilling rig was released.

A wellhead Christmas tree was installed, and the system was prepared for fracturing experiments in GT-2. Hydrologic (pressure-flow) testing continued. However, the severe winter weather interfered with the experimental schedule during February, March, and part of April.

The late winter tests showed that leakage was occurring around the casing packer, not through the standing valve in the casing packer as was previously thought. This leak permitted a pressure surge from the rig pump to be transmitted to the uncased bottomhole section during the initial pressure testing of the system. The fracture-initiation pressure was exceeded at a surface injection pressure of about 120 bar (1750 psi). Because this pressure was not measured accurately, the conditions of fracture formation were uncertain.

Fracture-reopening experiments suggested that the least component of earth stress at 2930 m (9600 ft) is only slightly larger than at 1980 m (6500 ft), 362 vs 345 bar (5250 vs 5000 psi). This unexpected result possibly was caused by additional, but as yet unverified, tensile stress contributions at depth.

Repeated and extended pressurization of the fracture system at 2930 m in GT-2 increased the local pore-fluid pressure at and near the fracture surfaces. Apparently this pore-fluid effect increased reinflation and fracture-extension pressures.

Fig. 3-1.
Cross-sectional view of GT-2.

In the spring, a workover rig contract for GT-2 was negotiated with the Calvert Western Drilling Co. Initially, activities were directed toward removing the inoperative packer assembly and cleaning the hole. This operation was interrupted for two 5-day periods to allow the United States Geological Survey (USGS) to test its high-temperature logging equipment, which had only marginal success. A straddle-packer assembly required for hydraulic-fracturing experiments in GT-2 was installed.

Experiments continued in GT-2 to increase understanding of the hydraulic-fracturing and fracture-extension behavior, in situ stress condition at depth, and the interactions of pressurized pore fluids with this stress field.

A major effort continued toward developing fracture-mapping and borehole-ranging techniques. Problems associated with poor acoustic coupling of geophones to the borehole wall, failure of geophones under high-temperature conditions, and the necessity of downhole amplification of geophone signals were attacked. A successful clamping device was developed to couple the geophone instrument package to the borehole, high-temperature downhole electronic amplifiers were tested and installed, and the geophone components were modified to withstand higher temperatures. Partially successful calibrations of downhole seismometer (geophone) sensitivity were made using surface dynamite shots and an explosive thumping device with signal averaging capability (Dinoseis) to generate acoustic signals. Results of these tests showed an attenuation in the signal amplitude in various directions, which suggests the presence of acoustic-absorbing regions, including the upper sedimentary and volcanic layers at the site.

Other techniques for determining fracture orientation and geometry were also examined. Among these were electrical, magnetic, seismic reflection, seismic refraction, seismic transmission, characteristic vibration, and tiltmeter methods, and--in cooperation with other organizations--development of improved high-temperature impression packers and borehole televiewers. The more promising methods were investigated further. An informal fracture-characterization workshop held at LASL on May 5, attended by a group of invited experts from industry, universities, and other laboratories, concluded that there were no state-of-the-art remote sensing methods to map a hydraulic fracture in deeply buried rock, but produced several suggestions for new fracture-mapping techniques.

Drilling of EE-1 began on May 26 with a Signal Drilling Co. rig. After several delays because of lost circulation, immobilized drill bits, and cementing problems, the Precambrian granite was reached at 732 m (2400 ft) on July 2. Drilling was interrupted at 741 m (2431 ft) to clean the hole and install 34.0 cm-diam (13-3/8-in.) casing. This was completed July 9.

The field program proceeded vigorously but progress was frequently impeded by component failure or inadequacy caused by the hostile, high-temperature downhole environment or by unexpected observations in the experimental program. Progress during FY75 can be summarized as follows:

1. Successful drilling into hard crystalline rock was accomplished to a depth of 2932 m (9619 ft) with a bottomhole temperature of 197°C--high enough to be useful for an energy extraction proof-of-concept experiment.

2. Heat is transferred by conduction through the Precambrian section of GT-2; the geothermal gradient in this section of the hole is 50-60°C/km. A local heat source is superimposed on an area of high regional heat flow.

3. Hydraulic fractures were successfully produced in open-hole sections and through casing perforations in GT-2.

4. In situ rock permeability was measured and is low (≤ 1 μ darcy).

5. Between 90 and 95% of fluid injected into fractured regions of GT-2 can be recovered.

6. Some development of fracture-mapping techniques involving downhole acoustic and electrical measurements that can withstand the 200°C environment was accomplished, but the techniques could not yet be used to provide quantitative information on fracture geometry and orientation.

7. Coring operations in GT-2 were successful.

8. Considerable experience was gained in learning about the limitations of instrumentation and equipment used in the GT-2 downhole environment. Needs were identified such that efforts in FY76 were then directed toward improving the reliability of downhole equipment for operation at 200°C and at hydrostatic pressures frequently greater than 400 bar (6000 psi).

3.2. FY76

The strategy for drilling EE-1 was centered around creating a connection between EE-1 and a target fracture extending outward from GT-2. (See Fig. 2-1.) The connected system would then be used in a 10- to 20-MW(t) circulation system. The fracture near the bottom of GT-2 was extended to a calculated radius of about 120 m (400 ft), and directional drilling techniques in EE-1 were used to intersect it. In addition, instrumentation and equipment development, hydraulic fracturing experiments, pressure-flow testing of the fractured system(s) and fracture-mapping and borehole-ranging technique development activities proceeded vigorously.

3.2.1. GT-2 Fracturing Experiments. In preparation for additional fracturing experiments in GT-2, the cemented-in liner was perforated by a service company at 2790, 2820, 2850, 2880, and 2910 m (9150, 9250, 9350, 9450, and 9550 ft) on July 31, 1975. Attempts to hydraulically fracture through perforations were hindered by packer leakage problems; eventually, fractures were produced and useful data collected in all but the 2790-m zone. Fracture initiation

pressures* in these experiments varied from 121 to 305 bar (1750 to 4420 psi) as compared with 121 bar required in the open-hole section at 2930 m (9600 ft). Fracture extension and reopening pressures were also erratic but generally higher than expected. For example, at 2880 and 2910 m (9450 and 9550 ft), fracture reopening pressures were 210 and 350 bar (3000 and 5000 psi), respectively, which suggest a geochemical healing process or a particle plugging process at the fluid-injection path into the fracture. Pore-pressure effects, wellbore stress concentrations, and possible tectonic stress variations may also contribute to these observed results, but further investigation is necessary.

In this experimental series, attempts were made to create a circulation path between two points of the same borehole by trying to unite two hydraulic fractures in GT-2. Theoretical calculations indicated that the local stress field around an inflated or growing fracture might induce another fracture to intersect it. The main uncertainty is that the magnitude of this stress effect could be too small. The procedure followed was to use a straddle packer across both sets of perforations at 2880 and 2910 m. About 1900 liter (500 gal) of water were injected, a volume equivalent to a single, 30-m (100-ft) radius fracture, and therefore, presumably large enough to create communication between 2880 and 2910 m. However, no communication was observed. Subsequent similar experiments involving other fractures in this region also did not indicate positively that any interfracture connection existed.

Because an impression packer could not be used in the bottom section of GT-2, and because other techniques of obtaining fracture orientation were not then available, it was decided that an oriented core from this region of the hole might reveal the hydraulic fracture. After extensive cleanup operations to remove debris from the hole, a 0.3-m (1-ft) core was cut at the bottom of GT-2 with a diamond coring bit. Because the heat shield on the core orienting device failed, no orientation was obtained. However, no evidence was found of a hydraulic fracture in the recovered core of biotite granodiorite gneiss.

After the polished-bore receptacle (PBR) at the top of the liner was redressed, the GT-2 pressurization string was pressure tested and the fracture in

*Throughout this report, unless otherwise noted, hydraulic pressures are measured at the wellhead level. The true hydraulic pressure at the location of a hydraulic fracture is approximately this given pressure plus normal hydrostatic pressure of a column of water extending from the wellhead to that depth.

the open-hole section at about 2930 m (9600 ft) was presumably extended to a 120-m (400-ft) radius on September 30. Whether the fracture actually extended from the bottomhole section of GT-2 during this pump-up is uncertain. Although, undoubtedly, a fracture was initiated at about 117 bar (1700 psi) from the open-hole section during pressure testing of the standing valve in the defective Otis packer assembly (see FY75), fracture extension may have occurred from other sections of perforated casing liner, particularly in the 2820-m (9250-ft) zone where fracture breakdown and extension pressures were lowest. Furthermore, the casing might have been ruptured at 2805 m (9200 ft) during the milling operation to remove the defective packer, possibly creating another point for fracture formation and extension. Following these experiments, the GT-2 workover rig was released on October 1.

3.2.2. EE-1 Drilling and Fracturing Experiments (Phase I).^{*} Drilling in EE-1 continued into the Precambrian region until 1957 m (6420 ft) was reached on August 11, 1975. At this depth fracturing experiments were to be conducted and drill bit size was to be changed. Up to this point, drilling rates of 3 m/h (10 ft/h) and long bit lifetimes were observed using a hard-rock mining bit with the hardest available tungsten carbide inserts. The hole deviated continuously in a west-northwest direction, essentially parallel to the GT-2 path, at a somewhat steeper vertical angle of inclination (5 - 7°). In the region from 1824 to 1902 m (5985 to 6240 ft), the abnormally high drilling rate of about 6 m/h, along with geophysical logs and cuttings, suggested that this zone might have a higher permeability than typically observed in Fenton Hill granite. Below 1902 m the normal drilling rate of about 3 m/h was resumed, indicative of more competent rock. A 27.3-cm-diam (10-3/4-in.) casing string was set and cemented in place from the surface to 1957 m, excluding the higher permeable zone from the competent region. It was necessary to case all the way from the surface rather than securing the casing to the 34.0-cm (13-3/8-in.) casing string because of the need to avoid potential downhole thermal stress problems during startup of the 10-MW(t) circulation loop. This operation was completed August 14.

At this depth, a hydraulic fracture was to be created in EE-1 and, using GT-2 and GT-1 (about 2-1/2 km to the north), techniques were to be investigated for

^{*} In Sec. 3.2.2, depths are measured along the borehole from the top of the Kelly bushing of the Signal drilling platform.

the detection of seismic signals generated by fracture growth in EE-1 (discussed later in this section.) Such techniques would be important to have later, if possible, when attempting fracture intersection between EE-1 and GT-2. Consequently, drilling was continued in EE-1 to provide a 142-m (466-ft) open-hole section below the casing at 1957 m (6420 ft) for hydraulic fracturing. In attempting to fracture in this region, a permeable zone, possibly a naturally fractured region, was encountered in the bottom 30 m of the open-hole section. Initial pumping pressures were 83 bar at 600 liter/min and 21 bar at 34 liter/min (1200 psi at 160 gpm and 300 psi at 9 gpm). The permeable zone was located with geophysical logs and by isolating sections of the hole using an inflatable packer. A spinner survey attempted in the region was unsuccessful because the logging tool failed. By using the same inflatable packer at 1975 m (6480 ft) to isolate the competent section from the lower permeable zone, a hydraulic fracture was created at a breakdown pressure of 130 bar (1900 psi) and a subsequent fracture extension pressure of 95 bar (1375 psi).

The next series of experiments was aimed at obtaining an impression of the fracture held open by fluid pressure. To permit simultaneous pressurization of the fracture and of an impression packer positioned over it, the bottom permeable zone in EE-1 was sealed with a cement plug up to 1975 m (6480 ft)--the position of the inflatable packer when the fracture was initially produced. Self-potential measurements indicated that the fracture was located between 1962 and 1967 m (6437 and 6454 ft). A first attempt with a specially developed high-temperature impression packer (presumably usable to 200°C) failed in this 150°C region. A second attempt used an oriented assembly of two inflatable packers of the same type used to create the fracture, because of their apparent ability to retain impressions on the borehole wall. These packers were centered at 1962 and 1966 m (6438 and 6449 ft), the hole was pressurized to 140 bar (2000 psi) to inflate the fracture, and impressions were then made. The impressions retained on both packers indicated an essentially vertical, 1-mm-wide fracture oriented N70°W. At about the same depth in GT-2, a fracture was oriented N35°E. These determinations of fracture orientation are suspect because of the uncertain relationship between fracture orientation at and away from the borehole as well as the potential errors in the orientation of the impression packer assembly relative to the borehole.

3.2.3. Fracture-Mapping and Borehole-Ranging Experiments (Phase I).*

Before drilling resumed in EE-1 acoustic and electric mapping techniques were investigated. Detection of downhole fracturing events or small explosive detonations deep in the granite has not been successful with the use of a surface array of very sensitive seismometers because of the large signal attenuation in the sedimentary and volcanic formations of the relatively high-frequency signals that contain most of the information about small sources such as these. (The surface seismometer array is now being used only to monitor the area seismically as part of the study of possible environmental effects associated with developing the hot dry rock geothermal resource.) However, a considerable effort has gone into developing a sensitive downhole seismometer system that can be emplaced in a borehole close to the signal source. A useful seismometer package has been developed which, to increase sensitivity, includes 12 geophones (4 each on 3 orthogonal axes), batteries, and amplifiers in ice-filled glass dewars that protect them against downhole temperatures for about 12 h. All components are enclosed in a pressure-tight shell capable of 400 bar (6000 psi) hydrostatic pressures and equipped with a motor-driven clamping arm that couples the package firmly to the walls of the hole.

Several early attempts to use this seismometer package for fracture mapping were unsuccessful, because of the type of amplifiers initially used and because a high-speed tape recorder and improved amplifier had not at that time been incorporated into the system, and only relatively low frequencies (less than 125 Hz) could be detected. (A high-speed tape recorder was subsequently added to the surface instrumentation to permit recording in the kilohertz frequency range.) In particular, no signals could be detected with the seismometer package locked in at 2130 m (7000 ft) in GT-2 when up to 3 m (10 ft) of Primacord were detonated at 685 m (2250 ft) in GT-1, about 2-1/2 km (1-1/2 mi) away. This of course made it necessary to abandon an attempt at seismic mapping of a fracture in EE-1 by detection of acoustic waves produced by explosive shots in GT-1 or at the surface and altered by passage through the fracture. Even with signal-averaging and the thumper operating near the GT-2 wellhead, Dinoseis signals could not be detected by geophones at 1500 m (5000 ft) or below in GT-2, although

* In Sec. 3.2.3, depths are measured along the borehole from the top of the Kelly bushing of the Signal drill rig.

good signals were recorded with the seismometer package locked in at 1070 m (3500 ft). (Again, perhaps this work should eventually be repeated with high-speed recording.)

During the hydraulic fracturing in EE-1 at about 1963 m (6440 ft), no signals were detected by the seismometer package locked into GT-2 at a similar depth and only about 76 m (250 ft) away. Subsequent work on the source of the mapping signals from the GT-2 fracture at 2805 m (9200 ft) suggests shear failure either at or near the fracture faces subsequent to the actual fracture formation. Analysis of the pressures needed for fracturing at both depths (1963 and 2805 m) indicates that shear failure is more likely at the lower depth.

However, good seismic signals were recorded when 0.3-m-long (1-ft) Primacord shots were fired in EE-1 at 1890, 1950, 2010, 2070 m (6200, 6400, 6600, 6800 ft), and the seismometer package was locked into the GT-2 borehole wall at a similar depth. This led to an attempt to evaluate the feasibility of mapping the fracture produced at about 1963 m (6440 ft) in EE-1 by firing Primacord shots in EE-1 at points within the fracture radius but above and below its center and also at a point outside the fracture radius, observing shadowing, refraction, reflection, and vibration effects with geophones in GT-2. The seismometer was locked into GT-2 at 1966 m (6450 ft) and 0.3-m (1-ft) Primacord shots were detonated in EE-1 at 1957, 1964, and 1972 m (6420, 6443, and 6470 ft), with the fracture inflated [at pumping pressures of 124 - 131 bar (1800 - 1900 psi)] and with it collapsed. There were distinct differences in the signals recorded by the seismometers in GT-2, but they are difficult to analyze because of their inherent complexity and because there were obvious variations in intensity of the detonations--in spite of the fact that the service company was using a special type of temperature- and pressure-resistant Primacord to produce them. In fact, in some of these shots only the detonators alone fired and the Primacord did not. However, signals from these detonators were clearly detected in GT-2.

In addition to acoustic mapping methods, electrical techniques involving self- (SP) and induced-potential (IP) measurements were also investigated. SP logs measure a potential difference between a local region of the borehole and a surface reference point. They are sensitive to thermoelectric potentials caused by temperature changes and galvanic (battery-like) potentials caused by rock surface-ionic interactions. SP logs can detect fluid movement under certain conditions, particularly where rock surface-ionic changes occur. IP logs

measure a potential difference produced as a result of a current source operating between a ground-level electrode and an electrode placed in an adjoining borehole. Because the induced signal's polarity alternates periodically, the magnitude of changes in the observed signal may be measured independently of a steady-state background due to SP effects. IP measurements are influenced by the higher conductivity of an inflated fracture.

During August 1975 SP/IP logs were run in the open-hole section of EE-1 below the casing before hydraulic fracturing was attempted there. After the hydraulic fracture had been produced at 1975 m (6480 ft), another SP/IP log was run in this section of the hole. An obvious difference between the before and after logs suggested that a hydraulic fracture intersected the borehole in the 1962- to 1967-m (6437- to 6454-ft) interval. Successive SP/IP logs were run over the interval 1957 to 1975 m (6420 to 6480 ft) with the fracture collapsed, being inflated, inflated, and being vented. Clear differences appeared over the 1962- to 1966-m (6437- to 6454-ft) interval among logs run in these four conditions. Of interest was a local reversal in polarity of the potential when water was leaving the crack rather than entering it, evidently resulting from the change in electrical streaming potential.

IP logs made in GT-2 while an electrical current was introduced at the 1966-m (6450-ft) level in EE-1 were significantly different from previous IP logs run in GT-2. Additional logs were planned in an attempt to use this technique to learn more about the geometry of the fracture extending outward from EE-1. However, failure of the service company's logging tool made further experiments at this depth impossible.

3.2.4. EE-1 Directional Drilling and Target Fracture Intersection (Phase II).^{*}

Following the series of seismic and other experiments just described, drilling in EE-1 was resumed August 31, 1975. The 142-m (466-ft) cemented zone was drilled out and the hole deepened. At about 2420 m (7935 ft) the drilling fluid loss rate suddenly increased to about 8-10 m³/h (50-60 bbl/h), suggesting that either another highly permeable zone had been penetrated or the cement seal in the zone around 1950 m (6400 ft) had washed out. The addition of lost-circulation materials to the fluid did not significantly reduce this loss rate. If pressurized

^{*}In Sec. 3.2.4, depths are measured from the top of the Kelly bushing of the Signal drill rig.

water were to be contained in the hole, it had to be cased below the 1952-m (6420 ft) depth at which the 27.3-cm (10-3/4-in.) casing string ended. Accordingly, enough 22.5- and 20.0-cm (8-7/8- and 7-7/8-in.) casing was obtained to case from the surface to about 2930 m (9600 ft), near where the intersection with the fracture from GT-2 was expected to occur. Again, complete casing from the surface was required to avoid potential downhole thermal stress problems during startup of the 10-MW(t) circulation loop.

Because the azimuthal orientation of the fracture extending from GT-2 was uncertain at this time, the decision was made to maximize the probability of intersecting it by directing EE-1 toward a point about 60 m (200 ft) directly below the bottom of GT-2--through which, so long as it extends downward at least 60 m, any vertical fracture from GT-2 must pass. Accordingly, directional drilling in EE-1 was begun at 2099 m (6886 ft). The hole was turned through a slow spiral from an azimuthal direction of about N78°W to about S23°E and back to S20°W at 2918 m (9575 ft), and was steepened to a deviation of 3-3/4° from the vertical--so that it could be flattened again as the target approached. To our knowledge, this is the first time that directional drilling had been attempted in hot granite, and it was very successful.

At about 2770 m (9100 ft), borehole-ranging experiments were begun, interspersed with drilling operations. On September 30, the fracture from GT-2 was extended to a radius of about 120 m (400 ft), to offer a target of suitable size for intersection by EE-1. On October 1, the depth of EE-1 was 2918 m and its bottom was believed to be nearly due west of GT-2 and about 9 m away.

Directional drilling in EE-1 continued until October 12 when the total depth of 3064 m (10 053 ft) was reached. Although GT-2 was kept pressurized while drilling EE-1 to a depth below the point where an intersection was expected, no definite pressure response in the GT-2 fracture system was observed. However, on approximately October 10 a small flow of about 4 liter/min (1 gpm) out of EE-1 was noted--the first evidence of a connection. On October 14, an inflatable packer was set in EE-1 at 2926 m (9600 ft). A hydraulic fracture was created in EE-1 at a surface injection pressure of 165 bar (2400 psi) and pressure response in GT-2 was noted. Continued injection at 33 liter/min (8.8 gpm) into GT-2 ultimately produced a 19-liter/min (5-gpm) flow out of EE-1. About 11 liter/min (2.8 gpm) were flowing out the GT-2 annulus, leaving 4 liter/min (1 gpm) unaccounted for (possibly permeation loss). Several subsequent attempts to fracture at greater depth in EE-1 were unsuccessful because of packer failures.

On October 23, a production casing string was set to 2926 m (9600 ft), cemented, and checked. The Signal Drilling Company rig was released October 27. (See Fig. 3.2 for a schematic view of EE-1.)

The attempt to intersect the GT-2 fracture with the EE-1 borehole was not successful. At this time the exact reason is not known, but a solution to this problem is being pursued. In general two contributing difficulties are apparent. One is the considerable uncertainty associated with the relative positions of the two boreholes. Downhole ranging techniques using detonators and geophone detectors were in initial development stages during the drilling program, and although they were useful, they had not yet matured as routine diagnostic techniques. The second is that the geometry of the downhole fracture (the direction in which it propagated, its height, depth, and general shape) was not well known. Present indications from acoustic measurements are that the GT-2 fracture runs northwest and extends to at least 3005 m (9860 ft) at the bottom. From IP measurements the top of the fracture is estimated at 2680 m (8800 ft), and from temperature logging the main fracture-to-wellbore connection is at 2810 m (9220 ft). However, this information was not known at the time the intersection was attempted. Based on the results of two acoustic ranging measurements available at the time the intersection was attempted, at 2915 m (9565 ft) EE-1 was thought to be almost due west of GT-2 and about 8 m (26 ft) away. Subsequent measurements have shown that the distance is correct. The direction must still be confirmed. If EE-1 is in fact

Fig. 3-2.
Cross-sectional view of EE-1.

due west, the best guess at present is that EE-1 passed below the lower edge of the GT-2 fracture, whereas an opposite direction would have placed EE-1 at 2854 m (9365 ft), just short of the GT-2 fracture.

3.2.5. Fracture-Mapping and Borehole-Ranging Experiments (Phase II).^{*}

Phase II drilling was interrupted at 2770 m (9100 ft) for an attempt to determine relative positions of EE-1 and GT-2 at that depth. Because earlier experiments had shown that good acoustic signals were received when only the detonators were fired, the Primacord was omitted. The seismometer package was locked into EE-1 at 2770 m and detonators were fired in GT-2 at approximately that level and at levels 15 m (50 ft) above and below it. For the first time very high speed tape recording was used, and excellent signals were recorded at 750 Hz and higher. Unfortunately, the timing signal was derived from the electrical impulse used to fire the detonators; this signal led the actual detonation time by a variable number of milliseconds and could not be used to determine transit time of the shock waves through the rock. However, the geophone record was sufficiently resolved so that the difference between P- and S-wave arrival times could be used to calculate a distance between the two holes. This result, about 16 ± 3 m (53 ± 10 ft), was in good agreement with the estimate of relative position based on magnetic surveys of the two holes.

When EE-1 was deepened to 2918 m (9575 ft) on September 25, a similar ranging experiment was attempted. The seismometer package was located at 2915 m (9565 ft) in EE-1, and detonators were fired in GT-2 at 2905 and 2920 m (9531 and 9581 ft). (A third detonator intended for firing at 2890 m (9481 ft), did not fire.) A single vertical seismometer was mounted on the cable a few feet above the detonators to serve as an accelerometer and provide a firing signal. Good signals were recorded. From P-wave transit times and sound velocities previously measured in both holes, the seismometer package in EE-1 was determined to be 8 ± 2 m (26 ± 6 ft) away from the detonation in GT-2 at 2905 m. Because of a camera malfunction in the orienting device, the directional relationship between the two holes could not be determined. A distance measurement based on the difference between P- and S-wave arrival times was in good agreement with that based on P-wave transit time.

In an attempt to determine with certainty the directional relationship and distance between the bottoms of GT-2 and EE-1, the above experiment was repeated with the large seismometer package set at 2913 m (9558 ft) in EE-1. Three

^{*}In Sec. 3.2.5, depths are measured along the borehole from the top of the Kelly bushing of the Signal drill rig.

commercial detonators, this time encased in a silicone sealant, were lowered into GT-2 on a commercial cable, attached to a LASL firing mechanism and to a single downhole geophone that provided a timing signal. The first detonator fired successfully at 2906 m (9535 ft); the second, at 2914 m (9562 ft), did not detonate; and the third, at 2899 m (9513 ft), fired satisfactorily. This time the commercial instrumentation package orienting device operated successfully, and EE-1, at 2913 m, was determined to be 8 m (26 ft) away from GT-2, in a nearly due west direction.

With the seismometer package at 2918 m (9575 ft) in EE-1 on September 30, the fracture at the bottom of GT-2 was inflated and extended by pumping about 13 500 liter (3600 gal) at rates ranging from 587 to 32 liter/min (155 to 8.5 gpm) and a maximum surface injection pressure of 152 bar (2200 psi). In a subsequent experiment on October 1, 45 000 liter (12 000 gal) were injected in GT-2 at rates varying from 160 to 640 liter/min (42 to 168 gpm) and a maximum surface injection pressure of 155 bar (2250 psi). Some of the acoustic signals accompanying the hydraulic fracturing were detected at frequencies less than 125 Hz, but the high noise level at these frequencies prevented analysis. Above 750 Hz, signals were obtained, but because the magnetic orientation instrumentation failed, a determination of fracture orientation was not possible.

On October 5, acoustic experiments were resumed. About 44 000 liter (11 700 gal) were pumped in GT-2 at 640 liter/min (168 gpm) and a maximum surface injection pressure of 148 bar (2150 psi). During pumping, the seismometer package was lowered in EE-1 and positioned at 2807, 2868, 2943, and 3004 m (9211, 9409, 9656, and 9856 ft) in another effort to acoustically map the GT-2 fracture. The experiment was successfully implemented. A preliminary analysis of the results has defined a generally planar locus of microfracturing events with the following properties.

1. The perpendicular distance between the EE-1 borehole and the face of the hydraulic fracture in GT-2 is between 9 and 18 m (30 to 60 ft).

2. The minimum lateral extent (diameter) of the fracture at 2807 m (9211 ft) is about 150 m (500 ft).

3. The fracture strikes N27°W at 2807 m.

A set of SP/IP logs were obtained while the hydraulic fracture at the bottom of GT-2 was being extended to a radius of about 120 m (400 ft). SP/IP logs in EE-1 did not indicate any hydraulic communication between the two holes at that time. However, information concerning fracture location was determined from IP measurements. Distinct differences were seen between IP logs taken in EE-1 when the fracture in GT-2 was small, about 30-m (100-ft) radius, and when it had been enlarged to a 120-m (400-ft) radius. Furthermore, after the extended inflation of GT-2 during target interception procedures, the top region of the fracture had moved up to about 2697 m (8850 ft), which could indicate that the injection point of the fracture in GT-2 had changed from about 2930 to 2800 m (9600 to 9200 ft). This point will be discussed later. IP logs in EE-1 also were able to identify the bottom of the casing as well as the fluid injection region about 2935 m (9630 ft).

Because of the importance of establishing relative effects, background logging runs should be made before fracturing. SP and IP techniques will be investigated further for use in fracture-mapping experiments.

3.2.6. Additional Fracture-Mapping and Borehole-Ranging Experiments.

On March 3-5 the first attempt was made to map the EE-1 fracture (Experiment 117).^{*} The geophone package was stationed at 2.94 km (9636 ft) in GT-2 for 4.5 h while the EE-1 fracture was sequentially inflated to 34 000 liter, shut in for 2 days, and further inflated and extended with an additional 75 700-liter injection. Of the 80 microseismic events recorded, 15 occurred during the first pumping and were randomly distributed in time. Six of these events gave meaningful information for mapping purposes. At 2.94-km depth the closest approach of the EE-1 fracture to the GT-2 borehole was 21 ± 6 m. The strike of the fracture was N53°W. Subsequent mapping experiments were done on May 6 but were hampered by a faulty vertical geophone, and no definite orientation could be obtained.

From June 23 to 29, about 587 000 liter (155 000 gal) were injected into EE-1 at 640 liter/min (170 gpm); acoustic signals were recorded at four depths [2929, 2853, 2784, and 2751 m (9610, 9360, 9133, and 9025 ft)] of the geophone sonde in GT-2. A total geophone recording time of 13 h was achieved, three times longer than any previous experiment. Event frequency generally increased

^{*}See Appendix A for a list of numbered field experiments.

as the injected volume increased with few events detected before 76 000 liter (20 000 gal) had been pumped. The highest event rate observed was 5 per min, considerably below the 40 per min observed during some phases of the October GT-2 fracture-mapping experiment. The recorded signals are being analyzed.

Acoustic ranging experiments continued from April through June using a mechanical acoustic source (wallbanger) in one borehole and a geophone package in the other. The wallbanger package provides a repeatable acoustic signal on demand by striking the wellbore (see Sec. 7.2) and is intended as an alternative to the detonator techniques described earlier. A geophone is placed in the wallbanger to identify the trigger signal, while an oriented 3-axis geophone package is used to observe the acoustic signal as it arrives in the second borehole. Several modifications to the spring suspension components of the geophones were made to increase their resolution in the downhole environment.

A preliminary ranging experiment (118) was completed on April 26. During this experiment, the 3-component geophone package was positioned in GT-2 and the wallbanger package in EE-1. Both instruments were tested at 14 equivalent depths in the 2740- to 2930-m (9000- to 9600-ft) interval. The impact or trigger signal, as recorded by the wallbanger geophone, was not clearly defined, and meaningful timing data could not be obtained. Another ranging experiment (126) was conducted in late May with an improved wallbanger package. In this case, the onset and wave characteristics of the impact signal were clearly identified, and travel times between signal source and geophones were determined. At several horizons in GT-2 and EE-1, separation borehole distances ranging from 24 m (80 ft) at 2800 m (9200 ft) to about 11 m (36 ft) at 2930 m (9600 ft) were estimated. A third ranging experiment using the wallbanger was conducted in June to provide additional data by positioning the geophone package at a single horizon in EE-1 at a depth of 2878 m (9442 ft) and using nine wallbanger locations in GT-2 symmetrically positioned around the fixed geophone position in EE-1 over a range from 2869 to 2890 m (9412 to 9482 ft). The wallbanger was fired several times at each horizon, and P-wave travel times were easily discernible. A hyperbolic curve of travel times symmetric about the EE-1 geophone position at 2878 m (9442 ft) with a minimum time of 1.4 ms and a P-wave velocity of 6 m/ms (20 ft/ms) fits these preliminary data reasonably well and results in a EE-1 to GT-2 wellbore distance of 8.5 m (28 ft) at that depth.

3.2.7. Pressure-Flow Testing of the EE-1/GT-2 System. Pressure-flow tests are being conducted to evaluate the present EE-1/GT-2 connection for its potential use in a 10- to 20-MW(t) energy extraction experiment. These experiments consist of transient pressure testing to determine in situ fracture face permeability and permeating areas, temperature logging to determine fluid injection and return locations in GT-2 and EE-1, flow testing to determine impedances and to characterize fracture-borehole flow geometries, and residence-time-distribution studies using tracer techniques to identify mean fracture volumes and the distribution of fluid velocities within the fractured region. The following conclusions have been reached concerning the present EE-1/GT-2 connection.

1. Flow into or out of the fracture in EE-1 occurs at about 2940 m (9650 ft)--in agreement with the results of other experiments.

2. Flow into or out of the fracture zone(s) in GT-2 occurs in two main locations [80% from 2800 to 2820 m (9200 to 9250 ft), 15% at 2870 m (9420 ft)] and the remainder at the bottom.

3. When flowing in either direction (EE-1 to GT-2 or GT-2 to EE-1) some of the injected fluid goes into fracture inflation and permeates into the rock; the remainder returns to the surface through the outlet borehole. These effects do not result in significant net fluid losses because 90 - 98% of the injected fluid is ultimately recovered when the system is deflated.

4. Total pressure drops through the system are high because of impedances in the downhole flow loop between the EE-1 and GT-2 wellbores.

5. Specific impedances of 65 - 30 bar/ liter/s (60 - 27 psi/gpm) are regularly observed in the GT-2/EE-1 connection. Over 15 flow experiments have been conducted from December 1974 through June 1976 in an effort to characterize these flow impedances. About 5.5 to 6.6 bar/ liter/s (5 - 6 psi/gpm) of the total impedance can be attributed to losses near both wellbores at the fracture connection points. The remainder is caused by effects removed from the wellbore. In general, as the mean EE-1/GT-2 fracture system pressure is raised the specific impedance decreases. Two effects might explain this: increasing the mean pore pressure increases the permeability of granite and increasing the mean pore pressure may increase the internal fracture conductance by increasing the effective width of the fractures.

6. The fractured region between GT-2 and EE-1 has a calculated "effective" permeability of 0.2 darcy--a factor of 10^6 larger than competent granite.

7. The product of fracture permeating area, A, and the square root of permeability, $\sqrt{k}$, has been determined for different flow experiments. A value

of $5.4 \times 10^{-5} \text{ m}^3$ was calculated when fluid was injected into GT-2, and $8.4 \times 10^{-5} \text{ m}^3$ when fluid was injected in EE-1. Assuming similar permeabilities, then the permeating area of the system inflated from GT-2 is 36% smaller than the system inflated from EE-1.

8. A dye tracer study of the system conducted in April showed that the flow within the inflated fracture system is dispersed over a wide range of velocities about a mean residence time corresponding to a fracture volume of 37 900 liter (10 000 gal) with EE-1 at 89 bar (1300 psi) and GT-2 fully vented. A second tracer experiment was conducted in May with EE-1 at 48 bar (700 psi) (a value below the effective fracture opening pressure, S_3) with GT-2 fully vented. In this case, the shape of the residence time distribution was similar to the 89-bar (1300-psi) case, but the mean fracture volume was somewhat less at 28 000 liter (7500 gal).

Two models have been proposed to describe the present GT-2/EE-1 connected system. The first assumes that a single fracture exists between EE-1 and GT-2 which is characterized by large flow impedances in the regions near both holes. The second consists of a self-propped two-fracture system, one connected to GT-2 at about 2820 m (9250 ft) and the other connected to EE-1 at about 2947 m (9670 ft). Flow between these two fractures occurs in a region of fracture-face overlap through high-impedance microcracks. More experiments are planned to delineate the nature of the connected system to define appropriate procedures to be used in an attempt to lower the impedance of the system.

3.2.8. Summary of Progress in FY76

Instrumentation and Equipment Development (see also Sec. 7). Downhole instruments were continually improved both with respect to their measurement sensitivity and their ability to withstand the high-temperature and high-hydrostatic pressure environment. Microseismic, temperature, acoustic source, SP and IP, and water sampling measurement capabilities have been achieved at total depth in GT-2 and EE-1 to a temperature of about 200°C.

Acoustic Fracture-Mapping and Borehole-Surveying Technique Development (see also Sec. 4).

- Both compressional and shear (P- and S-) phase components have been identified from downhole microseismic signals obtained during fracture inflation. Shear and compressional phase arrival times can be determined with sufficient

precision from plots of total energy vs time for the signal code so that distances to the focus of a microseismic event can be calculated within ± 6 m (20 ft) (about ± 1.0 ms).

- Analysis of particle motion occurring during the arrival of compressional phases provides an estimate of the direction to the focus.

- Microseismic events from GT-2 fracture inflation evaluated thus far appear to originate on or near a vertical or nearly vertical plane passing through the bottom part of GT-2 and striking about N27°W at 2.80 km. The main fracture in GT-2 is at least 150 m (500 ft) in diameter as determined by microseismic event analysis.

- Acoustic ranging has generally identified the relative positions of EE-1 and GT-2 at several depths.

- Continuous, low-frequency microseismic signals associated with pumping-induced radiation in the borehole or fracture at an excitation frequency of 7 Hz, and discrete, high-frequency (> 750 Hz) microseismic signals associated with microfracturing events have been measured and analyzed.

- SP and IP techniques have been successfully used to determine fracture location, fluid injection points, and casing location.

Drilling, Fracturing, and Circulation Loop Formation

1. Hydraulic fractures have been successfully produced from casing perforations and open-hole sections at temperatures of about 200°C using inflatable packers at surface injection pressures of 120 - 305 bar (1750 - 4420 psi).

2. Attempts made to connect two fractures in the same borehole were not obviously successful. This preliminary evidence casts doubt on the possibility of creating coaxial systems in this manner.

3. Drilling and directional drilling were very successful in an operational sense. The effectiveness of the directional drilling phase would have been increased by more accurate borehole surveys and quantitative fracture mapping results.

4. Suitable impressions of fractures were obtained with inflation packers under pressure propping conditions in EE-1.

5. A connection was established between two deep boreholes through a fractured region of hot granite for the first time.

Reservoir Assessment - Status of the Present EE-1/GT-2 Connected System (see also Secs. 5 and 6). The EE-1/GT-2 connection in its present configuration is not sufficient to support a 10- to 20-MW(t) heat extraction experiment. The

current connection has not been completely characterized either geometrically or hydrodynamically. The results of the most recent flow and fracture-mapping experiments are encouraging, however. A continuous decline in the specific flow impedance has been observed. The original EE-1/GT-2 connection had a value of 1320 bar/ liter/s (1200 psig/gpm), which has decreased to 30 bar/ liter/s (27 psig/gpm) by July 1, 1976. If two fractures exist and are connected by small microcracks extending from the faces of both fractures through a rock layer of 9 m (30 ft) or less, removal of a relatively small quantity of solid material by chemical dissolution or leaching could decrease the flow impedance to an acceptable level for a 10-MW(t) experiment. If the EE-1 borehole actually passes below the lower edge of the GT-2 fracture, a distinct possibility noted earlier in this section, it may be feasible to extend that fracture downward to intercept EE-1, and achieve a similar result. The redrilling of either EE-1 or GT-2 to intersect a known fracture in GT-2 or EE-1, respectively, could also produce a low-impedance connection. Once the geometry of the system has been more completely characterized, the strategy for improving it will be implemented.

A two-module surface heat exchanger (20-MW(t) capability) has been designed, fabricated, and delivered to the Fenton Hill site in preparation for installation when the downhole connection impedance has been sufficiently reduced.

MILESTONE CHART

FY75

JULY		AUGUST		SEPTEMBER		OCTOBER		NOVEMBER		DECEMBER	
				A	B					C	D

JANUARY		FEBRUARY		MARCH		APRIL		MAY		JUNE	
		E						F	G	H	I
										J	

FY76

JULY		AUGUST		SEPTEMBER		OCTOBER		NOVEMBER		DECEMBER	
K	L	M	N	P	R	X	Z	A*	C	E	F
			O	Q	T	Y	B	D	G	H	I
				U							J
											K

JANUARY		FEBRUARY		MARCH		APRIL		MAY		JUNE	
L				M	O	P	R	S	U	V	W
				N	Q		T				
											X

* AA, BB, CC ... from this point on.

Key to Milestone Chart

FY75

A	September 8	-- GT-2 drilled to 2042 m (6700 ft) with a rock temperature of 146°C at TD.
B	September 27	-- Hydraulic fracture produced to a calculated radius of 270 m (700 ft) in GT-2.
C	December 9	-- GT-2 drilled to 2932 m (9619 ft) with a temperature of 197°C at TD.
D	December 20	-- GT-2 geophysical logging complete, steel liner cemented in place, production tubing set in PBR (polished bore receptacle) mandrel at 2735 m (8973 ft). First hydraulic fracture produced in GT-2 at 2930 m (9600 ft).
E	February 3	-- Phase II fracturing experiments started in GT-2 at 2930 m (9600 ft).
F	May 9	-- Phase II concluded, hydraulic fracture created in bottom section of GT-2 ($k = 0.3 \mu\text{darcy}$, radius = 30 m (100 ft), 95% of fluid recovered.
G	May 26	-- EE-1 drilling started.
H	May 30	-- Observed acoustic signals from dynamite shots fired at the surface and from shallow boreholes, 6 m (20 ft). GT-2 workover rig in place.
I	June 5-20	-- Experiments were conducted by USGS to test newly developed high-temperature logging instruments.
J	June 30	-- Milled out Otis packer in GT-2.

FY76

K	July 2	-- EE-1 drilled to 732 m (2400 ft), Precambrian reached.
L	July 3-6	-- USGS returned for logging.
M	July 31	-- Perforations completed in GT-2 liner over 2790- to 2910-m (9150- to 9550-ft) interval.
N	August 12	-- Tested large seismic package with ice-filled dewars and amplification for first time in downhole environment of GT-2.
O	August 13	-- Fired Primacord explosive in GT-1, observed no signals in GT-2 with improved downhole seismic package in place.
P	August 14	-- EE-1 cased to 1957 m (6420 ft).
Q	August 15-21	-- Dinoseis experiments with signals observed at 1070 m (3500 ft) in GT-2 but not at 1500 or 1980 m (5000 or 6500 ft).

- R August 19 -- Drilled EE-1 to 2099 m (6886 ft), stopped drilling for hydraulic fracturing experiments.
- S August 22 -- First successful operation of large downhole seismic package [12 geophones (4 on each axis)] with ice-filled dewars and amplifiers. Acoustic signals were detected in GT-2 using an explosive source in EE-1. Beginning of acoustic ranging program.
- T August 25 -- Hydraulic fracture created in EE-1 at 130 bar (1900 psi). SP log identified intersection zone at 1962 - 1967 m (6437 - 6454 ft). Inflatable packers used to isolate zone for fracturing. Identified porous zone in EE-1 at 2070 m (6800 ft) [max. inflation pressure, 90 bar (1300 psi) at 34 liter/min (9 gpm)]. First attempts made at detecting acoustic signals from adjacent borehole (EE-1 pumped with seismic package in GT-2). Preliminary analysis indicated that no signals were observed.
- U August 28 -- Feasibility of downhole ranging experiments established. Explosives fired in EE-1, signals observed in GT-2 with travel times accurate to ± 1 ms. Attempts made to observe different signals with EE-1 fracture inflated and collapsed.
- V August 29 -- First IP measurement of a fracture in an adjacent wellbore. Identified top and bottom of fracture and showed that it grew upward from 1980 to 1860 m (6500 to 6100 ft).
- W August 30 -- Impression of inflated fracture obtained on impression packer at 1963 m (6450 ft). Orientation was $N70^{\circ}W \pm 10^{\circ}$.
- X September 20 -- First successful downhole ranging experiments at 2770 m (9100 ft) (fired in GT-2 and listened in EE-1).
- Y September 29 -- Observed fracture growth using IP log after 13 000 liter (3500 gal) pumped into GT-2.
- Z September 30 -- Created target fracture at bottom of GT-2 to a calculated radius of 120 m (400 ft) with 45 000 liter (12 000 gal) pumped. First seismic signals observed from inflated fracture looking from adjacent wellbore.
- AA October 5 -- Obtained seismic data at depths of 2807, 2868, 2943, and 3004 m (9211, 9409, 9656, and 9856 ft) from which extent and orientation of the GT-2 fracture was established. Continuous acoustic radiation from fracture at pump frequency (7 Hz) observed.

BB	October 10	-- A connection between GT-2 and EE-1 was observed for the first time. Flow impedance was about 1300 bar/ liter/s (1200 psi/gpm). Entry point was identified on October 13 by observing sharp 4-5° rise in borehole temperature at about 2895 m (9500 ft).
CC	October 14	-- Fracture created in EE-1 by pressurizing region below inflatable packer set at 2926 m (9600 ft). Volume pumped into fracture was 14 000 liter (3700 gal). Impedance flowing from GT-2 to EE-1 after fracture was made was about 220 bar/ liter/s (200 psi/gpm). Exit region of fracture from EE-1 was measured by temperature and SP logs to be at about 2940 m (9650 ft).
DD	October 20	-- Unsuccessful attempt to fracture EE-1 borehole below 2984 m (9791 ft). Wellbore from this depth to bottom withstood 230 bar (3300 psi) wellhead pressure without fracturing.
EE	October 23	-- Cemented bottom 490 m (1600 ft) of casing in EE-1 to 2926 m (9600 ft).
FF	November 5	-- GT-2 tower installation completed.
GG	November 6	-- Temperature log in GT-2 indicated major flow exit point near 2800 m (9200 ft) (Experiment 101).
HH	November 12	-- Impedance flowing from GT-2 to EE-1 measured as 240 bar/ liter/s (220 psi/gpm), GT-2 $A\sqrt{K} = 48 \text{ cm}^3$ (Experiment 102).
II	December 8	-- EE-1 tower installation completed.
JJ	December 23	-- Impedance flowing from EE-1 to GT-2 measured as 190 bar/ liter/s (170 psi/gpm), EE-1 $A\sqrt{K} = 11 \text{ cm}^3$ (Experiment 106).
KK	December 24	-- In flowing from EE-1 to GT-2 50 bar/ liter/s (45 psi/gpm) impedance at the wellbore initially observed, decreased as flow progressed. Total flow impedance measured as 143 bar/ liter/s (130 psi/gpm) over range of pressure from 14-76 bar (200-1100 psi), EE-1 $A\sqrt{K} = 12 \text{ cm}^3$ (Experiment 106).
LL	January 13	-- EE-1 wellbore impedance 1.5 bar/ liter/s (1.3 psi/gpm), EE-1 $A\sqrt{K} = 16 \text{ cm}^3$ (Experiment 110).
MM	March 2, 4	-- USGS testing logging equipment.
NN	March 5	-- Seismic experiment with EE-1 inflated. Seismic package in GT-2 at 2926 m (9600 ft). Orientation of EE-1 fracture measured, similar to GT-2 at same depth.

- 00 March 15 -- Permeability was observed to depend on pressure, increased by factor of 15 when surface pressure increased from 0 to 70 bar (0 to 1000 psi). Impedance between EE-1 and GT-2 began at about 110 bar/ liter/s (100 psi/gpm), decreasing with time to 66 bar/ liter/s (60 psi/gpm), EE-1 $A\sqrt{K} = 68 \text{ cm}^3$ (Experiment 111).
- PP March 20 -- Radioactive iodine tracer used in EE-1 and GT-2. Extent of fracture intersection with the EE-1 wellbore confirmed. (Experiment 116).
- QQ March 22-27 -- Sodium-fluorescein dye tracer study of EE-1/GT-2 fracture system. Mean fracture volume and residence time distribution measured for flowing 230 000 liter (60 000 gal) into EE-1 at 900 bar (1300 psi) with GT-2 vented, flow impedance 130-65 bar/ liter/s (120-60 psi/gpm), EE-1 $A\sqrt{K} = 74 \text{ cm}^3$ (Experiment 115).
- RR April 19 -- Impedance flowing from GT-2 to EE-1 varied from 140 to 65 bar/ liter/s (130 to 60 psi/gpm) over 10 h of flow, GT-2 $A\sqrt{K} = 52 \text{ cm}^3$ (Experiment 121).
- SS April 26 -- Wallbanger concept successfully demonstrated in EE-1, listening in GT-2 (Experiment 118).
- TT April 27 - May 4 -- Sodium-fluorescein dye tracer study with fracture system deflated at 50 bar (700 psi). Evidence of self-propping confirmed (Experiment 119).
- UU May 11-14 -- Impedance flowing from EE-1 to GT-2 decreased to 29 bar/ liter/s (26 psi/gpm) with high pressures maintained in EE-1 and GT-2.
- VV May 19-20 -- First test of the high-temperature ceramic amplifier developed by Mechanics Research, Inc., Los Angeles, CA. A seal in the sonde leaked, test inconclusive.
- WW May 27 -- Wallbanger used for ranging between EE-1 and GT-2, signal onset and travel times discernible for the first time.
- XX June 23-29 -- Acoustic signals recorded at four depths in GT-2 while pumping in EE-1. Total geophone recording time of 13 h. Sufficient signals obtained for a preliminary map of the EE-1 fracture.

4. MAPPING OF HYDRAULIC FRACTURES AND WELLBORES

4.1. General Considerations

A major objective of engineering hot dry rock reservoirs is to develop techniques for mapping hydraulic fractures in space and time. To create two-hole circulation systems, one borehole is directionally drilled to intersect a hydraulic fracture initiated from a second borehole. Without knowledge of the orientation and radial extent of the target fracture, this task is formidable.

The methods discussed in this section describe recent results and near-term plans for development of suitable fracture and borehole mapping techniques. Basically, there are three areas of investigation--downhole acoustic methods for distance ranging and fracture mapping, electric potential measurements, and magnetic field measurements. Methods described in Secs. 4.2 and 4.3 have been tried in the field and have yielded useful results. Advanced techniques that have been theoretically considered and/or laboratory tested and are being developed for future field testing are discussed in Sec. 4.4. Although many of the techniques that have been tested require a signal source and detector in different boreholes, emphasis should be placed on developing techniques for mapping fractures that can be used in only one wellbore.

4.2. Acoustic Techniques (R. L. Aamodt, J. N. Albright, E. D. Holmes, C. Newton, R. M. Potter, and R. Spence)

4.2.1. Ranging Methods. One method of completing a downhole heat extraction system is to accurately intersect a hydraulic fracture initiated from one wellbore with a second wellbore. Because present survey methods using magnetic and gyrocompass devices are not accurate enough at the high temperatures encountered near the bottom of deep boreholes (see Sec. 7-1), acoustic ranging techniques were developed to provide distance measurements as a function of depth between two wellbores.

Acoustic ranging is achieved by positioning an artificial acoustic signal source at known depths in one borehole, and a geophone detection system (see Sec. 7.2) whose orientation can be determined, in another hole. Because the propagation velocity of acoustic waves in rock is generally known or can be measured

in situ by standard logging techniques, the distance between boreholes can be calculated by measuring the travel time of an acoustic signal from source to detector.

The P-wave (primary or compressional wave) velocity, needed to calculate the distances, can be obtained from sonic logs. However, this technique determines a velocity that is vertically directed and is near the borehole. The average in situ P-wave velocity for the region between two nearly vertical boreholes can be obtained by positioning acoustic sources at several known depths. From these data a minimum travel time from the source borehole to a geophone in a fixed position in another borehole can be calculated. Application of the Pythagorean theorem gives the average in situ P-wave velocity.

Initial experiments were carried out between EE-1 and GT-2 in August 1975 at about 2.0 km (6500 ft). Detonators used for Primacord shots were fired at several levels in EE-1, and the resulting seismic signals were received at a fixed depth in GT-2. Table 4-I gives the results from the 1.97-km (6470-ft) set. Good picks (identification) of the P-wave arrival times on all three geophones indicated that a timing precision of ± 0.1 ms was obtainable. Using an average velocity, the distance between boreholes was calculated to be about 91 m (300 ft). A variable burn time in the detonator introduced errors up to 1 ms. The time difference between arrival of the P-wave and S-wave (secondary or shear-wave) provides another method for calculating the distance between the boreholes. Reproducible orientations (θ and ϕ) were obtained between the two boreholes by measuring the initial amplitude signal from the first half cycle of the P-wave as received by the horizontal geophones. The source-geophone distance was calculated to be 94 m (309 ft) using a P-wave velocity of 5830 m/s. The values given in the table are relative because no downhole orientation survey tool was used.

Another ranging experiment was performed September 20, 1975. A total of 10 detonators were placed at three locations in GT-2, and the geophone package was at about 2.8 km (9100 ft) in EE-1, as shown in Fig. 4-1. Four of the detonators misfired and of the remaining six, shots 2, 6, 7, and 8, gave usable S-P time intervals. The distances shown in the figure were calculated using a P-wave velocity of 5850 m/s and a ratio of P- to S-wave velocity of 1.732. The commercial magnetic compass downhole orientation device failed as a result of overheating, but again relative orientation between the boreholes was obtained using the amplitude ratio of the first motions of the horizontal geophones. The values are shown in Table 4-II, and the repeatability of the results within about 2° is encouraging.

TABLE 4-I
ACOUSTIC RANGING RESULTS AT 1.97-KM DEPTH^a

Shot Number	Phase Travel Time (ms)					
	P-Wave			S-Wave		
	H ₁	H ₂	V	H ₁	H ₂	V
1	16.2	16.1	16.2	28.5	27.5	28.0
2	15.8	15.9	15.9	-	-	-
3	16.2	16.2	16.2	27.7	27.9	28.4
4	16.0	16.0	16.1	28.2	28.2	28.2
5	16.1	15.9	15.9	27.4	27.6	27.3

Shot Number	Ratio of S-Wave to P-Wave Phase Travel Time		
	H ₁	H ₂	V
1	1.76	1.71	1.73
2	-	-	-
3	1.71	1.72	1.75
4	1.76	1.76	1.75
5	1.71	1.73	1.72

Shot Number	Chart Amplitude of First Motion (mm)			Resulting Relative Orientation	
	H ₁	H ₂	V	θ(degrees) ^b	φ(degrees) ^c
1	29	11	3	69	6
2	34	20	-	60	-
3	10	5	1	63	5
4	35	13	2	70	3
5	23	7	2	73	5

^aGeophones H₁, H₂, V in GT-2, detonators in EE-1.

$$b_{\theta} = \tan^{-1} \frac{H_1}{H_2}.$$

$$c_{\phi} = \tan^{-1} \frac{V}{\sqrt{H_1^2 + H_2^2}}.$$

TABLE 4-II
AMPLITUDE OF FIRST MOTION AT
2.8-KM DEPTH

Shot Number	H ₁ (mm)	H ₂ (mm)	θ(degrees) ^a
3	20	15.5	52
5	25	20.0	51
7	16	13.0	51
8	45	40.0	48

$$a_{\theta} = \tan^{-1} \frac{H_1}{H_2} .$$

Fig. 4-1.
Geometry of September 20 ranging
experiment.

A ranging experiment at about 2.91 km (9560 ft) was performed September 25, 1975. Signals from two successful detonator firings gave a hole-to-hole distance of about 8 m (26 ft); however, the service company orienting device failed because of a camera malfunction. This experiment was repeated September 30, 1975, again with two successful detonator firings and a GT-2 to EE-1 distance of about 8 m (26 ft). The downhole orientation system worked satisfactorily and the direction from GT-2 to EE-1 was estimated to be nearly due west at that depth.

Present efforts to upgrade the various components needed for successful ranging include a contract for a high-temperature downhole firing package. This system will provide high-voltage pulses to initiate prompt and repeatable firing of the detonators. A mechanical acoustic source (wallbanger) developed at LASL (see Sec 7.2) can now function as an alternate source of acoustic signals and will be used in further ranging experiments. Ranging experiments will continue to be directed toward the immediate goal of mapping the GT-2 and EE-1 boreholes in three-dimensional space.

4.2.2. Acoustic Fracture-Mapping Techniques. Downhole instrumentation capable of detecting and recording high-frequency acoustic signals was ready for use by September 1975. In late September records obtained with this instrumentation established the existence of detectable microseismic events uniquely associated with the reinflation and extension of a hydraulic fracture previously

created in GT-2. Signals from the microseismic events contained sufficient information to determine the foci of the events. If it is assumed, as seems reasonable, that the loci of such events originate from the fracture plane itself, the fracture can be mapped in space (size, shape, and orientation) and time (growth during injection).

Mapping Experiments. In October 1975 an experiment was conducted that recorded enough microseismic events to map the GT-2 fracture. Later, in March 1976, a similar experiment was conducted to map the fracture originating in EE-1. Additional fracture mapping experiments (see Sec. 3) were conducted in May and June.

The borehole and fracture geometry and the geophone positions for the October experiment are shown in Fig. 4-2. The hydraulic fracture to be mapped originated at about 2.80 km (9200 ft) in a lined section of GT-2 that had been perforated and then milled out (see Sec. 7.1.5). Four observation stations were occupied in succession in a water-filled, uncased section of EE-1 by a three-component geophone package capable of being repeatedly repositioned and coupled directly to the borehole walls (see Sec. 7.2). The magnetic compass orientation of the package at each depth was determined from an Eastman Whipstock magnetic survey tool attached to the bottom of the geophone package.

Fluid was injected into GT-2 at a rate of 10.6 liter/s (168 gpm) for 1 h, totaling about 47 m³ (12 400 gal). Each geophone station was occupied for 15 min, and at the end of the experiment the first station was reoccupied for another 15 min. While the geophone package was positioned at the first station, the fracture was being inflated. Fracture extension began some time during occupation of the last three stations. No information was obtained at the second station because the signal from the geophone was temporarily lost.

Fig. 4-2.
Geometry of experiment on October 10.

In March 1976, Experiment 117, an attempt to map the hydraulic fracture originating from the uncased section of EE-1, was conducted. The geophone package was stationed at 2.94 km (9640 ft) (see Fig. 4-3) for 4 h and 30 min (2 h the first day and 2 h 30 min the second day) during which time the EE-1 fracture was inflated to 34.8 m^3 (9040 gal), shut in, and further inflated and extended with an additional 77 m^3 (22 000 gal) of water. Injection rates varied from 10.6 to 13.2 liter/s (168-210 gpm). Only one observation depth was occupied in GT-2 because of the requirement of positioning the magnetic orientation tool attached to the bottom of the geophone package in the unlined section (only 12 m in length) of the hole.

Fig. 4-3.
Geometry of Experiment 117.

Analysis of Discrete Microseismic Signals. The microseismic events observed in these experiments produced signals as shown in Fig. 4-4. The events, originally recorded as analog signals on magnetic tape, were digitized at $50 \mu\text{s}/\text{sample}$

Fig. 4-4.
Geophone records of two characteristic microseismic events from an inflated fracture showing P- and S-wave arrivals.

and bandpass filtered between 750 and 2250 Hz for analysis. This filter selection was empirically determined as a compromise in avoiding unacceptably high noise levels at low frequencies and in introducing an acceptably small aliasing in spectral analyses.

The signals exhibit discernible P- and S-wave arrivals. The time interval between the arrivals can be measured, and the propagation velocity of the respective waves is known; therefore, the distance to the source of events can be determined. Generally, an S-wave arrival can be identified with little difficulty. It shows up clearly within the P-wave coda of signals as a high-amplitude arrival on vertical geophone records and as a phase and amplitude change on the horizontal geophone records. This is not the case with the P-wave onset, because the signal, possibly as a result of filtering, emerges gradually above the noise. Under the assumption that the filtering process is functioning properly, the combined error in estimating the time interval between the P- and S-wave arrival times is about ± 0.5 ms, resulting in a 4-m uncertainty in distance determinations.

Provided that the time interval between P- and S-wave arrivals from an event can be determined and that the wave velocities are known, only the arrival direction of the signal is needed to define the focus of an event. Because P-waves are linearly polarized in the direction of signal propagation, the azimuth and inclination of the signal polarization describes the direction to an event focus. The signal azimuth and inclination can be determined by inspecting velocity hodograms of two components of the velocity amplitude of a signal constructed from the geophone recordings. Figure 4-5 is a sequence of hodograms of a signal arrival recorded by the horizontal geophones. Clearly shown is the noise before P-wave arrival, P-wave onset, linear polarization of the P-wave defining the signal azimuth, and S-wave onset. The inclination to the source can be determined from a similar hodogram, one axis of which would necessarily be the vertical component of velocity amplitude.

The interpretation of signals arriving at a geophone package position with an inclination of less than 20° is unambiguous. Signals arriving at greater angles show a circular polarization at the beginning of the P-wave coda, and in this case, focus determinations cannot be made. Although the cause of the apparent abnormal polarization is uncertain, the polarization probably represents a partial conversion of P-waves into surface waves traveling at the borehole wall or into resonant vibratory modes of the geophone package. This angular limitation in focus determinations has restricted the mapping of hydraulic fractures

Fig. 4-5.

Representative hodograms of a microseismic signal (8-ms total time) received at the horizontal geophone.

in the vertical dimension to that which can be accomplished by repositioning the geophone package vertically in the borehole. For convenience, maps of seismic event foci are presented as projections of foci to the horizontal at the depth at which the events were recorded. Further, although the P-wave onset can be determined to within a cycle, the sense of the first arrival is usually uncertain. Consequently, a 180° ambiguity exists in azimuth measurements. This ambiguity is identified on maps as North designated by N(S). The direction to a fracture defined by microseismic event foci is resolved once the relative positions of the boreholes are determined from conventional magnetic survey logs. The orientation of a fracture shown on a map is unaffected by the ambiguity because the maps are centro-symmetric.

Measurements of Continuous Radiation. Continuous seismic radiation was observed during the October experiment. The signal is clearly seen when records containing the microseismic events are low-pass filtered at 30 Hz. Figure 4-6 shows the radiation as it is recorded on each geophone component. Although a

Fig. 4-6.

Geophone records of continuous seismic radiation from the GT-2 fracture induced by pumping.

thorough study of these signals has not been made, the radiation appears useful in determining fracture orientation.

The dominant frequency of the radiation is 7 Hz, which corresponds to the frequency of pump strokes during injection. The signal appears only after the volume of fluid injected into the fracture approaches that necessary for extension. A hodogram of the horizontal velocity amplitude components of the radiation, Fig. 4-7, shows that the radiation is elliptically polarized with the azimuth of the major axis of the ellipse closely corresponding to the fracture direction that is defined in maps of microseismic event foci. As a consequence, inferences can be made that the radiation is excited by pumping induced pressure fluctuations in the wellbore from which the fracture originates, and that the signal detected results from disturbances traveling along the fracture face.

Measurements based on records of continuous radiation are of limited use, because without substantial advances in theory neither the distance to a hydraulic fracture from an observation station nor the size of a fracture can be determined. Nonetheless, the method has provided additional measurements of fracture orientation, and for this reason, is important to develop.

Fig. 4-7.

A hodogram representative of the continuous seismic radiation observed during the October experiment (2-s total time). The N(S)-direction is along the y-axis.

Results of the October GT-2 Fracture Mapping Experiment. A total of 144 high-amplitude microseismic signals were detected during 35 min of observations. Forty-eight of these events produced signals that had a sufficiently large signal-to-noise ratio during the P-wave onset so that analytical results could be obtained.

Figure 4-8a shows a projection to the horizontal at 2.81 km (9210 ft) of the foci of events occurring during the initial 13.5-m^3 (3560-gal) inflation of the GT-2 fracture. EE-1 is located at the origin; radii are given for the distance to foci in terms of the time interval between P- and S-wave arrival times in milliseconds, and also in terms of the estimated distance to the events. Recent study of an uncertainty in the time intervals indicates that the distances shown in Fig. 4-8 will change somewhat as the filtering procedure is improved. Activity was clustered and is probably occurring near the GT-2 borehole. The trace of the fracture plane strikes $\text{N}27^\circ\text{W}$.

The activity at 2.94 km (9650 ft), when the injected water volume increased from 26.0 to 29.2 m^3 (6870 to 7720 gal), is shown in Fig. 4-8b. The data are of sufficient quality and number to define the fracture. Activity was less

(a)

(b)

(c)

(d)

Fig. 4-8.

Foci of microseismic events recorded at (a) 2.81 km during the initial period of inflation, (b) 2.94 km during inflation, (c) 3.00 km during inflation, and (d) 2.81 km during shut-in after inflation.

pronounced and occurred over a shorter band. At this observation depth, 140 m (460 ft) below the first station, the strike of the fracture is N40°W.

The activity 60 m (190 ft) deeper at 3.00 km (9840 ft), when the injected fluid was increased from 35.0 to 36.5 m³ (9250 to 9640 gal), is shown in Fig. 4-8c. The number of events that occurred was less than at other depths. Results show that the strike of the fracture has increased to N63°W.

When the station at 2.81 km (9210 ft) was reoccupied, fluid injection had been stopped at 47.2 m³ (12 400 gal) and the system had been shut in at the operating pressure. The events that occurred during this interval are shown in Fig. 4-8d. Even though injection had ceased, activity was pronounced. Comparison with Fig. 4-8a shows that in the period between successive observations at this depth, activity had increased to extend along a line exceeding 170-m length. The orientation of the fracture is clearly defined as N27°W.

Table 4-III summarizes the information contained in the fracture maps. The length of the fracture at 3.00 km (9840 ft) is considerably less than that at 2.81 km (9210 ft). This observation, combined with the reduced activity at 3 km is evidence that the fracture probably terminates near this depth. Pronounced activity and the greatest fracture length is found at 2.81 km -- an indication that the fracture extends upward from this depth. Induced potential logs indicate that the fracture probably extends upward at least to 2.70 km (8850 ft) (see Sec. 4.3). The total vertical dimension of the fracture must therefore exceed 300 m (980 ft).

As discussed above, continuous seismic radiation was also observed during the October experiment. Figure 4-9 shows the orientation of the GT-2 fracture as a function of depth and combines the

TABLE 4-III
THE GT-2 FRACTURE DEFINED BY
MICROSEISMIC EVENT FOCI

Depth (km)	Horizontal Length (m)	Orientation
2.81	> 170	N27°W
2.94	> 70	N40°W
3.00	> 35	N63°W

Fig. 4-9.

Apparent orientation of the fracture originating in GT-2 as a function of depth. Circles defined by microseismic events; triangles deduced from records of the continuous radiation.

values derived from records of the continuous radiation with those in Table 4-III for microseismic event foci. The estimated experimental error in each set of measurements is less than $\pm 10^\circ$. The agreement between the orientation derived from each method is good.

The apparent warp of the fracture is best shown by the three-dimensional perspectives given in Fig. 4-10. In the model the fracture is shown as symmetric about the GT-2 wellbore, and the shape of the fracture is represented as a regular form with lateral dimensions corresponding to those determined from microseismic event foci. The lines on the computer-generated fracture surface denote equivalent depths.

The orientation of the fracture with respect to magnetic north changes 30° counterclockwise in the depth interval in which the measurements were made. This amount of rotation is beyond the range of the experimental error. One interpretation of the apparent rotation is that the hydraulic fracture itself may not be warped, but rather the direction of the ambient magnetic field (used for determining geophone package orientation) may change over the vertical distance of measurement. Because conventional magnetic borehole surveys of GT-2 before fracturing do not show any anomaly at the depths in question, this is probably not the case. If, on the other hand, the warp of the fracture is real, it must be produced by the stress distribution changing with depth in the host rock.

Results of Experiment 117-EE-1 Fracture Map. Eighty microseismic events occurred during this experiment. Fifteen of these occurred during Phase 1 of the experiment and appeared to be randomly distributed in time. Only 6 of these 15 events gave meaningful information for mapping purposes. The remaining 65 events occurred during Phase 2. The rate of occurrence of these events, which was initially less than one event per minute, doubled in the later part of the experiment. No fracture map could be derived from the Phase 2 data. The inability to determine the focus of more events resulted from low signal-to-noise ratios during P-wave arrivals, which made identification of the P-wave onset and measurement of the direction to the source of the event uncertain.

The results for Phase 1 are shown in Fig. 4-11. Using our present wave form analysis techniques, the closest approach of the EE-1 fracture to the GT-2 borehole at 2.94 km (9650 ft) is 21 ± 6 m (69 ± 18 ft). The lateral extent of the fracture is about 48 m (160 ft). The directional strike of the fracture is $N53^\circ W$, which corresponds within measurement accuracy to the GT-2 fracture orientation at this depth.

Fig. 4-10

Three-dimensional perspectives of the fracture originating in GT-2. Views are horizontal at depth of 2.80 km. Distances given are in meters. Angle of rotation around the vertical axis in (a) 10°, (b) 45°, and (c) 60°. (Figure prepared by D. Willerton, J. McClary, and A. Eddy.)

Fig. 4-11

Foci of microseismic events recorded during Experiment 117.

After the March experiment, the orientation of the EE-1 fracture at the wellbore was measured using information derived from two conventional borehole logs, i.e., a temperature and an iodine isotope survey. Both logs provided an additional measure of the length of the borehole-hydraulic fracture intersection through which water can either be injected or returned. Assuming that the EE-1 fracture is vertical, knowledge of the length of the borehole-fracture intersection enables the fracture orientation to be calculated directly from surveys of the drift and dip of the EE-1 wellbore. The N53°W orientation determined by this method agrees within measurement error with the orientation defined from discrete microseismic and continuous seismic radiation data.

4.3. Electrical Techniques (R. L. Aamodt, F. West, and P. Kintzinger)

4.3.1. Spontaneous Polarization Logs. Potential differences between two points in the Earth arise from several mechanisms, such as differences in ion concentration in ground water or preferential absorption of a charge on capillary walls carrying water. If one electrode is emplaced on the surface near the top of a wellbore and a second is immersed in the water column inside the wellbore, as in the EE-1 pipe shown in Fig. 4-12, the potential difference between the two points can be measured by a voltmeter or potentiometer at the surface. A plot of these potential differences as a function of electrode

Fig. 4-12.

Arrangement of electrodes for induced potential logging.

Fig. 4-14.

Spontaneous polarization logs taken before and after fracturing, showing intersection of fracture with wellbore.

depth in the wellbore constitutes an SP (spontaneous polarization or self-potential) log. Anomalies characterized by large localized fluctuations in potential have proved useful as an indication of permeable zones in the adjacent rock (Fig. 4-13), and changes in the SP curve have been used to determine where a newly made fracture intersects a wellbore (Fig. 4-14). However, because SP curves taken a few days (or even a few hours) apart often differ, and because

Fig. 4-13.

Spontaneous polarization log indicating porous region.

details of the causes of SP anomalies are unknown, their interpretation is highly subjective and requires confirmation by other means.

4.3.2. Induced Potential Logs. By introducing a current source into one wellbore and measuring the resultant potential in the other (as shown in Fig. 4-12), and by using the same detection and recording system used for the SP measurement, many of the difficulties of SP log interpretation can be avoided. In this method, called induced potential (IP) logging, the current source is reversed in polarity every few seconds and the differences in the detected signal amplitude are measured. The result of an IP log in GT-2, taken after a fracture was created in EE-1 near 1.96 km (6440 ft), is shown in Fig. 4-15. The fracture apparently grew upward, and the top and bottom are well defined. Figure 4-16 shows the result of a log in EE-1 with the GT-2 fracture in inflated and deflated condition. The difference between the measured voltages was small, as the fracture

Fig. 4-15.
Induced potential log delineating fracture.

Fig. 4-16.
Induced potential logs showing extension of top of GT-2 fracture.

is evidently partially open (self-propped) when deflated. However, a region of newly created fracture is apparent, defining the top of the GT-2 fracture near 2.68 km (8800 ft). The IP technique is applicable only in uncased portions of a wellbore and is most useful if a background run can be made before a fracture is created.

4.4. Advanced Mapping Methods. (J. N. Albright, W. M. Johnson, A. R. Koelle, J. A. Landt, R. M. Potter, and F. G. West)

4.4.1. Acoustic Techniques (Measurements and Data Analysis).

Absorption-Reflection Methods. Recent success with the downhole mechanical seismic source permits field tests of a newly proposed method for measuring the vertical extent and orientation of hydraulic fractures. The method uses observations of phenomena that form the basis of the much more advanced techniques now used in the seismic exploration industry.

The method requires positioning, in separate boreholes or the same borehole, a signal source system and a geophone detection package capable of measuring orientation. Because the fractures to be measured are always vertical and the boreholes are not, source-detection positions can be found in each borehole such that the hydraulic fracture, if it extends to the depth of observation, is either present in or outside the area directly between the boreholes or between source and detector in the same borehole.

At source-detector locations where the hydraulic fracture is between the boreholes, acoustic emission from the signal source will be highly attenuated in shear-wave components as the fracture is intercepted. The detected signal will be rich in compressional wave components and easily distinguishable from signals that passed through only unfractured rock. If, on the other hand, a hydraulic fracture has penetrated the depth of observation but nowhere traverses the area between the boreholes, acoustic emission from the source will be detected as a direct signal through unfractured rock, followed by a partial replica of the direct signal whose shear component has been reflected from the fracture surface; this latter signal will be somewhat attenuated because it has traveled a greater distance. Because acoustic wave propagation velocities are generally known, a measurement of the time between the arrival of each signal and its replica enables the distance from the detector to the fracture face to be calculated. With this method, hydraulic fractures can be detected whether or not they traverse the area between the boreholes. In special cases, the

method gives the distance from the geophone package to the fracture face. A systematic study of a region in which a hydraulic fracture has been created will provide corroborative data on fracture orientation and vertical extent.

Advanced Sonic Ranging. The industrial technique of acoustical imaging and mapping developed for use in diamond drill holes coupled with computer analysis of reflected echoes has improved knowledge about the fault and mineral vein structure between holes. Fluid-filled hydraulic fractures should provide more highly reflective surfaces for the 5- to 20-kHz acoustic waves. Because portions of the emitted wave are specularly reflected from surfaces, the distance of a crack from a wellbore and the vertical extent of the crack may possibly be determined.

Acoustic measurements leading to fracture maps may be obtained from a single wellbore with the absorption-reflection and advanced sonic ranging methods. In both cases, the fracture itself serves as an active reflection or absorption plane for acoustic signals generated within the wellbore. Single wellbore mapping techniques are desirable in implementing directional drilling strategies to intercept target hydraulic fractures with a second wellbore.

4.4.2. Borehole Televier. The borehole televier, a sonar type of device, was developed by the oil industry to map fractures and other downhole features. The oil, geothermal, mineral, and water industries have recognized the importance of the natural fracture system in locating various resources. The detection and borehole mapping of natural and induced fractures is also important to the HDR project. However, present borehole televiers are inoperative at temperatures of 200°C or above and therefore are of limited use to the geothermal industry. The U.S. Geological Survey (USGS) is developing a televier with a higher temperature capability. To assist this effort the Fenton Hill facilities have been made available to the USGS, and further testing of the tool at the site is planned for late 1976.

4.4.3. Magnetic Induction Techniques. The induction log is used by the oil industry to map the electrical resistivity of formations surrounding a borehole. A laboratory demonstration at LASL indicated that the induction log could be modified to detect fractures filled with conductive fluid. Because the proposed tool is a totally new design, industry was unwilling to undertake the design in view of the slight chance of regaining developmental costs. Consequently, design and development was begun at LASL, with industrial participation

planned as work proceeds. EG&G has expressed a willingness to help on electronic design and construction. Two well logging companies, Dresser and Birdwell, have offered to supply "off-the-shelf" hardware and to share their experience in downhole induction techniques.

In addition to the progress made in investigating the interest and capability within industry, significant progress has been made on the design and with fracture analysis. The system has been conceptually designed. Coil rotation will be done electronically, which will require two sets of orthogonal coils. Orientation will be referenced to the Earth's geomagnetic field using a compass or magnetometer, devices that have been used at high temperatures. The electronics will be protected by a dewar to provide proper operation at 250°C. Preliminary analysis indicates that the signal from the fracture is at least an order of magnitude greater than the signal from the surrounding rock. The analysis also indicates that the tool will give the "true" fracture orientation if there is only one fracture. In the unlikely case of multiple fractures, the tool will average their signals and provide a maximum signal that is not a true indicator of fracture orientation.

Several unresolved problems remain. Present induction logs use an epoxy/fiberglass mandrel and housing for the coils that cannot withstand 250°C. It is also not known how much the borehole fluid will affect tool response. Hole eccentricity and tool noncentering may generate spurious signals.

4.4.4. Piezoelectric (Electromagnetic) Signal Measurements. Some effort has continued on the possibility of using natural electric potentials generated by stressing or fracturing rock. The piezoelectric potential of a rock is directly proportional to its stress level, the polarity changing when the stress field reverses from compressive to tensile. The compressive stress field at the wellbore will decrease with increasing pressure until a tensile stress field develops. If the pressure is increased to the point of fracture, the piezoelectric potential should instantaneously drop, while a transient triboelectric or pyroelectric potential is generated. Thermal stresses and thermal stress cracking might also be monitored by this method. The pyroelectric potential can be estimated by the use of the difference in depth of penetration for the two electrode spacings. The electric pulses created by the fracturing should be easily correlatable with acoustic events monitored by the geophone array. Cross-correlation of the relative timing of electric and sonic events should

provide another method of crack delineation. Rock samples collected from the crystalline rock outcrop area are planned to be used in a laboratory determination of the magnitude of electric transients to be expected under various conditions.

5. GEOTHERMAL RESERVOIR PROPERTIES

5.1. Field Techniques (R. L. Aamodt, D. W. Brown, R. G. Lawton, H. D. Murphy, R. M. Potter, and J. W. Tester)

5.1.1. Fracture Inflation and Deflation^{*}

Theory. The local state of stress in the earth may be described in terms of three orthogonal principal stresses, S_1 , S_2 , and S_3 , considered positive in compression, with $S_1 \geq S_2 \geq S_3$. In the absence of active tectonic forces or sharp variations in surface relief, the maximum stress, S_1 , will be vertical and equal to the lithostatic pressure exerted by the overlying rock, whereas S_2 and S_3 will be horizontal. Each stress may be separated into a portion, σ , acting through the rock matrix and a fluid pore pressure, P_o , so that $S_i = \sigma_i + P_o$. The horizontal matrix stresses σ_2 and σ_3 are usually about one third of σ_1 .

When a portion of a vertical borehole is stressed by pumping fluid into it, the walls expand and eventually rupture, creating a crack (hydraulic fracture). As more fluid is pumped into the crack it grows at the tips and becomes wider. Because the rock is most easily displaced against the smallest earth stress, the plane of the crack will normally be perpendicular to S_3 , irrespective of variations in rock strength or preexisting fractures, and this tendency increases with depth. Thus, fractures deeper than about 1 km are usually vertically oriented.

In very competent rock, the initial breakdown pressure is higher than that required to extend the crack because of a stress concentration near the wellbore in addition to the inherent cohesive strength of the rock matrix itself. However, if the rock contains preexisting fractures, as is usually the case, this initial pressure differential may be small.

The pressure required to extend a hydraulic fracture was first derived by Sack,¹ and may be written, ignoring gravitational effects, as

$$P - S_3 = \left[\pi ET / [2(1-\nu^2)R] \right]^{1/2}, \quad (5-1)$$

where P is the crack extension pressure, T is the apparent rock surface energy per unit area of new crack, ν is Poisson's ratio, E is Young's modulus, and R

*All depths in Sec. 5.1.1 are measured from the Kelly bushing.

is the fracture radius. Sack's expression is based on an idealized fracture, shaped like a very oblate spheroid. Other expressions have been developed which are based on different geometries at the crack tip. These methods agree, however, that at large radii the magnitude of $P - S_3$ is small. Table 5-I shows some values of $P - S_3$ evaluated from Eq. (5-1), using values of T , E , and ν derived from sonic logs and fracture experiments, of 100 J/m^2 , $8 \times 10^{10} \text{ Pa}$ ($8 \times 10^5 \text{ bar}$), and 0.25, respectively.

Fracture Stability. The pressure inside a fracture varies with depth, just as it does in a column of water at the same temperature and pressure. The pore pressure component of the earth stress varies with depth in the same manner, so that it just compensates the pressure change inside the fracture. If the matrix stress, σ_3 , were constant over the fracture face, it would be possible to reach the fracture extension pressure simultaneously everywhere on the fracture tip. However, there will generally be a difference between the values of σ_3 at the top and bottom of the fracture,² and the fracture extension pressure will be attained first at one place or the other, causing preferential growth in that direction. This tendency can be reduced by creating the fracture by pumping at a high rate, but it may still be difficult to keep the entire fracture inflated during the heat extraction phase. This problem is likely to be overshadowed in practice by other effects, because the simple theory discussed above does not take into account deposition of materials near the fracture tip, stress corrosion, nonlinear effects, cooling or heating of the rock face, thermal stress cracking, or local variations of pore pressure.

Earth Stress Measurement. When a closed fracture is pressurized, the pressure rises almost linearly until the fracture opens, as shown in Fig. 5-1, which shows the pressure-time history during the initial pump-up of a fracture in GT-2 at about 2-km (6560-ft) depth. When the fracture opens, at a pressure near S_3 , the pressure levels off. Because pressure drops due to the flow of fluid into the fracture, the actual earth stress is usually assumed to be the instantaneous shut-in pressure (ISIP),³ measured immediately after flow stops, plus the hydrostatic pressure of a column of water from the surface to the fracture entrance. Other methods have been devised for measuring S_3 , but are in general agreement with the ISIP method. Increases of about 10 bar (150 psi) in the ISIP during extended pump-ups have been attributed to changes in pore pressure near the wellbore. The surface plant for a heat extraction loop must be designed to withstand the pressure required to hold the fracture open, unless natural self-propping or artificial propping of the fracture is accomplished. Calculations

TABLE 5-I
FRACTURE EXTENSION PRESSURE ($P-S_3$) VS
RADIUS OF FRACTURE (R)

R		P - S_3	
(m)	(ft)	(bar)	(psi)
3	9.8	21.1	306
10	32.8	11.6	168
30	98	6.68	97
100	328	3.66	53
300	984	2.11	30.6

Fig. 5-1.
Surface pressure and flow history of a
hydraulic fracture initiated in GT-2
at about 2-km (6560-ft) depth.

of the pressure drop at energy extraction rates greater than 50 MW(t) from a 200°C reservoir through standard proppant materials give unacceptably high values, so the HDR single fracture concept has evolved under the assumption that the fracture is held open by pressure or that an artificially propped fracture is created by selective removal of the rock itself. Thus values of S_1 and S_3 are important in determining reservoir operating conditions. The results of earth stress measurements in GT-1, GT-2, and EE-1 are shown in Table 5-II. The approximate surface plant pressures are derived by subtracting the hydrostatic pressure of the upwelling water in the hot leg from the value of S_3 at depth. The values of σ_3 are anomalously high for the shallower depths, whereas that near 3-km depth is somewhat low, less than one third of σ_1 . The difference between σ_1 and σ_3 creates shear forces on the rock, and these forces are more

TABLE 5-II
EARTH STRESS MEASUREMENTS

Depth		Approximate Surface Plant Pressure		Pore Pressure (bar)	Total Earth Stress (bar)		Rock Stress (bar)	
(m)	(ft)	(bar)	(psi)		S_1	S_3	σ_1	σ_3
765	2510	75	1090	15	180	147	165	132
1990	6530	153	2220	135	504	333	369	198
2930	9610	115	1670	227	753	367	526	140

likely to cause rupture at high pore pressure. Thus, deeper fractures in GT-2 or EE-1 should be a better source of acoustic signals when pressurized than will fractures at lesser depths.

Rock Integrity and Fluid Losses. Numerous measurements were made on a fracture at almost 2-km (6560 ft) depth in GT-2 to see if the rock was sufficiently impermeable so that a pressurized circulation loop could be operated without excessive water loss. The ambient pore-fluid pressure measured by drill stem hydrology tests was that of a column of water with its top at 500 - 600 m (about 1700-2000 ft) depth, that is, an ambient pore pressure of about 800 psi subhydrostatic to the full wellbore. When a fracture is newly formed or extended, some of the fluid that permeates into the rock cannot be recovered because the wellbore pressure at full hydrostatic is about 55 bar (800 psi) higher than the ambient pore pressure. However, after a fracture has been pressurized for several days to at least surface hydrostatic pressure, an enhanced pore-pressure field exists around it, and recovery rates are higher. Recovery of injected water is also improved when the impedance at the entrance to the fracture is lowered. Near the end of the GT-2 fracture experiments at 1.9 km (6500 ft), about 4300 kg of sand was pumped into the GT-2 fracture to prop it open when deflated. In subsequent tests the fracture was pressurized to 140 bar (2000 psi) and held at that pressure until 7615 liter (2012 gal) had been injected; 92% of the injected water was recovered, the highest percentage recovered at this depth. There do not appear to be any regions of high permeability over this fracture face, although the fracture radius was calculated to be more than 200 m (650 ft). A very porous zone was observed in EE-1 between 2073 and 2088 m (6800 and 6850 ft), whereas a fracture in the same hole at 1962 m (6440 ft) appeared on electric logs to have grown upward.

The fractures at 2940 m (9650 ft) in EE-1 and 2810 m (9220 ft) in GT-2 also showed no highly permeable zones.

During a fluid-time-residence study that began March 23, 1976 (Experiment 115), the EE-1 fracture was pressurized to about 90 bar (1300 psi) for 35 h while 227 400 liter (60 080 gal) were injected into EE-1, with GT-2 flowing (see Sec. 5.1.4). A total of 204 000 liter (53 900 gal) was eventually recovered from GT-2, almost 90% recovery. Questions remain about the ultimate loss rate from a large, continuously pressurized system [there are indications that permeability increases as the pore fluid pressure is raised (see Sec. 5.1.2)],

but the observed losses in short-term tests have been unexpectedly low, so the long-term prognosis is favorable.

Fracture Dimension. Sneddon's⁴ expression for the radius of a penny-shaped crack,

$$R = \left[\frac{(3/16) EV}{(1-\nu^2)(P-S_3)} \right]^{1/3}, \quad (5-2)$$

where V is the volume of fluid in the fracture and other symbols are as defined in Eq. (5-1), may be combined with Eq. (5-1) to eliminate $P-S_3$, giving crack radius in terms of volume. With the values for the constants given in Eq. (5-1) this expression may be written

$$R(m) = 1.79 [V(\text{liter})]^{0.4} \quad \text{or} \quad R(\text{ft}) = 10[V(\text{gal})]^{0.4}. \quad (5-3)$$

Computer calculations show that 60 - 80% of the volume pumped into a newly created fracture in rock of 0.3 microdarcy permeability is effective in extending the fracture, with the higher values corresponding to higher pumping rates (10 liter/s). The remaining 40 - 20% of the injected volume goes into fracture face permeability or fracture inflation without extension. Thus the fracture in EE-1 near 1963 m (6440 ft), in which about 2300 liter (608 gal) were injected at 0.57 liter/s (9 gpm) should have a radius of about 35 m (115 ft).

From the IP measurements discussed in Sec. 4.3.2, the distance from top to bottom appears to be about 110 m (350 ft). If the fracture were penny-shaped its radius would be 50% greater than calculated from Eq. (5-3). However, because the fracture grew preferentially upward, it was probably elongated in that direction, and the disagreement may be less than indicated. Our conclusion is that radius calculations based on penny-shaped crack theory are probably valid within 50%, sufficiently accurate for permeability calculations but probably not for reservoir heat-extraction modeling (see Sec. 6.1). Fracture measurements by acoustic techniques, as discussed in Sec. 4.2, appear to be more definitive in specifying fracture geometry.

Fracture Flow Impedance and Propping. The fracture experiments at 1900 m (6500 ft) done on September 15, 1974 consisted of repeated fluid injection and

shut-ins during which the pressure decayed as fluid permeated into the fractured region. Shut-in curves were matched by a radial diffusion model from the wellbore but could not be matched by a planar model, typical of diffusion into the face of a fracture. Calculated permeabilities for the radial model were about 10^{-4} darcies, assuming a closed fracture and uniform permeation from the entire uncased section of the wellbore. This result is 4 orders of magnitude greater than the permeability measured on GT-2 core samples (see Sec. 5.2.2). A more logical assumption is that the fracture itself is not completely closed but does present a high impedance to flow.

By assuming laminar flow between the faces of the fracture, the effective permeability or conductance of the fracture itself is $(W^2/12) \times 10^{12}$ darcies, where W is the fracture width in meters. For the observed conductance and wellbore height of 61 m, the equivalent fracture width is about 42 μm . Additional evidence that supports the fracture flow impedance hypothesis is the observed change in the pressure-time behavior during fracture inflation after the fracture was propped open by injecting 3400 kg (7500 lb) of 20 - 40 mesh sand and 907 kg (2000 lb) of 10 - 20 mesh sand on September 28, 1974. Before propping, about 2 min of pumping at 2.65 liter/s (42 gpm) were required to reach 124 bar (1800 psi); after propping, 25 min were required. In addition, after propping, injection pressure varied linearly with the square root of time with a constant injection rate. This behavior corresponds to a one-dimensional model with permeation perpendicular to the faces of a high fluid conductivity fracture. By applying the techniques developed in Sec. 5.1.2, a fracture area - square root of permeability ($A\sqrt{k}$) product of $2.4 \times 10^{-5} \text{ m}^3$ was calculated.

Summary of Fracture Experiments. Several attempts to fracture GT-2, using open-hole packers to isolate the desired region, were made during interruptions in drilling. These experiments were designed to show that granite could be fractured at reasonable surface pressures and to measure fluid losses. No clearly defined fracture was produced during these experiments, which are summarized in Fig. 5-2, because of packer malfunctions. After a steel liner was cemented in GT-2 between 1920 m (6300 ft) and 1981 m (6500 ft), packers were set in the liner, and the region below was fractured. Figure 5-3 summarizes the inflation experiments in this region. One fracture was made through perforations in the liner at 1943 m (6375 ft). As shown in Fig. 5-4, the pressure required to create and grow this fracture was much higher than for the adjacent open-hole

fracture of Fig. 5-1. This behavior has been found to be characteristic of fractures induced through liner perforations, but does not appear to be caused by pressure drops in the perforations themselves, as the pressures remain high at low flow rates.

After completing the GT-2 borehole, a metal liner was cemented in, leaving about 12 m (38 ft) of open hole below the liner. Numerous fracture-inflation experiments, summarized in Figs. 5-5 and 5-6, were done in this region. During these experiments fracture-inflation pressure was measured, the effects of increasing the local pore-fluid pressure were studied, the permeability of the rock was measured, a way of

Fig. 5-2.
Tabulation of mechanical and inflatable packer experiments in GT-2.

Fig. 5-3.
Summary of GT-2 fracture inflation experiments.

Fig. 5-4.

GT-2 perforation fracture at 1943 m (6375 ft) - pressure and flow history.

Fig. 5-5.

GT-2 pressurization history from day 25 to 75 in 1975.

Fig. 5-6.

GT-2 pressurization history from day 105 to 130 in 1975.

Fig. 5-7.

Pressure history for perforation fractures in GT-2.

measuring the relative area of the fracture as it grew was found (see Sec. 5.1.2), and techniques for acoustic mapping of fractures were developed (see Sec. 4).

A series of perforations were then created in the metal liner, to study the variation of earth stress with depth and to attempt to grow two fractures in the same wellbore together by pressurizing them simultaneously. As may be seen in Fig. 5-7, these fractures did not show repeatable behavior, but often required higher pressure to reopen a fracture than was initially required to create it. These fluctuations were attributed to clogging of the perforations from suspended solids in the wellbore, and consequently no further information could be learned about stress variation with depth. The fractures at 2880 and 2911 m (9450 and 9550 ft) were pumped simultaneously in an attempt to grow them together. When

only the lower fracture was pressurized, no communication was found between the fractures. Although these experiments were preliminary, the method of growing fractures together by simultaneous pressurization needs more study before it is eliminated as a reservoir preparation technique.

During the directional drilling of EE-1, as the EE-1 wellbore approached the GT-2 fracture, the fracture was pressurized continuously so that if it was intersected, an observable drop in pressure would result and fluid would flow up the EE-1 borehole. The pressure history during this time is shown in Fig. 5-8. When drilling in EE-1 was completed (on day 283) at a depth of 3064 m (10 053 ft), a small flow of about 0.06 liter/s (1 gpm) was observed, coming from GT-2 into EE-1 near 2880 m (9450 ft). The GT-2 pressure response, however, did not show any appreciable change as shown on Fig. 5-8. The EE-1 well was fractured, using an inflatable packer at 2926 m (9600 ft), in an attempt to improve communication between the wells. Some improvement was noted, and further experiments have been devoted to study of this two-fracture system (see Secs. 5.1.2-5.1.6).

Fig. 5-8.
GT-2 pressurization history from day 272 to 291 during
the EE-1 directional drilling program.

5.1.2. In Situ Permeability. The product of the area of a fracture times the square root of the permeability of the surrounding rock can be measured by pumping into the fracture at a constant flow rate. By assuming constant, one-dimensional, permeable flow into a homogeneous porous media from the faces of the fracture and by also assuming that the hydraulic conductivity of the fracture is very large compared with that of the rock, the surface pressure P in Pa is given by⁵

$$P = \frac{2\mu\dot{Q}}{kA} \sqrt{\frac{Kt}{\pi\bar{\beta}}} \quad (5-4)$$

where

- $\dot{Q}$ = volumetric flow rate, m^3/s
- k = permeability, m^2
- μ = fluid viscosity, $Pa \cdot s$
- A = total permeating surface area, m^2
- $K = k/\bar{\beta}\mu$ = hydraulic diffusivity, m^2/s
- t = time, s
- $\bar{\beta} = \phi\beta_w + (1-\phi)\beta_r$ = mean compressibility, Pa^{-1}
- ϕ = porosity
- w = water
- r = rock

Equation (5-4) assumes that the ambient pore fluid pressure is fully hydrostatic and predicts a linear relationship between P and $\sqrt{t}$. Furthermore, the slope of these lines, $P/\sqrt{t}$, is related to the area times the square root of permeability, $A\sqrt{k}$, by rewriting Eq. (5-4) as

$$A\sqrt{k} = 2 \sqrt{\frac{\mu}{\bar{\beta}\pi}} \frac{\dot{Q}\sqrt{t}}{P} \quad (5-5)$$

Using appropriate rock and water properties at 200°C,

$$\begin{aligned} \bar{\beta} &= 2.723 \times 10^{-11} \text{ Pa}^{-1} \\ \mu &= 0.00014 \text{ Pa} \cdot s \text{ (0.14 centipoise),} \end{aligned}$$

$A\sqrt{k}$ can be expressed as,

$$A\sqrt{k} = 2560 \frac{\dot{Q}\sqrt{t}}{P} \quad [m^3] \quad (5-6)$$

In actual practice, it is not the pressure in the fracture that is measured but the surface wellhead pressure, which is equal to the fracture pressure minus the hydrostatic contribution with corrections for system pressure loss. This pressure loss consists of losses due to friction and form drag in surface piping, flowing friction in the wellbore, and, as the flow enters the fracture, an additional wellbore-to-fracture impedance. Because the flow rate is constant, the pressure loss due to these effects is also constant and can be estimated by extrapolating the pressure curves to zero time.

Typical data for the GT-2 and EE-1 fractures are presented in Figs. 5-9 (a and b). The GT-2 test was conducted January 27, 1976 by pumping into the GT-2 fracture at a constant rate of 2.1 liter/s (34 gpm). A plot of P versus $\sqrt{t}$ provides a good fit to Eq. (5-4), and from the slope of the straight line and Eq. (5-5) $A\sqrt{k}$ for the GT-2 fracture at this time was $5.2 \times 10^{-5} \text{ m}^3$.

Deviation of the late-time data from the linear fit is thought to be caused by pressure-dependent permeability effects. As will be shown, the rock permeability is dependent on pore pressure, and such deviations are to be expected as the pressure in the fracture is increased. Furthermore, because the results

Fig. 5-9.

Surface injection pressure as a function of the square root of time. (a) Flow into GT-2 at 2.1 liter/s (34 gpm) in Experiment 113 on January 27, 1976. (b) Flow into EE-1 at 2.1 liter/s (34 gpm) in Experiment 110 on January 13, 1976.

described above were obtained with an initial pore pressure of zero (taking full wellbore hydrostatic pressure as the baseline) the $A\sqrt{k}$ derived is more properly designated $(A\sqrt{k})_0$.

An extrapolation of the linear fit in Fig. 5-9a to zero time provides an estimate of 7.8 bar (115 psi) for the pressure losses between the surface and the fracture. Although this pressure loss is probably not linear with flow rate, especially at much higher flow rates, it is instructive, for purposes of comparison, to divide it by the flow rate to yield a specific impedance. Using this technique, the specific impedance from the surface to the GT-2 fracture is 3.7 bar·s/liter (3.4 psi/gpm), which as we will show later is small compared with the overall circulation impedance.

The EE-1 results (Fig. 5-9b) were obtained January 13, 1976, also while pumping at a rate of 2.1 liter/s (34 gpm). Again, a good linear fit to the data was obtained, leading to an $(A\sqrt{k})_0$ of $1.6 \times 10^{-5} \text{ m}^3$ for the EE-1 fracture at this time. Extrapolation to zero time yields a pressure loss of only 2.5 bar (30 psi), and a specific impedance of 1.2 bar·s/liter (1.1 psi/gpm). As expected, the GT-2 surface-to-fracture specific impedance is higher because the water in GT-2 must flow through smaller production tubing and downhole perforations and/or a damaged section of the liner.

These values of $(A\sqrt{k})_0$ are most useful when they are interpreted as a parameter that characterizes a fracture. Changes in $(A\sqrt{k})_0$ indicate irreversible change in a fracture, for example, fracture extension.

A historical summary of the $(A\sqrt{k})_0$ for both fractures is presented in Fig. 5-10. Since its creation during the sustained pumping of October 1975, the GT-2 fracture has not changed significantly. This is not the case for the EE-1 fracture. The EE-1 fracture, since its creation on October 15, 1975, has been enlarged during the course of several flow experiments. Although both maximum pressure and total volume pumped are important parameters governing the extent of fracture enlargement, pressures greater than 90 - 100 bar (1300 - 1450 psi) are required to extend this fracture.

Fig. 5-10.
Summary of $(A\sqrt{k})_0$ for the GT-2 and EE-1 fractures.

The effects of pore pressure on $A\sqrt{k}$ are indicated in Fig. 5-11. These results were obtained from Experiment 111. The sequence of operations was to first pump into the fracture until a pressure of 28 bar (400 psi) above hydrostatic was reached, and then adjust the flow rate such that this pressure was maintained for 2 h. Consequently, a new pore pressure is established in the rock surrounding the fracture. Following the 2-h "soak" the procedure was repeated at the additional pressure levels shown in the figure. The start of each change in pressure level was taken as a new zero time, and the results, when plotted versus $\sqrt{t}$, yield straight lines as shown. Using the principle of superposition, the $A\sqrt{k}$ for each increment of pressure can be calculated; the results are indicated on the figure. Increasing the pore pressure from 0 to 69 bar (1000 psi) above hydrostatic resulted in a factor of 3.8 increase in $A\sqrt{k}$. Because A did not change (that is, the pressure was kept below the fracture extension pressure), the permeability must have increased by a factor of 15.

Additional permeability data for the EE-1 fracture were obtained in Experiment 114. These results and those from Experiment 111 are plotted in Fig. 5-12

Fig. 5-11.

The effect of pore pressure on $A\sqrt{k}$ during Experiment 111. Each line represents a pressurization from the previously established pressure maximum.

Fig. 5-12.

Relative permeability as a function of the change in pore pressure above full wellbore hydrostatic.

and show that the permeability increases sharply (up to a factor of 100) as the pore pressure is increased from 0 to 90 bar (1300 psi).

Examination of the results of earlier experiments with the original fracture extending from the bottom of GT-2 indicates similar increases in permeability with pore pressure. A series of pressurizations, using amounts of injected fluid calculated so as not to increase the fracture size, was performed in March 1975, when the GT-2 hydraulic fracture originated from the open-hole region below 2930 m (9607 ft). The P vs $\sqrt{t}$ results for seven experiments are shown in Fig. 5-13. The day 58 line was obtained from the early pressure history of a 4600-liter (1200-gal) injection. The six following injections did not exceed 3000 liter (800 gal) in size and had different initial pore pressures (taking full wellbore hydrostatic pressure as the zero base) which were obtained by either shutting-in previous pressurizations overnight or by venting overnight. Values of $A\sqrt{k}$ corrected for the system compressibility were calculated for each injection, according to Eq. (5-5). The values of $A\sqrt{k}$ for days 62 and 69 were identical and by definition represent the value of $A\sqrt{k}_0$ for this particular fracture. A dimensionless permeability ratio $\sqrt{k}_0/\sqrt{k}$ was calculable from these values because A was constant. This ratio decreases linearly with the initial pore pressure, as shown in Fig. 5-14.

Another series occurred during the continuous inflation of the GT-2 fracture in October 1975 with the fracture now initiated from 2.81 km (9220 ft). Figure 5-8 gives the pressure history of the various inflations either with the small Kobe pump (about 0.6 liter/s) or the high-capacity service company pump (about 11 liter/s). During this period the present GT-2 hydraulic fracture at 2800 m (9200 ft) was initiated either through perforations or a failure in the cemented steel liner (see Sec. 3). Examination of the pressure records shows that the fracture was formed during the pressurization on day 273 and was further enlarged by the two pressurizations on day 274. The small Kobe pump kept the system pressure above 69 bar (1000 psi) in a series of seven major flows ranging from 9500 to 61 000 liter (2500 to 16 000 gal). Each flow was followed by a shut-in period in which the pressure slowly declined. Figure 5-15 shows the pressure as a function of the square root of time for these events.

The results from these two fractures in GT-2 and Experiments 111 and 114 in EE-1 are combined in Fig. 5-14, which shows $\sqrt{k}_0/\sqrt{k}$ versus pressure above hydrostatic. The combined data show a definite linear trend with a calculated abscissa intercept of 102 bar (1480 psi). A value of zero for the ratio $\sqrt{k}_0/\sqrt{k}$ would

Fig. 5-13.
Wellhead pressure as a function of the square root of time
for constant rate injection into the fracture originating
from the open hole region below 2930 m (9607 ft) in GT-2.

mathematically imply infinite permeability at the face of the fracture plane at this pressure. A reasonable interpretation would be that when the pressure approaches the maximum horizontal component of earth stress, S_2 , the effective stress in the S_2 direction approaches zero with concomitant opening of microfractures. This conclusion is similar to that reached by Brace⁶ and others. The least squares line using the entire data set has the equation

Fig. 5-14.

The square root of the ratio of permeability at full well-bore hydrostatic pressure (k_o) to that at a pressure above hydrostatic (k) as a function of pressure above hydrostatic.

$$\sqrt{\frac{k_o}{k}} = 1.00 - 0.0098P \text{ (bar)}, \quad (5-7)$$

and the value at $\sqrt{k_o}/\sqrt{k} = 0$ of 102 bar (1480 psi) is believed to be an estimate of S_2 at about 2820 m (9250 ft).

5.1.3. Flow Impedance Testing. The circulation of flow through the present downhole system, apparently consisting of two nearby hydraulic fractures, is characterized by high impedance. Figure 5-16 presents results of an experiment in which EE-1 was pumped while GT-2 was vented. Because buoyancy effects are not important in short-term experiments, the net pressure difference is simply the EE-1 pressure, whereas flow recovered at GT-2 is the net, circulated flow. As Fig. 5-16 shows, a linear relationship exists between the pressure difference and the circulated flow rate. The slope of the line yields the specific impedance, which for this experiment is 142 bar·s/liter (130 psi/gpm).

Fig. 5-15.

Wellhead pressure as a function of the square root of time for constant rate injection into the fracture originating from the liner at 2820 m (9250 ft). The numbers indicate the time sequence of pumping events and show that the fracture has not grown during this large injection of fluid at low pumping rates.

Fig. 5-16.

Recovered GT-2 flow rate as a function of EE-1 injection pressure for Experiment 106.

The impedances associated with surface piping, flowing friction in the wellbore, and wellbore-to-fracture pressure losses are very small compared to this total circulation impedance; consequently, most of the impedance is associated with the flow paths between the two fractures.

The results of many flow circulation tests indicate that flow appears in the vented wellbore in two or more time phases indicating different communication paths between the fractures. In the first phase, flow appears at the venting well less than 10 min after fluid is injected in the other wellbore. Because this response time is so fast compared to the calculated response time for low-permeability granite separated by distances of a few meters or more, this early-

phase of flow must be via a set of natural fissures, or a zone of locally high permeability, or even possibly by means of an intersection of the two hydraulic fractures themselves.

Following this early-arriving flow, a slow but steady increase in flow rate is observed. This flow component is most likely caused by permeation of water through the rock connecting the two hydraulic fractures. As expected, this additional increment of flow rate varies with time and the pressure levels at the two boreholes as well as the sizes of the fractures. Because of the very large increase in permeability with pore pressure, an overlapped fracture matrix permeability communication path can be very significant, particularly for long-term tests, or for tests in which both wellbores are pressurized to high levels.

In terms of a specific impedance the considerations above suggest that long-term flow tests are characterized by an initially high impedance, which slowly decreases at a rate dependent on the pressure conditions at both boreholes. Figure 5-17 summarizes the results of the impedance tests. The circled data points represent the initial, first phase impedance; the vertical bars represent the full range of transient impedance exhibited during each long-term test.

Anomalous pressure build-up curves obtained during Experiments 102 and 106 (Figs. 5-18 and -19) suggest that the declines in initial impedance observed during these experiments are due to the removal of an impedance in the fractures, possibly a partial removal of rock, water, and drilling fluid interaction products that had partially closed the fractures to flow.

Figure 5-17 indicates that the lowest impedance measured to date is about 30 bar·s/liter (27 psi/gpm). Because of the uncertainties in the area of overlap of the two fractures and the extreme variation of permeability with pore pressure, the minimum value of impedance attainable with the present system is difficult to estimate. In addition, selective removal of material in the rock by leaching could reduce the overall impedance to a value less than 5.5 bar·s/liter (5 psi/gpm) which would be acceptable for a 10-MW(t) energy extraction experiment resulting in a total pressure drop less than 97 bar (1400 psi).

An alternative flow impedance model of this system has also been proposed. In this model, a major fraction of the impedance is caused by fractures partially closed to both wellbores, which results in steep pressure gradients along the fracture faces because of their limited conductances. Because current mapping results (see Sec. 4) for the EE-1 and GT-2 fractures place them only a few meters apart, fracture intersection is at least a reasonable possibility.

Fig. 5-17.

Specific flow impedance history between the EE-1 and GT-2 wellbores in the connected system.

In fact, this may be the source of the early arriving flow. In this model, flow impedances would also be predicted to decrease as the mean pressure of the fracture system increased. As pressure increases above S_3 , the fractures would be propped open and their conductances increased. Selective dissolution of material would also decrease the total impedance if this model is correct. However, the time-dependent nature of the impedance discussed in the preceding paragraphs would not be easily explained by this fracture closure, near-wellbore impedance model. The major difficulty in trying to establish the credibility of either model is that little information is available concerning the pressure field across the fracture faces away from the wellbore.

Fig. 5-18.

A pressure buildup curve during Experiment 102 for flow into GT-2.

Fig. 5-19.

A pressure buildup curve during Experiment 106 for flow into EE-1.

5.1.4. Fluid Residence Time Distribution Studies. During March 23-26, 1976, a fluid residence time distribution (RTD) study (Experiment 115) of the GT-2/EE-1 connected fracture system was conducted. The basic concept was to inject a 380-liter (100-gal) slug of fluid containing 100 ppm of sodium-fluorescein dye into EE-1, pump it down the EE-1 wellbore, through the fractured

zone, and up the GT-2 wellbore. The dye concentration-time (or volume throughput) dependence was then examined by periodically taking fluid samples at the GT-2 wellhead and spectrophotometrically analyzing the solutions to determine dye concentrations.

As the tracer- or dye-containing slug flows through the fractured region it will be dispersed or mixed to a degree dependent on the distribution of fluid circulation velocities within the region. This will result in a residence time distribution that will provide a signature to identify the system flow characteristics and a quantitative measure of the mean residence time that can then be used to calculate an effective fracture volume after the effects of both wellbores have been removed. The mean residence time and the distribution about the mean are important parameters in evaluating and modeling the heat-extraction capability of the system. They are controlled mainly by system geometry, pumping rates, and changes in fluid properties, such as density and viscosity, which affect the flow pattern.

Throughout Experiment 115, the EE-1 surface injection pressure was maintained at 90 bar (1300 psi) while GT-2 was fully vented. With this pressure at EE-1, presumably the EE-1 fracture was at least partially inflated. The results of Experiment 115 can be summarized as follows:

(1) The outlet tracer distribution curve indicated that a substantial amount of mixing and dispersion occurred within the fractured region. The standard deviation about a 7-h mean residence time for a 0.8- to 0.9-liter/s (13- to 14-gpm) flow rate was at least 2 orders of magnitude greater than the initial dye slug width of 380 liter. A 0.55-ppm-maximum dye concentration was observed in the outlet flow, indicating a 200-fold reduction from the injected concentration.

(2) A 30 000- to 38 000-liter (8000- to 10 000-gal) fracture volume is calculated from the measured mean residence time. This is consistent with our latest estimates from permeability and fracture inflation experiments.

(3) No direct short circuit between the EE-1 and GT-2 boreholes was observed. The first arrival of dye at GT-2 corresponded to a minimal flow connection volume of 11 400 liter (3000 gal).

(4) Up to the shut-in of EE-1 flow, with 231 000-liter (60 080-gal) total injected volume 34% of the fluorescein dye had been recovered. With the fracture system fully deflated, about 63% of the dye and 90% of the water were recovered.

A second tracer study, Experiment 119, was conducted on the EE-1/GT-2 system using a 48-bar (700-psi) EE-1 injection pressure, which would be below S_3 and result in a closed (noninflated) fracture system. The outlet RTD curve indicated that dispersion similar to that observed in Experiment 115 occurred. The effective mean fracture volume was somewhat lower, however, about 21 000 liter (5500 gal) vs 34 000 liter (9000 gal).

Because the fracture system volume was still substantial at 48 bar (700 psi) with no direct short circuit (a minimum fracture volume of 7600 liter [2000 gal]), a certain amount of self-propping probably exists. If the system is comprised of two parallel fractures separated by a region of rock 4 - 8 m thick, fracture closure is not complete but may have a relatively small volume compared to the pore fluid volume contained in the overlapped region, possibly $\geq$ 19 000 liter (5000 gal). Dispersion within the rock pore fluid volume could then be the major cause of the observed RTD. However, the extent of possible overlap between fractures is still uncertain. If the system consists of a directly connected set of fractures, then the degree of self-propping is even more pronounced because pore fluid volume effects are not important in determining the RTD, and the total observed dispersion is caused by mixing within the fractured region.

5.1.5. Spinner Surveys.^{*} Standard well logging spinner surveys used for measuring the flow of fluids into and out of perforations in casing, porous zones, or natural open fractures have proven useful in delineating the extent of the intersection of hydraulic fractures with the borehole wall. Such a survey was run in GT-2 during September 1974 and characterized with great detail two collateral hydraulic fractures (Fig. 5-20).

The spinner tool is moved at various velocities up the hole with no flow, and the free turbine wheel records a rate proportional to the logging velocity (about 7.1 rps in the figure). Pumping into the borehole at constant rate produces an additional velocity field, which is additive to the upward logging speed. The increase of 3 rps shown in the figure is equivalent to the increase in fluid velocity in the GT-2 borehole from the pumping rate actually pumped (11.4 liter/s). Half the flow leaves the borehole from 1989 to 1993 m (6528 to 6540 ft) and the other half from 1997 to 2001 m (6553 to 6566 ft). Additional information concerning fracture width and orientation can be obtained from analysis of such curves.

* All depths in Sec. 5.1.5 are measured from the Kelly bushing.

Further attempts to use this technique at greater depths have not been successful because of failure of the instrument at temperatures $> 150^{\circ}\text{C}$. Other techniques, such as temperature logging (see Sec. 5.1.6), have provided information similar to that available from a spinner survey.

5.1.6. Wellbore Temperature

Logging. Temperature logs were made in GT-2 during Experiments 101 and 102 when water was pumped into GT-2 at the constant rate of 0.6 liter/s (9.5 gpm).

In Experiment 101, a background (no pumping) temperature log was conducted on November 6, 1975, and flow test logging was performed on November 7. The results of the logs are shown in Fig. 5-21. Also shown are the results of an earlier tempera-

ture log conducted in March 1975 before EE-1 was drilled and connected to the GT-2 fracture. Figure 5-21 shows major departures from the original (March 1975) temperature log of GT-2. The results of the temperature logs from Experiment 102, conducted November 12, 1975, are presented in Fig. 5-22. The temperature departures do not change significantly with time and suggest that large quantities of cold water have been forced into the interval between 2800 and 2850 m (9186 and 9350 ft) and smaller quantities into the interval between 2880 and 2920 m (9448 and 9580 ft).

The equation describing energy conservation in the flowing wellbore is given in Sec. 6.2 along with the equation describing the heat transfer in the formation surrounding the wellbore. If the assumptions are made that the properties of the material surrounding the wellbore and the wellbore geometry are constant, then a relationship can be derived [see Eq. (6-20)] to describe the ratio of fluid velocities in the wellbore at different depths Z .

Fig. 5-20.
Spinner survey of GT-2--spinner rotation velocity (rps) as a function of depth.

Fig. 5-21.
Temperature logs in GT-2 during Experiment 101.

Fig. 5-22.
Temperature logs in GT-2 during Experiment 102.

In applying this equation, $t_2 - t_1$ must be small compared to t_1 and the wellbore radius must not vary with depth. These conditions are satisfied by the fourth flow log of Experiment 102, which started 430 min after flow initiation, and by choosing the reference depth $Z_1 = 2790$ m. Using Eq. (6-20), the fluid velocities relative to the velocity at $Z = 2790$ m were calculated and are shown in Fig. 5-23 (plotted in the equivalent units of flow fraction). 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. Further analysis of flow temperature logs results in estimates of in situ rock thermal conductivity and temperature gradients (see Sec. 6.2).

Fig. 5-23.
Relative fraction of flow leaving the GT-2 wellbore as a function of depth.

5.2. Laboratory Studies* (J. P. Balagna, L. A. Blatz, R. W. Charles, J. G. Dodson, A. C. Eddy, C. C. Herrick, C. E. Holley, A. W. Laughlin, J. M. Potter, J.-C. Roegiers, W. L. Sibbitt, J. W. Tester, and R. J. Vidale)

5.2.1. Core Studies

Introduction. During the drilling of GT-2 and EE-1, 26 cores totaling about 35 m in length were taken from the Precambrian section. Samples from these cores have been used for various studies (Fig. 5-24) aimed at physically and chemically characterizing the reservoir rocks of the LASL HDR experiment.

Information of this type will be used for predicting and analyzing fracture initiation and growth as well as in characterizing the performance of the system from a geochemical standpoint (see Sec. 5.2.2.).

After each core was collected, a preliminary lithologic log was prepared at the drill site. The cores were then photographed in color for a permanent record before any samples were analyzed. For reconnaissance purposes each different lithology in each core was sampled, and petrographic, chemical, and rubidium-strontium geochronological studies were performed on these samples. Additional samples were taken as necessary for specific purposes such as physical property measurements and certain other geochronological studies.

Numerous studies have been completed or are in progress on the samples. Much of this work has been supported by ERDA-Division of Physical Research funding and done in cooperation with the U.S. Geological Survey, the U.S. Bureau of Mines, and various university groups.

Petrographic Studies. Petrographic characterization of the core was considered basic to all other core studies. The characterization included determining the constituent mineral phases, their abundances and textures, and several fracture-related studies. The fracture studies included measuring the spacing, size, and orientation of fractures, and determining the nature of sealing or healing.

On the basis of texture and mineralogy, and in conjunction with spectral gamma logs and whole-rock chemistry, the Precambrian section can be divided into banded gneisses, schists or amphibolites, biotite granodiorite, and monzogranite dikes.⁷

As determined by modal analysis, most of the banded granitic gneisses have compositions corresponding to monzogranite and granodiorite; a few are tonalitic (International Union of Geological Sciences (IUGS) Classification Scheme), Fig. 5-25.

*In Sec. 5.2. all depths are measured along the borehole from the top of the Kelly bushing on the drill rig platform.

Fig. 5-24.

Flow sheet of core handling procedures and reservoir rock characterization studies completed (*) or in progress in GT-2 and EE-1 samples.

The dominant minerals of the banded gneisses are quartz, SiO_2 , (Q); microcline, a potassium feldspar (KAlSi_3O_8), (A); plagioclase feldspar, 23-25% anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) and 77-75% albite ($\text{NaAlSi}_3\text{O}_8$), (P); and biotite, $\text{K}_2(\text{Fe,Mg})_2(\text{OH})_2(\text{AlSi}_3\text{O}_{10})$, (B). Compositions of the major banded gneisses may be compared by the ratios of Q:A:P:B, from averaged modal percentages: granitic Q:A:P:B = 36:31:28:1; granodioritic Q:A:P:B = 35:13:39:7; and tonalitic Q:A:P:B = 28:<0.5:53:13. Myrmekite, epidote, apatite, sphene, zircon, allanite, amphibole, rutile, and opaques occur as trace or accessory minerals. The gneissic structure is characterized by narrow felsic and mafic bands, delineated by sub-parallel biotite and chlorite laths.

The Precambrian rocks of Fenton Hill show moderate to strong hydrothermal alteration. Alteration products include chlorite, calcite, and sericite. Alteration is greatest near the natural fractures along which water has moved. Laboratory investigations of this natural in-situ alteration will allow prediction of induced alteration resulting from the future long-term rock-water interaction in the reservoir.

The granitic gneisses generally extend over about 1830 m (6000 ft) of the Precambrian section; mafic rocks are common throughout about 610 m (2000 ft) of

Components:

- Q Quartz
- A Alkali feldspar
- P Plagioclase feldspar

Samples from GT-2:

% (Q+A+P) in total rock composition

- 97-99
- 94-96
- ◐ 90-93
- ▲ 85-89
- 73-84

Fig. 5-25.
Quartz-alkali feldspar-plagioclase feldspar (Q-A-P) diagram for the felsic and intermediate rocks of GT-2 (IUGS classification).

- Key:
- 1a - quartzolite (silexite)
 - 1b - quartz-rich granitoids
 - 2 - alkali-feldspar granite
 - 3a - syenogranite
 - 3b - monzogranite
 - 4 - granodiorite
 - 5 - tonalite
 - 6 - alkali-feldspar syenite
 - 7 - syenite
 - 8 - monzonite
 - 9 - monzodiorite and monzogabbro
 - 10 - anorthosite, gabbro, and diorite

the gneissic interval. These mafic assemblages vary in the predominance of schistose vs granoblastic texture, and thus some of the schists are amphibolitic. They also vary in degree of metamorphic differentiation and development of porphyroblasts. The major constituents of these mafic rocks are plagioclase

An₃₆ (42%), ferrohastingsite (14% in the schists, 47% in the amphibolites), biotite (8% in the schists, 2% in the amphibolites), and quartz (15% in the schists, 6% in the amphibolites). Calcite (CaCO₃), and muscovite (a potassium mica) are common alteration products, whereas chlorite ((Mg,Fe⁺²,Fe⁺³)₆AlSi₃O₁₀(OH)₈) is rare. Epidote (a hydrated calcium-aluminum-iron silicate) is a common accessory mineral. Minor constituents are apatite, zircon, sphene, allanite, and opaques.

The major banded gneisses were intruded by an extensive biotite granodioritic body and by two 15-m-thick (50-ft) leucocratic monzogranite dikes, which may be contemporaneous with the granodiorite pluton. The tops of the granite dikes were encountered at the 1300-m (4250-ft) and 2440-m (8000-ft) levels. The dikes are essentially homogeneous and granitoid, with little or no lineation or foliation, and are relatively fine-grained. There is some sericitization and chloritization evident, as well as secondary epidote and calcite.

The biotite-granodiorite pluton extends from about 2600 m (8500 ft) to at least 2910 m (9540 ft) in GT-2. Below this a foliated biotite granodiorite was cored; this may or may not be lithologically distinct from the granitoid biotite granodiorite above it. The main biotite-granodiorite body where current fracture experiments are being conducted is generally fairly fine-grained compared to the gneisses and has a homogeneous granitoid texture. There are localized segregations of monzogranite composition.

The granitoid biotite granodiorite differs considerably from the foliated biotite-granodiorite in modal percentages of the major felsic constituents. The granitoid body contains 10% more microcline, 9% less plagioclase, and 5% less quartz than the gneissic unit at the bottom of the hole. Both contain 12% biotite and high sphene (1-2%) and epidote (1-2%).

Megascopic fracture studies indicate a frequency of visible but closed, or open and mineralized fractures of about 1 per 8 cm, locally increasing to 1 per 1 cm. There are horizontal, vertical, and roughly 60° dipping fractures. Petrographic and scanning electron-microscope and electron-microprobe studies indicate that the cores have undergone multiple microfracturing events followed by healing or sealing.⁸ Calcite is the most common fracture-filling mineral. Other minerals sealing fractures or in mineralized veins include muscovite, biotite, chlorite and pyrophyllite, siderite, hematite and rutile, saussurite or epidote, fluorite, tourmaline, and fine-grained felsic minerals.

Although there is considerable lithologic variability above 2600 m (8500 ft) as determined by the detailed petrographic examinations discussed above, the

reservoir rock below that depth (biotite granodiorite) is remarkably homogeneous. This uniformity of properties, in addition to the observation that fractures are sealed, indicates ideal conditions for the initial heat extraction experiments.

Zircon Morphology Studies. Because of their ubiquitous occurrence in a wide variety of rocks, great resistance to chemical and thermal alteration, and utility in radiometric age studies, zircons have been used as petrogenetic indicators in numerous studies of igneous, metamorphic, and sedimentary rocks. This study was to analyze the morphology and other physical characteristics of zircons from GT-2 core samples and apply this information to the determination of the origin of these rocks. This work was performed by R. A. Heimlich, Kent State University, and will be reported soon.⁹

Zircon separates were prepared from nine core samples from GT-2. Mean elongations, rounding index, euhedrism, nature of overgrowths, extinction angles, presence of truncated zoning, and the reduced major axis were determined on 200 unbroken zircon crystals from each sample. These parameters were then examined in light of criteria in the literature distinguishing between metaigneous and metasedimentary rocks. (See Table 5-III.)

TABLE 5-III
INTERPRETATION OF ZIRCON DATA COMPARED AGAINST PETROGENIC CRITERIA

Criterion of Origin ^a	Sample Number								
	2580	3151-1	3151-7	3698	4283	4896	6153	7102	9521
Mean Elongation	IG? ^b	IG?	SED	SED?	SED?	IG?	SED?	SED	IG?
Rounding Index	SED ^c	SED	SED	SED	SED	SED	SED	SED	SED
Amount of Euhedral Crystals	SED	SED	SED	SED	SED	SED	SED	SED	SED
Amount of Overgrowths	SED	SED	SED	SED	SED	SED	SED	IG	IG
Extinction Angle	SED	SED	SED	SED	SED	SED	SED	SED	SED
Truncated Zoning	SED	SED	SED	SED	SED	IG	SED	IG	SED
RMA Projection	IG?	IG	IG?	SED	IG?	SED	SED	SED	SED

^a First four digits refer to depths in feet.

^b Igneous (or Metaigneous).

^c Metasedimentary.

Results from the GT-2 samples are ambiguous. In no case do all seven criteria unequivocally indicate either a metaigneous or metasedimentary origin for a sample. Most criteria indicate a metasedimentary origin for all samples. Other petrographic and chemical criteria indicate that samples 4283 and 9521 are igneous or metaigneous in origin.

Chemical Studies. Thirty-nine complete whole-rock chemical analyses have been completed on core samples from Fenton Hill. These analyses were used in conjunction with petrographic data and the results of spectral gamma logging to distinguish four major Precambrian rock units. Typical compositions of these units are presented in Table 5-IV (see also Appendix B).

TABLE 5-IV
CHEMICAL COMPOSITIONS OF TYPICAL
PRECAMBRIAN ROCKS FROM GT-2
(wt%)

	(1)	(2)	(3)	(4)	(5)
SiO ₂	63.86	72.08	55.10	65.05	77.43
TiO ₂	0.97	0.19	1.44	0.56	0.11
Al ₂ O ₃	14.57	14.20	15.54	16.00	11.98
Fe ₂ O ₃	3.10	0.67	1.87	1.13	0.34
FeO	3.02	1.37	7.14	2.89	0.38
MgO	1.41	0.45	4.67	1.46	0.03
CaO	3.24	1.12	5.14	3.15	0.69
MnO	0.092	0.050	0.140	0.079	0.015
SrO	0.045	0.017	0.023	0.043	0.004
Na ₂ O	3.30	3.33	2.87	4.50	3.43
K ₂ O	4.18	4.73	3.31	2.89	4.68
H ₂ O(-)	0.07	0.14	0.11	0.12	0.07
H ₂ O(+)	0.98	1.06	1.28	1.22	0.54
CO ₂	0.23	0.10	0.48	0.69	<0.01
P ₂ O ₅	0.59	0.05	0.51	0.18	<0.01

- (1) Biotite granodiorite (average of 5 samples, from bottom of GT-2).
- (2) Leucocratic monzogranite dike (average of 3 samples).
- (3) Ferrohastingsite - biotite schist (average of 2 samples).
- (4) Biotite granodioritic gneiss [depth 960 m (3151 ft)].
- (5) Leucocratic monzogranitic gneiss [depth 1056 m (3464 ft)].

As discussed above, the major Precambrian unit at the Fenton Hill site is a series of banded gneisses of variable composition. A total of 29 samples of the gneisses were analyzed to cover the entire spectrum of lithologies. Excluding the magnetite-sulfide folia, the extremes in chemical composition of the gneisses are shown as analyses 4 and 5 in Table 5-IV. Such extreme changes in composition may occur over distances as small as a few centimeters.

The correlation between SiO_2 contents and other major element oxides is low within the gneisses. As expected, the alkalis generally increase with increasing SiO_2 . Magnesia, CaO , FeO , and Fe_2O_3 contents show a general decrease with increasing SiO_2 content.

The second metamorphic unit at Fenton Hill is a ferrohastingsite-biotite schist, interlayered with and in fault contact with the gneisses. Two analyses of this unit have been completed, one of which is shown in Table 5-IV.

Based on the two analyses, petrographic work, and spectral gamma logging, this unit is chemically homogeneous. The composition is very similar to typical basaltic andesites, and the unit probably represents a series of flows, sills, or dikes of basaltic andesite metamorphosed to lower amphibolite grade.

Five analyses of the biotite granodiorite from the bottom of GT-2 have been completed and the average composition of this unit is shown in Table 5-IV. A Harker diagram (major oxides vs SiO_2) for this unit is presented in Fig. 5-26. For comparison a biotite granodioritic gneiss with a similar SiO_2 content has been plotted on the Harker diagram.

All petrographic and chemical evidence indicates that the biotite granodiorite is an extremely homogeneous rock unit. Considering the thickness of the unit (330 m), the small variation in SiO_2 and other major element oxides supports the petrographic evidence that the biotite granodiorite is a single igneous unit. The abundance of certain oxides distinguish the unit from biotite granodioritic gneisses with similar SiO_2 contents. For example, TiO_2 , P_2O_5 , and K_2O contents are considerably higher in the igneous unit than in the metamorphic rocks, whereas MgO and Na_2O contents are lower.

Core 27 from the bottom 0.5 m of GT-2 consists of a biotite granodiorite gneiss petrographically similar to the biotite granodiorite from immediately above. These rocks can be chemically distinguished on the basis of the much lower K_2O and P_2O_5 contents of the gneiss.

The leucocratic monzogranite dike sampled by Core 10, 1295 - 1311 m (4250 - 4300 ft), is also chemically homogeneous. The mean of three samples of this unit is

Fig. 5-26.
Harker diagrams for biotite granodiorite from bottom of GT-2.

shown as analysis 2 in Table 5-IV. Except for a somewhat higher K_2O content, the dike is compositionally similar to many of the gneisses with similar SiO_2 contents.

U, Th, and K Abundances and Heat Generation in Core Samples. Abundances of uranium, thorium, and potassium were determined in 30 of the 39 core samples used for whole-rock chemical analysis. Uranium and thorium only were determined in eight samples. The results of these analyses are presented in Table 5-V. Plots of U vs Th and U vs K are given in Figures 5-27 and -28.

Large variations exist in the abundances of all three elements. Uranium ranges from 0.64 to 37.4 ppm, thorium from 1.14 to 34.64 ppm, and potassium from 1.21 to 5.39%. These large variations result from heterogeneity of the banded gneisses and the presence of mineralized fractures.

Fig. 5-27.

U vs Th for GT-2 and EE-1 samples.

Fig. 5-28.

U vs K for GT-2 and EE-1 samples.

In the banded gneisses, uranium ranges from 0.64 to 5.43 ppm, thorium from 1.14 to 23.89 ppm, and potassium from 1.21 to 5.39%. Only one sample of schist was analyzed with values for uranium, thorium, and potassium of 1.39 ppm, 5.83 ppm, and 2.49%, respectively. The chemically homogeneous leucocratic monzogranite dike is also relatively homogeneous with respect to uranium, thorium, and potassium contents. Uranium ranges from 5.11 to 12.00 ppm, thorium from 17.74 to 23.89 ppm, and potassium from 3.49 to 4.40%. The biotite granodiorite was also considered to be chemically homogeneous; uranium ranges from 2.87 to 6.61 ppm, thorium from 1.97 to 22.20 ppm, and potassium from 2.99 to 3.58%. A felsic pod or segregation within the biotite granodiorite had uranium, thorium, and potassium contents of 37.40 ppm, 34.64 ppm, and 4.08%, respectively.

In accordance with convention, Figs. 5-27 and 5-28 show log-log plots of U vs Th and K vs U. Although both plots show considerable scatter, the scatter on the K vs U plot is particularly large. This is probably due to the mobility of uranium and potassium during multiple metamorphic or hydrothermal events. The K/U ratio offers promise for distinguishing between igneous and metamorphic rocks. This ratio for rocks believed to be of igneous origin is 0.6×10^4 (range, 0.10×10^4 to 1.25×10^4). For rocks exhibiting metamorphic textures, the ratio is 1.61×10^4 (range, 0.44×10^4 to 3.62×10^4).

TABLE 5-V
CONCENTRATIONS OF HEAT GENERATING ELEMENTS IN GT-2 CORE SAMPLES

Sample Number ^a	Th (ppm)	U (ppm)	K (wt%)	
2580-26	9.95	2.18	1.79	
2600-3	11.65	2.75	3.09	
2855-2	14.73	2.60	4.56	
3151-5a	11.33	5.43	2.40	
3694-1.1	10.23	0.95	3.44	
3696-1.2	13.66	5.38	N.D.	
3699-2.1	8.82	1.85	4.19	
3703-2.1	11.71	1.49	1.70	
4279-2	17.74	12.00	4.40	} Dike
4280	23.89	11.30	3.88	
4281-4	19.38	10.5	N.D.	
4282-4	18.89	5.11	3.49	
4893-1a	16.92	2.89	N.D.	
4893-1b	4.79	1.15	N.D.	
4893-1c	11.47	2.01	N.D.	
4895-2	15.94	3.42	N.D.	
4896-2	12.25	3.19	3.94	
4917-2	17.39	2.85	3.59	
4919-5	17.68	3.02	3.72	
4920-3gn	7.59	2.30	4.84	
4920-3peg	5.09	1.68	3.52	
5234-10	1.14	0.64	1.21	
5234-11	11.73	2.05	1.61	
5487-M1	14.18	3.05	4.51	
5487-M2	8.75	1.78	N.D.	
5487-M4	12.17	2.28	N.D.	
5654-1	5.83	1.39	2.49	
6160-4	4.83	1.88	2.82	
6344/6350-4	11.81	4.26	4.18	
7103-1-A	7.53	2.12	5.39	
7103-1-5E	14.29	1.15	1.73	
7103-8H	7.19	0.95	1.52	
7918-1b	5.26	1.06	2.42	
8583-1A	10.83	4.36	4.27	
8583-1B	22.20	2.87	3.58	
9520-3	14.29	5.10	3.27	} Biotite granodiorite
9521	34.64	37.40	4.08	
9529-2	1.97	6.61	2.99	

^aFirst four digits refer to depth in feet.

Using the measured abundances of uranium, thorium, and potassium a heat generation contribution of 5.47×10^{-13} cal/cm³/s was calculated. If the model of Roy et al,¹⁰ which assumes a thickness of 9.4 km for the radioactive layer beneath the Basin and Range Province is used, the calculated heat generation term yields an equivalent heat flow of 0.51 HFU. This value can then be added to the

1.4 HFU Basin and Range reduced heat flow value to obtain an unperturbed heat flow of 1.91 HFU. Because the measured heat flow in the Precambrian rocks at Fenton Hill is about 3.7 HFU, almost one half of this value must be due to thermal effects from the Valles Caldera and Rio Grande Rift.

Gas Content of Quartz from Core Samples. Crystallizing minerals may trap fluids in several locations as growth proceeds. Some samples may be representative of the fluids from which the mineral grew and thus can provide information on fracture sealing processes. Rupturing of fluid inclusions can also provide estimates of the temperature of deposition of the sealing material.

Barker¹¹ analyzed the gases evolved from three samples of quartz from GT-2 core samples, one from the monzogranite dike, one from a small pegmatite, and one from a fracture filling. All samples showed H₂O as the dominant gas; CO₂ and hydrocarbons were also present as trace constituents. No sulfur gases were observed.

Geochronological Studies. The results of three different geochronological studies, rubidium-strontium, potassium-argon, and fission track, are now available for the Precambrian samples from Fenton Hill. Work has been started using the uranium-lead method, but no results are as yet available.

Because daughter element and track retention are a function of time and temperature, the different methods are able to distinguish different geologic events. The term "age" used here refers to that time when the mineral or rock last began to retain the daughter isotope (⁸⁷Sr or ⁴⁰Ar) or when fission tracks ceased to be annealed. Because of differences in retention or annealing behavior, these ages are not necessarily concordant and do not necessarily refer to original time of formation of the rocks. Thus, by using a combination of the various methods the time and perhaps the duration of at least the most recent thermal perturbation may be estimated. Results from the application of each of the methods are summarized below.

Rb-Sr Method. A rubidium-strontium geochronological study of the Precambrian rocks at the Fenton Hill site was undertaken in collaboration with D. G. Brookins of the University of New Mexico.¹² Twenty-seven samples of the banded gneisses from the interval 770 - 2440 m yielded an isochron with an age of $1.68 \pm 0.03 \times 10^9$ yr and an initial strontium ratio of 0.705 ± 0.0015 . This age was interpreted as the time of formation of these gneissic rocks. The initial strontium ratio of 0.705 suggests that these gneissic rocks were not derived from igneous rocks emplaced shortly before the metamorphic event. At least a moderate premetamorphic history is implied. Four samples of the leucocratic monzogranite

dike gave a $1.44 \pm 0.03 \times 10^9$ -yr age and an initial ratio of 0.706 ± 0.002 . This 1.44×10^9 -yr age correlates with a magmatic-metamorphic event noted elsewhere in northcentral New Mexico. Fourteen whole-rock samples from the biotite granodiorite demonstrated open-system behavior for rubidium and strontium, and consequently did not yield an isochron. This behavior was apparently caused by the present high temperature of these rocks and perhaps fluid movement at the time of the formation of the Valles Caldera, $1.4 - 1.1 \times 10^6$ yr ago.

K-Ar Method. The potassium-argon studies were done in collaboration with R. B. Forbes and D. L. Turner of the University of Alaska.¹³ Biotite, a mineral amenable to potassium-argon dating, was separated from 11 samples of core from GT-2. To a depth of 2580 m these biotite samples yielded relatively constant apparent ages of about 1.4×10^9 yr. One muscovite sample from 1670 m gave a similar age. Below 2550 m the biotite ages decreased to 1.25×10^9 yr. Only three samples of amphibole were suitable for dating, and these yielded ages ranging from 1.23 to 1.46×10^9 yr.

The cluster of potassium-argon ages at about 1.4×10^9 yr from above 2580 m reflects reheating of the 1.68×10^9 -yr-old gneisses by the emplacement of the 1.44×10^9 -yr-old leucocratic monzogranite dikes. The further lowering of the potassium-argon biotite ages below a depth of 2580 m is caused by additional argon loss due to the present high temperatures established somewhere between 10 and 1×10^6 yr ago.

Fission Track Studies. Fission track ages were determined on apatite and sphene separated from the cores from GT-2 and from nearby exposures of Precambrian rocks.¹⁴ The apatite data is shown in Fig. 5-29. A 242×10^6 -yr date was obtained on surface Precambrian rock with an age assumed equal to that of the Fenton Hill gneisses (1.68×10^9 yr). Because fission tracks in apatite are annealed by long thermal events above 105°C (Ref. 14), the reduction of the Precambrian age of the surface sample indicates when that sample passed through the 105°C isotherm.

A suite of apatite separates were prepared from core samples from GT-2. With one exception the ages on these samples decrease linearly from 69×10^6 yr at a depth of 790 m to zero at 1880 m. This age decrease reflects the present geothermal gradient in GT-2. The age of the apatite from a depth of 1590 m fell off the line (Fig. 5-29), indicating a younger age than expected. This additional perturbation is readily explained by a disturbance in the measured gradient at this point. Geophysical and temperature logging of GT-2 indicate that a fracture

Fig. 5-29.
Apatite fission track age variations
with depth in GT-2.

zone at this depth is yielding hot water, which has further annealed the apatite. It is probably not fortuitous that the amphibole potassium-argon age from this depth also appears to be disturbed. In marked contrast is the biotite potassium-argon age, in good agreement with the ages of adjacent samples. Additional work must be done before these results can be properly interpreted.

Future Work. R. Zartman of the USGS has begun uranium-lead geochronological studies on core samples of the biotite granodiorite from GT-2. If this

rock system has remained closed for uranium and lead this work should yield the initial age of this unit. Similar studies on the banded gneisses may give the age of the original material from which the gneisses were formed.

To complete the history of the reservoir rocks at Fenton Hill, attempts will be made to date the various minerals sealing fractures. As was previously discussed, a wide variety of minerals are present as fracture fillings. Although the grain size of these minerals is small and none is ideally suited for geochronologic work, fission track measurements will be attempted to date these minerals.

$^{87}\text{Sr}/^{86}\text{Sr}$ Ratios as an Isotopic Tracer for Fracture Filling Calcite. It was important to the HDR experiment to know if fractures within the Precambrian section continued up into the overlying Paleozoic sediments. If continuous fractures exist, fluid leakoff could occur during the injection experiments.

Calcite is the most abundant fracture-sealing mineral within the Precambrian rocks. Because the Madera Limestone overlies the Precambrian rocks it was suspected that calcite might have been transferred downward through any continuous fractures and deposited within the Precambrian rocks. To test this hypothesis $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were measured in calcite from fractures¹⁵ and compared with measured ratios in the limestone and Precambrian granitic rocks. Ratios in the granitic rocks ranged from 0.769 to 0.962 in contrast to a limestone ratio of 0.7095. The ratio in the calcite ranged from 0.7258 to 0.7336. Because the

calcite ratios were much higher than those of the limestone, the interpretation was made that much of the calcite was locally derived. This in turn implies that fractures probably are not continuous downward through the Precambrian unconformity.

Physical Property Measurements. In cooperation with the U. S. Bureau of Mines several physical properties were measured on core samples from GT-2.

For comparison with density logs measured by a service company, the densities of 17 core samples were determined and these results are shown in Table 5-VI. Direct measurements are in good agreement (about $\pm 2\%$) with values obtained from the logs.

TABLE 5-VI
COMPARISON OF LABORATORY AND
FIELD DENSITY DETERMINATIONS

<u>Sample Number^a</u>	<u>Density (g/cm³)</u>	
	<u>Lab</u>	<u>Log</u>
2580-6	2.628	2.70
2580-5	2.651	2.70
2600-4	2.662	2.71
2600-3	2.662	2.71
2844-6	2.621	2.64
2844-4	2.610	2.64
2857-7	2.610	2.64
2857-5	2.609	2.64
3151-5	2.665	2.68
3151-7	2.651	2.68
3464-8	2.611	2.62
3697-1	2.625	2.63
4279-1	2.632	2.60
4894-1	2.638	2.59
4915-2	2.649	2.64
4916-1	2.641	2.64
5234-1	2.691	2.55

^a First four digits refer to depths in feet.

Acoustic velocities were measured in the same 17 samples (dry, ambient temperature and pressure) (Table 5-VII) and compared with log results. In this case, as expected, the agreement was not as good as the density comparison; discrepancies as high as 16% occurred. In general, laboratory measurements gave consistently lower wave velocities in both shear and longitudinal modes, averaging 5-1/2% lower in the latter and 3% lower in the former. These differences reflect the fact that laboratory measurements were made on dry samples under pressure and temperature conditions different from those existing in situ. Elastic parameters were calculated from these data with the results shown in Table 5-VIII. Porosity measurements were also made on 14 core samples. Values ranged from 0.5 to 7.0%.

TABLE 5-VII
COMPARISON OF LABORATORY AND FIELD ACOUSTIC
VELOCITY MEASUREMENTS

Sample Number ^a	Vp (km/s)		Vs (km/s)	
	Lab	Field	Lab	Field
2580-6	5.82	6.05	3.39	3.44
2580-5	5.92	6.05	3.46	3.44
2600-4	5.94	6.00	3.44	3.42
2600-3	5.93	6.00	3.43	3.42
2844-6	5.83	6.31	3.48	3.48
2844-4	5.90	6.31	3.44	3.48
2857-7	5.98	6.34	3.51	3.55
2857-5	5.80	6.34	3.46	3.55
3151-5	4.98	5.78	2.87	2.97
3151-7	4.97	5.78	2.95	2.97
3464-8	5.66	6.02	3.19	3.43
3697-1	5.86	5.86	3.52	3.51
	5.88		3.46	
4279-1	5.77	5.99	3.35	3.49
	5.90		3.51	
	5.92		3.42	
4894-1	5.82	5.93	3.43	3.52
	5.88		3.50	
4915-2	5.64	5.98	3.41	3.54
4916-1	5.42	5.98	3.37	3.54
5234-1	5.90	6.03	3.42	3.56

^a First four digits refer to depths in feet.

TABLE 5-VIII
ELASTIC PARAMETERS DERIVED FROM SONIC WAVE DATA*

<u>Elastic Property</u>	<u>Lab</u>	<u>Log</u>
E (Young's modulus), Pa	7.16×10^{10}	7.87×10^{10}
μ (Shear modulus), Pa	3.02×10^{10}	3.14×10^{10}
K (Bulk modulus), Pa	4.70×10^{10}	5.41×10^{10}
ν (Poisson's ratio)	0.257	0.255

*Average of interval 783-1597 m.

Paleomagnetic Measurements. Considerable difficulty was encountered in obtaining oriented core samples. In the deeper sections of both drill holes, high temperatures destroyed the photographic film used in the orienting device. At shallower depths, breakage of the core and rotation in the core barrel made many orienting measurements questionable. Paleomagnetic measurements have been used in an attempt to orient the core.

Three samples were initially sent to R. L. Dubois of the University of Oklahoma. One sample oriented during drilling was used as a standard. A magnetic declination of 323.9° was measured on this sample, and the magnetic direction was assumed to be constant in the other samples. Magnetic directions were then measured in the other samples, thus providing an orientation. A test of this orienting method is provided by the presence of prominent vertical foliation in one of the samples. The foliation in most Precambrian rocks of this portion of New Mexico strikes NE. Paleomagnetic orientation of the foliation indicates a strike of $N30^{\circ}E$. Additional work must be done on the orientation of other cores and testing the results, but the data at this time are very encouraging.

Summary of Core Studies.

1. Petrographic, chemical, and spectral gamma logging evidence indicates that four major Precambrian units exist at Fenton Hill: banded gneiss, mafic schist-amphibolite, biotite granodiorite, and leucocratic monzogranite.

2. The homogeneity of the biotite granodiorite from the bottom of GT-2 and its lack of open fractures indicate ideal conditions for the heat extraction experiments.

3. The gneisses and schists were formed 1.68×10^9 yr ago from original sedimentary rocks (gneisses) and basaltic andesites (schist).

4. At 1.44×10^9 yr ago the metamorphic complex was intruded by at least two monzogranite dikes and perhaps the biotite granodiorite.

5. During the period 9.1 to $<0.43 \times 10^6$ yr reheating occurred coincident with volcanism within the Jemez Mountains. This rise in temperature caused annealing of fission tracks in apatite, yielding zero ages at a depth of 1880 m.

6. Multiple metamorphisms of the Precambrian rocks have sealed or healed most of the existing fractures producing an extremely low permeability reservoir rock (see Sec. 5.2.2). Locally derived calcite is the major sealing mineral.

7. Determination of paleomagnetism in core samples appears to be an alternative method for orienting cores when high temperatures adversely affect the photographic film in the standard orienting device.

8. Sonic log data yield reasonable values for elastic properties and can be used in hydraulic fracture analyses.

9. Heat flow and heat generation measurements indicate that approximately one half of the heat flow in the Precambrian rocks is derived from the Valles Caldera and Rio Grande Rift.

5.2.2. Geochemistry Studies. Geochemistry-related work¹⁶ is directed toward increasing our fundamental understanding of hot dry rock geothermal systems, and to some extent, natural hydrothermal systems, and toward developing experimental and theoretical techniques for modeling total geothermal systems as they exist in the field. For the past several years, efforts have concentrated on the geochemistry pertaining to LASL's HDR project with the work focused in three main areas:

(1) Rock dissolution and reprecipitation rate measurements,

(2) Rock permeability measurements, and

(3) Computer modeling of multicomponent equilibria in rock-water systems.

The first two areas provide data that assist in the planning and evaluation of field experiments at Fenton Hill. The third activity is a necessary ingredient in developing a model for describing the short- and long-term performance of HDR systems (see Sec. 6). In addition, because of the complexity of geochemical systems, computer techniques are used for studying various aspects of the experiments in areas (1) and (2).

Several features of a granitic hot dry rock reservoir are being examined. Central among these is rock permeability, specifically the development of chemical means to alter permeability and thus to improve the heat extraction capacity of the reservoir either by reducing flow impedances or reducing in situ water

losses. Furthermore, the potential deleterious effects that geochemical reactions may have on the reservoir are being examined. For example, hydrothermal alteration products of the granite-water system may form lower density solid materials, e.g., clays, at sufficient rates to cause deposition within the system, particularly the fracture itself. This could then lead to high flow impedances. In addition, if dissolved or suspended material deposits as scale within the surface heat exchanger sections of the system, exchanger performance might be reduced to an unacceptable level. These phenomena are being studied in laboratory-scale experiments as well as in field experiments because of our limited quantitative knowledge of the kinetic parameters that affect rock dissolution and permeability, reprecipitation of hydrothermal alteration products, and scale deposition, and because of the difficulty and costs associated with accomplishing field experiments in a controlled manner where all important parameters are defined.

Rock Permeability. Permeability of the reservoir rock in a geothermal energy system will be progressively affected by the chemical interaction between the aqueous working fluid and rock matrix. This will cause changes in the geometry and the heat exchange properties of the reservoir system. Laboratory studies have been undertaken to determine changes in permeability as a hot aqueous solution was forced through core rock obtained from the reservoir region in GT-2. A description of the major mineral components for the cores studied was presented in Sec. 5.2.1.

No previous data existed on the permeability of igneous or metamorphic rocks at elevated temperatures. Experiments were designed to permit variation of temperature, confining pressure, and the differential pressure driving the flow of fluid through the specimen. The apparatus used for this study was similar to that designed by Brace, et al.¹⁷ for permeability studies at room temperature (21°C) on Westerly granite. A resistance-heated furnace was added that enclosed the high-pressure specimen chamber and permitted temperature regulation between 20°C and 200°C to $\pm 1^\circ\text{C}$.

Figure 5-30 summarizes the results of the permeability studies. Distilled water was used as the starting fluid. Curve A shows the Westerly granite experimental results of Brace, et al;¹⁷ curves B, C, and D show the data from this study on a GT-2 core granite sample taken at 8580 ft. This GT-2 granite specimen is significantly coarser grained than Westerly and has a permeability about one-third that of Westerly at 21°C. In general, measured permeabilities ranged

from about 0.1 to 0.003 μ darcy, which is extremely low when compared to typical sandstone and limestone formations.

As shown in Fig. 5-30, rock permeability decreased with increasing confining pressure, P_c . As pressure is increased small cracks and other channels in the rock are forced to close.¹⁷ Increasing temperature, T , causes differential expansion of mineral grains, increasing dissolution rates of most minerals, and increasing formation rates for altered mineral phases. The minimum permeability curve for 8580 granite should reflect the P, T conditions the minerals were subject to in situ. This will occur somewhere between 100 and 200°C at lithostatic pressures. Changing the P, T conditions from this minimum either causes mineral shrinkage opening grain boundaries and fractures increasing permeability or causes mineral expansion and additional fracturing of the rock which also increases permeability. Chemical effects will be subordinate to this thermal expansion effect for periods up to a week.

Rock Dissolution Studies: Noncirculating System. A rocking bomb system has been built to accelerate equilibration of aqueous solutions in contact with GT-2 rock specimens at 200°C and above. The rock solution quickly approaches a steady-state, quasi-equilibrium composition which may be approximated in a large slow-moving geothermal system. Table 5-IX gives chemical compositions of solutions as

Fig. 5-30.
Permeability as a function of confining pressure for various temperatures.

Fig. 5-31.
Total weight loss rate (g/cm²·h) vs time for 8580 granite slabs reacted with 0.1 N Na₂CO₃ at 200°C.

a function of time starting with San Antonio River water, the water being used at the Fenton Hill test site. Figure 5-31 shows rates of rock weight loss [as $\log (g/cm^2/h)$] as a function of time for a 0.1 N sodium carbonate (Na_2CO_3) starting solution. The presence of Na_2CO_3 has been shown to increase permeability

TABLE 5-IX
SOLUTION ANALYSES FOR ROCKING BOMB EXPERIMENTS^a

Sample Number	Sample Time (h)	SiO_2	Na_2O	K_2O	CaO	Al_2O_3	pH
Run 26	200°C	San Antonio Water		GT-2	8580 Rock ^b	(2300 psi)	
1	24	107	46	9.0	10.5	5.7	
2	120	257	40	12.1	7.8	5.7	
3	144	310	43	11.0	7.7	3.8	
4	216	374	42	13.3	10.0	3.8	
5	288	385	49	13.3	8.8	3.8	
6	336	374	51	12.1	9.0	3.8	
7	360	364	54	13.3	9.1	3.8	
Run 24	230°C	San Antonio Water		GT-2	8580 Rock	(2200 psi)	
1	72	389	35	15.7	4.9		6.2
2	122	385	49	11.1	4.9		7.5
3	169	466	47	11.3	6.3		7.5
4	233	466	42	11.8	4.5		7.5
5	284	500	47	11.8	5.0		7.5
6	329	492	51	12.5	7.3		7.5
Run 25	260°C	San Antonio Water		GT-2	8580 Rock	(2200 psi)	
1	52	492	32	15.1	3.8		7.3
2	141	518	47	10.8	4.1		7.5
3	192	543	36	15.5	3.8		7.5
4	237	620	36	15.7	4.3		7.5
5	333	751	41	14.3	3.5		7.5

^aConcentrations in ppm.

^bSee Table 5-XI for modal analysis of cores taken from 8580 ft.

by selective dissolution of quartz (SiO_2). For both starting compositions, solutions approached a constant chemical composition within a matter of hours.

Experiments have been initiated to correlate observed rock-fluid interactions with computerized reaction calculations (for example, PATHCALC, Helgeson¹⁸). The plan is to compare experimental and theoretical results for monomineralic systems first and then polymineralic systems such as Fenton Hill granite. Initially, uniform prisms of polycrystalline albite ($\text{Ab}_{96.6}\text{An}_{2.9}\text{K}_{0.5}$) from Symlar, PA, were reacted with a 0.1 N Na_2CO_3 solution for 6 - 2015 h at 0.483 kbar (7000 psi) = P_{Tot} and 200°C. Na_2CO_3 solution gives a large quantity of observable reaction products and tests a potential method for increasing permeability of the rock reservoir. Time-dependent secondary phases identified by scanning electron microscopy (SEM) are calcite (CaCO_3), faujasite ($\text{Na}_{3.5}\text{Al}_{3.5}\text{Si}_{8.5})_{24} \cdot 16\text{H}_2\text{O}$), and analcime ($\text{NaAlSi}_2\text{O}_6 \cdot \text{H}_2\text{O}$). Calcite and faujasite appear first, increase to a maximum amount at about 24 h, and disappear gradually. Analcime appears after about 24 h and increases in amount at least up to 2015 h. The results of reacting albite and Na_2CO_3 solutions partially agrees with calculations based on a significant modification of the PATHCALC code developed by C. C. Herrick and P. Rogers at LASL.

Rock Dissolution Studies: Circulating System

Apparatus. Circulating systems were designed to reproduce in part the physical and chemical conditions of the hot dry rock system. Minimum "surface" (surface heat exchange) and "downhole" (hot rock reservoir) temperatures, total pressure, flow conditions, and initial rock and solution compositions were varied.

Two circulation systems have been built by modifying the design of Morey and Fournier¹⁹ to allow recirculation of the fluid. The first system built is capable of operating at 300°C and 200 bar (3000 psi) while the second can operate at 300°C and 700 bar (10 000 psi).

In both systems, rock samples are suspended in the pressure vessel and reacted with a fluid of known initial composition. Fluids are pumped at a known rate with a diaphragm-type circulation pump, and desired temperatures are regulated by use of thermocouples and heating tapes. Fluid is first heated to the rock temperature, then pumped through the pressure vessel, reduced in pressure, and cooled with a heat exchanger. The loop is completed by pumping the solution to

operating pressure and returning it to the pressure vessel. Sampling ports were installed to monitor changes in the solution composition with time. Heated portions of both systems were plated with gold to inhibit spurious reaction with iron, nickel, or chrome.

Dissolution Rate Measurements. Rock weight loss was measured in a series of runs in the circulating system. Results are shown in Fig. 5-32 for a system pressure of 200 bar (3000 psi). The minimum temperature in the circulating loop heat exchanger was 60°C for all runs with a flow rate of 17 cc/min. The reservoir temperature was varied from 200 to 300°C to match present and projected Fenton Hill conditions. The rock samples consisted of rectangular slabs 3 by 4 cm by 0.3 cm thick, and weighed about 20 g each. Starting solutions included distilled water, San Antonio River water, distilled water and CO₂ ($P_{CO_2} = P_{H_2O}$ at 260°C, a common natural pore solution), and 0.1 N NaCl solution (a common natural brine). Table 5-X summarizes run conditions and data obtained.

Fig. 5-32.

Steady-state weight loss rate vs temperature for various rock types in the circulation loop.

$P_{Tot} = 3000$ psi (200 bar)

Run 7	Kilauea basalt in distilled water
12	5984 biotite amphibolite in distilled water
13	6160 monzogranite in distilled water
16	6160 monzogranite in H ₂ O + CO ₂
17	6160 monzogranite in 0.1 N NaCl
20	2580 granite in San Antonio water
22	8580 same
23	8580 same

The rate of weight loss for biotite amphibolite (5984 ft, Table 5-XI) was much lower than for the felsic rocks of more typical GT-2 composition (at 1878 and 2615 m). In contrast, the loss rate for Kilauea basalt was much higher. The felsic rocks showed similar rates of weight loss at 260°C when reacted with distilled water, and salt solution. At fixed temperatures the weight loss rate remained constant for durations of 250-350 h. For felsic rocks the loss rate increased almost exponentially with temperature from 200 to 300°C.

Compositions of solutions in contact with the reservoir rock were measured periodically during the circulating system runs for the felsic samples of Table 5-X. Silica concentration in

TABLE 5-X
SOLUTION COMPOSITIONS AND RATES OF ROCK WEIGHT LOSS^a
CIRCULATION LOOP RESULTS

<u>Rock Type</u>	<u>Run</u>	<u>Solution</u>	<u>Temp</u> (°C)	<u>Pressure</u> (bar) (psi)		<u>Run</u> (h)	<u>SiO₂</u>	<u>Na₂O</u>	<u>K₂O</u>	<u>CaO</u>	<u>Al₂O₃</u>	<u>pH</u>	<u>Weight</u> <u>Loss Rate</u> (g/cm ² ·h)
Kilauea Basalt	7	Distilled H ₂ O	200	172	(2500)	137	357	248	47	0.03	17	8.3	9.17 x 10 ⁻⁵
GT-2 5984 ^b Amphibolite	12	Distilled H ₂ O	260	152	(2200)	239	428	48	17	0.6	< 4	7.4	3.04 x 10 ⁻⁵
6160 Biotite ^b Granodiorite	13	Distilled H ₂ O	260	152	(2200)	312	432	24	11	0.6	2.1	6.5	10.2 x 10 ⁻⁵
6160	16	H ₂ O + CO ₂	260	152	(2200)	390	210	40	11	0.6	-	7.5	8.68 x 10 ⁻⁵
6160	17	1/10 N NaCl	260	152	(2200)	312	272	-	5	1.7	-	-	11.1 x 10 ⁻⁵
8580	20	San Antonio River Water	200	152	(2200)	337	222	50	9	1.5	< 3.8	9.5	2.70 x 10 ⁻⁵
8580	22		250	152	(2200)	239	428	48	17	0.6	< 3.8	7.4	7.96 x 10 ⁻⁵
8580	23		300	152	(2200)	248	466	30	21	0.3	< 3.8	7.5	13.3 x 10 ⁻⁵

^aAll concentrations in ppm. Entries not shown are below detection limits of about 0.1 ppm.

^bSee Table 5-XI for modal analysis of cores.

TABLE 5-XI
MAJOR MINERAL MODAL ANALYSES
ROCK SAMPLES FROM GT-2 CORES

<u>Sample</u>	<u>K-Feldspar</u>	<u>Plagioclase</u>	<u>% An^a</u>	<u>Quartz</u>	<u>Biotite</u>	<u>Amphibole</u>
5984-1	1	40	(30)	6	2	47
6160	10	38	(33)	41	7	--
8580	21	34	(31)	29	11	--

^a% Percent anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) end member of plagioclase.

the river water and distilled water runs increased with time approaching a steady-state plateau (Fig. 5-33). Na, K, and Ca concentrations also approached constant values. This approach to steady-state concentrations was similar to that observed for the agitated bomb experiments described earlier. Final silica concentration for both circulating systems and rocking bomb measurements are plotted in Fig. 5-34. Solubility data for quartz and amorphous silica in distilled water from Fournier²⁰ are also shown.

The rocking bomb data show that silica concentrations in solutions equilibrated with granite are higher than those equilibrated with pure quartz and lower than those equilibrated with amorphous silica. Silica concentration in the steady-state solution compositions reached in the rocking bombs is significantly higher than those in the circulating system. Maximum silica concentrations in the aqueous solution were apparently not reached in the circulating system experiments. The ratio of rock surface area to solution volume will be increased in future experiments.

The total solution composition observed in the rocking bomb experiments (Table 5-IX) demonstrates the low concentration of dissolved material in the working fluid; it could be used for drinking water. These solutions are dilute and do not contain concentrated chlorides, thus they cannot be classified as brines, like seawater (35000 ppm total dissolved solids) or like many natural geothermal fluids, and they should be much less destructive (corrosive and erosive) to the energy extraction system than many natural geothermal fluids.

Detailed observation of the changes occurring in the rock is an essential part of these studies. The changes may consist of preferential dissolution of grains, various kinds of channeling through the rock, filling of channels by

Fig. 5-33.

Silica concentration vs time in the circulating loop.

- Run 23 8580 granite in San Antonio water at 300°C.
- 20 8580 granite in San Antonio water at 200°C.
- 22 8580 granite in San Antonio water at 250°C.
- 13 6160 monzogranite in distilled water at 260°C.

Fig. 5-34.

Concentration of silica in solution vs temperature for granite from 2615 m in the rocking vessel and the circulating system. The other curves represent saturation with respect to amorphous silica and quartz.²⁰

recrystallizing matrix minerals, and appearance of alteration products such as clays, which may or may not remain in place. These observations reveal the processes that result in changes in permeability, rock weight, and solution composition which are measured empirically on the bulk sample. This leads to an understanding of the mechanism of change and makes prediction and modeling possible.

Several preliminary studies have been directed at measuring detailed changes in the rock and solution. These include microscopic (optical and SEM)

observation of textural changes, porosity measurements, and mass balance calculations for estimates of specific mineral reactions. Quartz (SiO_2), plagioclase ($\text{CaAl}_2\text{Si}_2\text{O}_8 \cdot \text{NaAlSi}_3\text{O}_8$), and potassium feldspar (KAlSi_3O_8) are dissolved and eroded from the rock; their chemical components appear in the solution and may be deposited as scale in the surface heat exchanger. An insufficient amount of aluminum is found in the solution; however, Auger spectroscopy and ESCA (electron spectroscopy for chemical analysis) suggest that an aluminum silicate residual remains on the sample surface, thus accounting for the missing aluminum. The aluminum-rich surface coating on the mineral grains may protect them from further reaction.

Mass Balance. For most runs, the total calculated mass in solution was less than the total weight loss of the sample. This indicates that there was a continuous transport of material [particularly silica (SiO_2)] from the heated rock through the solution phase to some other part of the system. In one case the remaining rock sample and solution were removed from the system after the run and a 0.1 N Na_2CO_3 solution was circulated at 60°C for 24 h to dissolve any silica scale that may have deposited in the surface heat exchanger or other parts of the system. The solution was then analyzed for silica. The amount of silica retrieved was sufficient to account for the mass deficiency between the calculated and experimental weight losses.

Enhancement and Suppression of Rock-Solution Reactions. Chemically induced dissolution may be required to decrease flow impedances within the fractured reservoir and thus increase the heat exchange efficiency of the system. On the other hand, suppression of chemical reaction rates in the reservoir may be desirable to minimize transport of mineral components into the working fluid and therefore reduce scale deposition rates in the surface heat exchange system. A study has been initiated to determine what additives will enhance or suppress rock dissolution in the reservoir.

Part A of Table 5-XII shows the relative chemical effects on reservoir rock of initial working solution consisting of distilled water, San Antonio river water, and 0.1 N Na_2CO_3 solution at 260°C . The final silica content of the solution is essentially the same for distilled and river water but significantly greater for the carbonate solution. Weight loss of the samples during the total run has been normalized to sample surface area and hours of run time in the last column. This gives only a rough approximation of steady-state weight loss because time of approach to steady state (about 75 h) is included in the weight

TABLE 5-XII
CIRCULATING SYSTEM RESULTS WEIGHT LOSS RATES AND SiO₂ CONCENTRATIONS

Run	Temp (°C)	Working Fluid	SiO ₂ Content of Final Solution (ppm)	Duration (h)	Sample Sur- face Area (cm ²)	Average Mass Loss Rate (10 ⁻⁵ g/cm ² /h)
<u>A</u>						
22	250	San Antonio water	428	239	36	10.0
13	260	Distilled water	432	312	40	9.8
14	260	0.1 <u>N</u> Na ₂ CO ₃	2436	340	40	33.7
<u>B</u>						
10	230	5% mineral oil	218	360	-	0.9 (average for 10 slabs)
11	230	Distilled water	223	260	-	1.6 (average for 6 slabs)
<u>C</u>						
20	200	San Antonio water	222	337	45	2.7
HP-1	200	1.0% water soluble oil	30	300	26.9	2.8
HP-2	200	0.1% water soluble	30	198	26.7	2.6

loss. Actual steady-state weight loss would be slightly (~ 20%) lower. Weight loss rates in the presence of the carbonate solution are 3.5 times higher than those for distilled and river water.

Examination of the exposed rock sample after the run showed that almost all of the quartz grains had been dissolved away leaving a residual lacework of biotite and feldspar. Periodic treatment of a hot dry rock reservoir with Na₂CO₃ solutions might provide a relatively inexpensive means of increasing permeability, decreasing flow impedances, and expanding the energy extraction capability of the system. The resulting sodium silicate scale that may appear is water-soluble and can easily be washed out of the surface heat exchanger.

Parts B and C of Table 5-XII show relative weight loss of samples with solutions of 5% mineral oil, distilled water, river water, 0.1% soluble oil, and 1% soluble oil. The "soluble" oil was a stable suspension of oil in water normally

used as a coolant in metal finishing operations. So far, only mineral oil has decreased the sample weight loss significantly relative to that for water.

Implications to the Field Program. Laboratory measurements of rock permeability at downhole temperatures and pressures of hot dry rock geothermal sites have been achieved. In addition, chemical reactions between the reservoir working fluid and rock that will enhance or impede movement of the fluid within the reservoir have been identified. Permeability measuring equipment, static and rocking bomb systems for equilibration, and circulating systems that model the entire hot dry rock energy extraction loop have been designed, constructed, and successfully operated. The results of these experiments can be directly applied to our field experiments. In particular, laboratory permeability studies have increased our confidence in the in situ reservoir rock permeability measurements in the field and have demonstrated that chemical techniques can be used to increase or decrease the permeability of granite. In addition, the circulating system experiments have shown that solution mass transport does occur between hot granite and cooler sections of the system, posing a potential scaling problem. Before the magnitude of this problem can be fully assessed, laboratory experiments will have to be redesigned to more closely simulate field conditions. In particular, before techniques for altering rock permeability or reactivity are applied in the field, we need to examine how chemical concentration, rock surface morphology, ratio of rock surface area to fluid volume, temperature gradients, fluid residence time, and fluid velocity affect the kinetics of dissolution and reprecipitation.

5.2.3. Rock Thermal Conductivity. The magnitude of the thermal conductivity (λ) of rock comprising a hot dry rock geothermal reservoir controls the rate of heat transfer from the rock surrounding the hydraulically fractured region to the fluid circulating within the fracture. Thus, it is a critical parameter in estimating and modeling the performance of any hot dry rock energy extraction system (see Sec. 6.1). In addition to affecting the rate of conduction, thermal conductivity values are also important to the thermal stress cracking process, which will hopefully enhance heat transfer surface areas and thus increase the energy extraction capacity of the reservoir.

Most of the dense granitic rocks from the Fenton Hill site at the 200°C (392°F) level have thermal conductivity values within the range from 2 to 2-3/4 W/m·K (about 4.78 to 6.57 x 10⁻³ cal/cm·s·°C). Nearly all these rocks exhibit

negative temperature coefficients; thus, at room temperature some of the conductivity values approach 4 W/m·K (nearly 0.01 cal/cm·s·°C). These rocks are classified as poor conductors because their conductivity values are an order of magnitude greater than the insulating materials. Stainless steel has a conductivity of about 16 W/m·K (about 0.038 cal/cm·s·°C).

The thermal conductivities of many dry rock samples cut from the drill cores from GT-1 and GT-2 have been measured from room temperature to 150°C, and a few measurements were made at 190°C. These measurements were made in a guarded, steady-state, divided bar apparatus (cut-bar thermal conductivity comparator). (See Fig. 5-35). This is a secondary method; the accuracy is limited by the two standard reference materials (fused silica and Pyroceram 9606). These two reference standards introduce a systematic uncertainty of the order of 4 or 5%. The precision (repeatability) of the measurement is high, and random errors are less than 1%.

A series of intercomparison measurements of the apparent thermal conductivities of the two reference standards were made over the temperature range from

ambient to 150°C. These tests involved three different melts of fused silica from two different sources and two different production batches of Pyroceram 9606. In addition a set of samples from the GT-1 core that had been prepared and evaluated by the USGS at Menlo Park, CA, was obtained for comparison of measurements. The two sets of values were in agreement with a random discrepancy of the order of 1%. This comparison was limited to room-temperature conditions.

Fig. 5-35.
Cut-bar thermal conductivity comparator:

- <: Temperature sensors
- G.H.: Guard heaters, upper, middle, and lower
- P: Insulation - Silica aerogel
- B: Insulation - Fiberglass blanket
- C: Guard cylinder

The data from the cut-bar thermal conductivity comparator were compared with the definitive set of data reported by Birch and Clark in 1940.²¹ The data for similar types of rocks are in

good agreement with respect to the value of the thermal conductivity and the temperature coefficient.

A detailed study of the pertinent data indicates that for most engineering applications expensive, time-consuming, difficult measurements of the apparent thermal conductivities over a wide temperature range are not necessary. Ideally, one conductivity measurement on a wet, compact igneous rock at room temperature should be sufficient if the rock has been characterized. This data point is then placed on the appropriate grid of conductivity vs temperature (as published in Ref. 21) and extrapolated to the temperature range of interest up to a maximum temperature of about 350°C. If the rock has been characterized by an accurate modal analysis, porosity, etc., then the apparent thermal conductivity of the dry rock can be estimated within about $\pm 10\%$. This value could then be used in lieu of the one experimental value.

The effective thermal conductivity of a dense rock (porosity of void fraction less than 0.01) saturated with water has not been measured in this laboratory. According to the pioneering work of Clark²² the effect is to increase the conductivity by 10 - 15% and thus approximate the in situ condition. This effect should be measured in the types of rock encountered at Fenton Hill. A saturation chamber designed to impregnate dense rocks with water is being constructed.

The thermal conductivities of solid rock specimens can now be measured on the cut-bar comparator and by means of the line-source technique. The two methods agree within about 3%. The line-source technique is a primary method, and it is attractive because the experimental measurements may be made in less than 400 s. The effective conductivity of chips (drill cuttings) may also be measured by both methods.

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6. GEOTHERMAL RESERVOIR MODELING (R. G. Lawton, H. D. Murphy, J. W. Tester, and R. D. McFarland)

Two important areas to the HDR program involve predicting the heat extraction capacity of hot dry rock reservoirs over periods extending to tens of years, and projecting the estimated costs of developing these reservoirs. Techniques have been developed to examine reservoir performance by modeling fluid flow and heat transfer in hydraulic fractures and wellbores of specified geometry. In addition, an economic model was formulated that bases the total capital investment of a power plant on the costs of production and reinjection wells and major pieces of equipment, including pumps, turbines, generators, heat exchangers, and condensers. These topics are covered in this section.

6.1. Heat Extraction and Fluid Flow Modeling

6.1.1. Reservoir Features and Expected Performance for an Ideal Hot Dry Rock Geothermal Reservoir. Based on the theory of elasticity and brittle material fracture mechanics,¹ the fractured hot dry rock reservoir is idealized as being circular with a fracture gap width, $\bar{w}$, which varies elliptically with radius. The maximum fracture width, w^* , is extremely small compared with the maximum fracture radius, R ; for example, a typical value of w^* is 3 mm for a fracture radius of 500 m. Furthermore, because the direction of the least principal earth stress is horizontal, the fracture plane should be vertically oriented, and therefore fluid buoyancy effects are important.

The maximum thermal power that can be extracted from the rock surfaces occurs when the entire rock surface is suddenly and uniformly lowered in temperature from its initial value, T_r , to the cold water injection temperature, T_i . This power, P , is given as a function of time, t , by²

$$P = 2\pi R^2 \sqrt{\frac{\lambda_r \rho_r c_r}{\pi t}} (T_r - T_i), \quad (6-1)$$

where λ_r , ρ_r , and c_r are respectively the thermal conductivity, density, and specific heat capacity of the rock. Because the thermal conductivity of the rock is low, large fracture surface areas are required to produce substantial

amounts of power for extended periods. For example, if the temperature difference, $T_r - T_i$, is 200°C, a 500-m fracture is required for 25 MW(t) extracted continuously for 10 yr. Even after 10 yr the initial rock temperature is decreased less than 5% for distances of 40 m or more away from the fracture surface (Ref. 2, pp. 58-62). Thus, heat is being removed from only a relatively narrow zone of rock immediately adjacent to the fracture, and conduction in the rock will be essentially one dimensional (perpendicular to the plane of the crack) even for more complicated examples, where the surface temperature is not uniform.

A simple heat balance shows that the minimum mass flow rate, $\dot{m}$, required to extract the thermal power is

$$\dot{m} = \frac{P}{c (T_r - T_i)} ,$$

where c is the specific heat capacity of the water. Using typical values the 25-MW(t) example will require a flow rate of about 30 kg/s. The characteristic, or average, velocity, V , in a fracture is defined as

$$V = \dot{m} / \rho R w^* ,$$

where ρ is the density of water. The characteristic velocity is rather large, of the order 10^{-2} m/s, which means that heat transport due to fluid conduction is negligible compared with fluid convection.

The approximate relations above are based on a reasonable distribution of water flow in the fracture; fresh cold water is assumed to be accessible to all regions of the fracture. However, in actuality this is not always the case. The fluid may "short circuit" along some preferred path, and the energy extraction capacity of the reservoir could be severely reduced.

6.1.2. Governing Equations. Heat is removed from the reservoir by a circulating pressurized liquid water phase. Small changes in fluid density caused by heating are considered only in the body force term, which accounts for buoyancy effects. In addition, the possible beneficial effects of thermal-stress cracking to heat transfer surface area are neglected. (See Harlow and Pracht³ for a simplified model of this phenomenon.) Thus, the fluid is entirely confined to the gap between the impermeable rock surfaces, and heat is transferred to this fluid only by thermal conduction through the solid rock.

The governing equations are written below in nondimensional form, using x,y coordinates in the fracture plane, for a variable fracture gap width, w, and variable fluid properties. As will be shown, some terms can be neglected and the resulting simplified set of equations can be solved numerically.^{4,5}

Momentum. Only the y-momentum equation is presented; the x-momentum equation is similar except that it lacks a body force term. Because the x and y dimensions are large compared with the fracture gap width, the shear stress terms due to x and y velocity gradients are neglected, resulting in

$$Re^* \left(m \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = B_y - \frac{\partial p}{\partial y} + \frac{k^*}{(w^*)^2} \frac{\partial}{\partial z} \left(\mu \frac{\partial v}{\partial z} \right) . \quad (6-2)$$

Here, $B_y = K T$, where the dimensionless parameter, K, is related to the ratio of a Grashof (Gr) number to a Reynolds (Re) number:

$$\begin{aligned} K &= (Gr/Re) \cdot k^*/(w^*)^2, \\ Gr &= (w^*)^3 g \beta (T_r - T_i) (\rho/\mu^*)^2, \text{ and} \\ Re &= \rho V w^*/\mu^*. \end{aligned}$$

Re^* is a modified Reynolds number equal to $\rho V k^*/\mu^* R$. The values u and v are dimensionless velocities in the x and y directions; $u = \bar{u}/V$ and $v = \bar{v}/V$. Other dimensionless parameters (all of order unity) are $x = \bar{x}/R$, $y = \bar{y}/R$; $z = \bar{z}/w^*$ (direction perpendicular to the fracture plane); time, $t = \bar{t}/t^*$; viscosity, $\mu = \bar{\mu}/\mu^*$; temperature, $T = (\bar{T} - T_i)/(T_r - T_i)$, and pressure, $p = \bar{p}/p^*$. The overscored parameters are dimensional quantities. β is the fluid volumetric expansion coefficient, t^* the actual time, μ^* a characteristic fluid viscosity, k^* a characteristic fracture permeability, and $\bar{T}$ the local fluid temperature. The characteristic pressure, p^* , is defined in terms of the viscous drag losses. For laminar flow with constant viscosity across the fracture gap width the last term in Eq. (6-2) can be shown to be $-\mu v/k$, where for an open crack, the effective permeability, k, is $w^2/12$. Again, w and k are dimensionless quantities, $\bar{w}/w^*$ and $\bar{k}/k^*$. Then, the characteristic pressure is defined as $p^* = \mu^* V R/k^*$.

For typical values of the characteristic parameters, Re^* is approximately 10^{-3} and K is approximately unity, as is $k^*/(w^*)^2$ for an open crack. Furthermore, the parameter $m = R/t^* V$ is reduced to the order of 10^{-2} after only one day of operation. The momentum equations can then be simplified to

$$-\frac{\partial p}{\partial x} = \frac{\mu u}{k}, \quad (6-3)$$

$$-\frac{\partial p}{\partial y} = \frac{\mu v}{k} - K T.$$

Continuity. The basic continuity equation for an incompressible fluid requires no simplification. Expressions for u and v from Eq. (6-3) are substituted into the basic continuity equation to obtain

$$\frac{\partial}{\partial x} \left(\Gamma \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left[\Gamma \left(\frac{\partial p}{\partial y} - K T \right) \right] = 0, \quad (6-4)$$

where $\Gamma = \frac{wk}{\mu}$.

Fluid Energy Equation. Viscous dissipation, work, and kinetic and potential energy terms are small and therefore neglected. The resulting dimensionless energy equation is

$$\frac{2\bar{q}R}{w^* c_p V (T_r - T_i)} + \frac{1}{Pe} \left[\frac{\partial}{\partial x} \left(w\lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(w\lambda \frac{\partial T}{\partial y} \right) \right] = w \left(m \frac{\partial T}{\partial t} + \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right), \quad (6-5)$$

where $\bar{q}$ is the heat flux from one fracture surface into the fluid. λ is a dimensionless water thermal conductivity, $\bar{\lambda}/\lambda^*$, of the order unity. A Peclet (Pe) number can be defined as

$$Pe = \frac{VRc_p}{\lambda^*},$$

where λ^* is a characteristic thermal conductivity. For typical fracture conditions and fluid properties, Pe is of the order 10^8 , so the second term is negligible. Because the parameter m has been shown to be of the order 10^{-2} after one day and all other terms are of the order unity, the fluid energy equation reduces (after one day) to

$$\frac{2\bar{q}R}{c\rho V\bar{W} (T_r - T_i)} = u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} . \quad (6-6)$$

The heat flux from the rock into the fluid ($\bar{q}$) at the fracture surface is obtained from a separate solution of the energy equation in the rock.

Rock Energy Equation. For constant rock properties, heat transfer through the rock is described for three-dimensional conduction by

$$\frac{\partial \theta}{\partial t} = \frac{\partial^2 \theta}{\partial z^2} + Fo \left(\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} \right) , \quad (6-7)$$

where z is a nondimensional distance, $z = \bar{z}/L$, and L is a characteristic conduction length, $L = \sqrt{\alpha_r t^*}$. θ is the nondimensional rock temperature,

$\theta \equiv (\bar{\theta} - T_r)/(T_i - T_r)$, and Fo is a Fourier number, $Fo = \alpha_r t^*/R^2$, and $\alpha_r = \lambda_r/c_r \rho_r$.

Because Fo is $\leq 10^{-3}$ even for times as great as 30 yr, the rock energy equation reduces to a one-dimensional conduction equation

$$\frac{\partial \theta}{\partial t} = \frac{\partial^2 \theta}{\partial z^2} . \quad (6-8)$$

This equation, however, must be solved at each x, y point of interest in the fracture plane.

The heat flux into the fluid at the fracture surface ($z = 0$) is given by

$$q = - \left. \frac{\partial \theta}{\partial z} \right|_{z=0} , \quad (6-9)$$

where the nondimensional heat flux is

$$q = \bar{q} / \left[\lambda_r (T_r - T_i) / \sqrt{\alpha_r t^*} \right] .$$

Boundary conditions for the rock conduction equation are

$$\begin{aligned}\theta(x,y,z, t=0) &= 0 \\ \theta(x,y, z=0, t) &= 1 - T(x,y,t) \\ \theta(x,y,z \rightarrow \infty, t) &= 0.\end{aligned}$$

Because the fracture gap width goes to zero at the outer edge of the fracture, the x and y boundary conditions in the fracture plane are satisfied. At the axis of symmetry within the fracture, temperature and pressure gradients in the x-direction are zero as is u, the x component of velocity, and the horizontal gradient of the vertical velocity, $\partial v / \partial x$. The initial fluid temperature, however, must be specified everywhere in the x,y plane.

As heat is extracted from the fracture, the rock will contract and the fracture gap width will increase with time. In dimensionless form the gap width at any point and time, w, is simply the sum of the initial width, w_i , plus the accumulated rock contraction:

$$w = w_i + \frac{2\delta\sqrt{\alpha_r t^*}}{w^*} (T_r - T_i) \int_0^\infty \theta dz, \quad (6-10)$$

where δ is the linear thermal expansion coefficient of the rock. The integral in Eq. (6-10) is simply related to the total heat removed from the rock, which results in

$$w = w_i + \frac{2\delta\sqrt{\alpha_r t^*}}{w^*} (T_r - T_i) \int_0^1 q dt. \quad (6-11)$$

6.1.3. Solution Procedure. Equations (6-3), (6-4), (6-6), (6-8), and (6-9) represent a considerable simplification of the equations first proposed in the pioneering work of Harlow and Pracht,³ which included advection as well as transient terms in Eq. (6-3), and conduction and transient terms in Eq. (6-6). By formal nondimensionalization and rationalization of the complete equations, these additional terms are shown to be negligible for calculations of practical interest.⁵

Even in their simplified forms, the equations derived above are still formidable--they represent a set of five, two-dimensional transient partial differential equations. Furthermore, because they are coupled (temperatures depend upon velocities, which depend upon pressures, which in turn depend upon temperatures, etc.) they are highly nonlinear, and thus numerical methods provide the only practical form of solution.

Because Eqs. (6-8) and (6-9) must be solved at every point of interest in the fracture plane, at every time step, the key to rapid computations was to solve them by some simple and efficient scheme. An application of the Duhamel superposition integral (Ref. 2, p. 30) provided such a scheme.

Using the superposition principle, the dimensionless rock temperature becomes⁵

$$\theta = -2 \sum_{j=0}^{n-1} \left\{ \frac{T_{j+1} - T_j}{t_{j+1} - t_j} - \frac{T_j - T_{j-1}}{t_j - t_{j-1}} \right\} (t - t_j) i^2 \operatorname{erfc} \left(\frac{z}{\sqrt{(t - t_j)}} \right), \quad (6-12)$$

and the nondimensional heat flux (q) is, operating on Eq. (6-12) according to Eq. (6-9),

$$q = \frac{-2}{\sqrt{\pi}} \sum_{j=0}^{n-1} \left[\frac{T_{j+1} - T_j}{t_{j+1} - t_j} - \frac{T_j - T_{j-1}}{t_j - t_{j-1}} \right] \sqrt{t - t_j}; \quad t_{n-1} \leq t \leq t_n. \quad (6-13)$$

Thus, the rock temperature at any point and the heat flux conducted to the fluid can be easily calculated from the history of the fluid temperatures. At the n th time step, the unknown heat flux at any point in the fracture is solved for in terms of the previously calculated $n - 1$ fluid temperatures for that point, plus the yet-to-be determined temperature, T_n , at the end of that time step. This relationship is then substituted into Eq. (6-6). This equation plus Eqs. (6-3) and (6-4) are then converted to finite difference equations, which are expressed in an implicit form to avoid restrictions on the size of the time step imposed because of numerical stability considerations. The convection terms in Eq. (6-6) are formulated using "upwind differencing of the second kind,"⁶ which enhances numerical stability.

Finally, the set of simultaneous algebraic equations obtained as a result of finite differencing are solved iteratively, using successive overrelaxation.⁵ Typically, geothermal reservoir simulations are performed using a grid of 200 node points to represent the fracture. Ten time steps are usually used to cover the first year of operation--fewer time steps are required thereafter.

Instabilities arise in these simulations when the dimensionless parameter K becomes too large, i.e., when the effects of buoyancy are very large compared with the dissipative effects of viscosity. Whether these instabilities are purely numerical in origin or manifestations of a real physical instability, such as an abrupt transition from one type of flow pattern to another, is uncertain.^{4,5} Numerical and analytic stability analysis as well as laboratory modeling of heat extraction are required to resolve the problem.

6.1.4. Examples of Computational Results.

Flow Patterns. Flow patterns are shown in the form of streamlines in Figs. 6-1 through 6-5. In these figures, which show the right half of the fracture plane, each pair of streamlines (including fracture boundaries) bound 10% of the total water flow. In the figures the term "relative power" is merely the thermal power divided by the analytic value for uniform upward flow in a rectangular fracture having the same heat transfer area.

For these calculations, the fracture is assumed to be symmetrical about a vertical centerline; that is, the water inlet and outlet both lie on the vertical centerline and the fracture is circular (penny shaped) with a radius of 500 m. The fracture width is initially elliptical with a maximum width of 3 mm at the center of the disk. The average initial rock temperature is 250°C with a constant geothermal gradient of 50°C/km. The water inlet temperature for these calculations is 65°C.

Figure 6-1 shows a 500-m-radius fracture with a flow of 144 kg/s, with no buoyancy, which is very similar to a situation with a high impedance, as would be the case for a fracture propped open with particles. For this case, there is a tendency to short-circuit from inlet to outlet which becomes somewhat more pronounced with time, enhanced by the thermal contraction of the rock in the cooler regions. At the time shown, the maximum fracture thickness has increased from 3 to 9 mm and moved down 125 m to the water inlet.

With thermal contraction
 No buoyancy
 Time = 4.17 Ms (48.3 days)
 T_{out} = 140°C
 Power = 45.4 MW
 Relative power = 0.42
 Flow = 144 kg/s (total)

Fig. 6-1.
 Flow streamlines after 48 days with
 buoyancy suppressed.

Figures 6-2 and 6-3 show flow patterns for a case with buoyancy and thermal contraction and without proppant (a propping agent) in the fracture, at two different times. The development of a large recirculating zone resulting from the increasing dominance of the buoyancy forces as the fracture opens up is evident. There are, of course, flow streamlines within the recirculation zone that are not shown in the figures.

Figures 6-4 and 6-5 show results for a somewhat different water supply situation. Here, the water inlet is in the upper region of the fracture very near the

No proppant
With thermal contraction
Buoyancy
Time = 0.161 Ms (1.86 days)
 $T_{out} = 228^{\circ}\text{C}$
Power = 98.5 MW
Relative power = 0.88
Flow = 144 kg/s

Fig. 6-2.
Flow streamlines after 2 days with buoyancy.

No proppant
With thermal contraction
Buoyancy
Time = 7.79 Ms (90.2 days)
 $T_{out} = 176^{\circ}\text{C}$
Power = 66.8 MW
Relative power = 0.68
Flow = 144 kg/s

Fig. 6-3.
Flow streamlines after 90 days with buoyancy.

outlet. As shown, with no proppant, the dominant buoyancy forces create a downward and outward flow so that the power extracted from this fracture is reasonably large. If, however, a high proppant impedance is present, the flow will short-circuit. For a high-impedance case the relative power decreases from 0.43 after about 2 days to 0.11 after 1 yr.

Pressure Change. In general, the pressure losses well inside an inflated, unpropped fracture should be small so that total system pressure losses and the

No proppant
With thermal contraction
Buoyancy
Time = 0.161 Ms (1.86 days)
 $T_{out} = 222^{\circ}\text{C}$
Power = 94.9 MW
Relative power = 0.85

Fig. 6-4.
Flow streamlines after 2 days; new inlet location with buoyancy.

No proppant
With thermal contraction
Buoyancy
Time = 9.51 Ms (110 days);
 $T_{out} = 132^{\circ}\text{C}$
Power = 40.3 MW
Relative power = 0.43
Flow = 144 kg/s

Fig. 6-5.
Flow streamlines after 110 days; new inlet location with buoyancy.

question of "self-pumping" depend on the pressure losses in the supply/return pipes, in the surface plant, and at the inlet and outlet regions.

Of particular importance is the region of the reservoir very near the outlet. Velocities in this region can exceed 50 m/s, and the pressure drops associated with these velocities are very high. Furthermore, the flow is highly accelerated as it converges upon the outlet. In this region the assumption of Darcy-type flow is invalid and boundary layer equations are required to describe the fluid mechanics. A computer code, RADFLO, has been developed that numerically

integrates these equations assuming that the flow is laminar and the surrounding rock surfaces are hydrodynamically smooth. For typical wellbore diameters and fracture widths, the calculated pressure loss in the outlet region is about 4 bar (60 psi) for a mass flow rate of 100 kg/s, and about 10 bar (150 psi) for a flow rate of 200 kg/s.

However, actual pressure losses are likely to be even higher because the rock surfaces are not smooth and the flow may be turbulent. Unfortunately, turbulence models for such a highly accelerated flow have not yet been developed. A laboratory model to study the flow in the outlet region is being built to supply the required information regarding flow patterns, velocity profiles, pressure gradients, and the effects of fluid acceleration.

Parametric Prediction of Power Extraction Rates. The parametric curves in Figs. 6-6 through 6-8 of power and temperature as a function of time demonstrate the ability of a larger fracture to maintain a useful power level for a reasonable length of time under the pessimistic conditions of no secondary fracturing and a relatively low ratio of buoyancy forces to viscous forces.

Figure 6-9 presents parametric results for a very small fracture, suitable for a 10-MW(t) interim circulation loop between EE-1 and GT-2. The results are presented in terms of the ratio of the power at a given time to the initial power. To demonstrate proof-of-concept, a relatively rapid power decay is desirable so that the relation between theoretical and actual performance--especially in such areas as the effect of thermal stress fracturing--can be assessed in a short time. As can be seen, depending upon the placement of the inlet and outlet, the effects of short circuiting can be severe at early times.

As the crack widens because of thermal contraction, buoyancy effects reduce the degree of short circuiting, so that in some cases the power extracted can actually increase with time. There is a possibility that such an increase, if observed in the field, could be incorrectly interpreted as evidence for augmentation of the reservoir by thermal stress cracking.³

Fig. 6-6.
Thermal performance of 500-m-radius fracture.

Fig. 6-7.
Thermal performance of 1000-m-radius fracture.

Fig. 6-8.
Thermal performance of 1500-m-radius fracture.

Fig. 6-9.
Power drawdown for an ideal 100-m-radius fracture.

6.2. Wellbore Heat Transmission Modeling

The equation describing heat transfer in the rock surrounding a wellbore is

$$\frac{\partial^2 T_r}{\partial \kappa^2} + \frac{1}{\kappa} \frac{\partial T_r}{\partial \kappa} = \frac{\rho_r c_r}{\lambda_r} \frac{\partial T_r}{\partial t}, \quad (6-14)$$

and the equation for the flowing fluid in the wellbore is*

$$\frac{\partial T}{\partial t} + U \frac{\partial T}{\partial t} = - \frac{2}{\rho c} \left(\frac{\lambda_r}{\kappa} \frac{\partial T_r}{\partial \kappa} \right) \text{ at } \kappa = a, \quad (6-15)$$

where U is the fluid velocity in the wellbore.

*Subscript r refers to rock properties; variables without subscripts refer to fluid properties.

By expressing Eqs. (6-14) and (6-15) in nondimensional form, a functional relationship between dimensionless temperature difference, ΔT_D , and dimensionless time, $t_D = \lambda_r t / (\rho_r c_r a^2)$, appears for a specified ratio of the volumetric heat capacity of the rock to that of the fluid

$$\Delta T_D = \frac{2\lambda_r (T - T_0)}{\rho c a^2 U \frac{dT}{dZ}} = \Phi\left(\frac{\lambda_r t}{\rho_r c_r a^2}\right) \cdot \Psi\left(\frac{\rho_r c_r}{\rho c}\right), \quad (6-16)$$

where T = fluid temperature at time t , depth Z

T_0 = initial fluid temperature.

Equation (6-16) is valid when both the fluid velocity, U , and the temperature gradient, dT/dZ , do not vary significantly with time. The latter condition requires that the following dimensionless group be less than 0.3:

$$\frac{\rho c a U}{\lambda_r Z} \sqrt{\alpha_r t} \leq 0.3. \quad (6-17)$$

A wellbore heat transmission computer model was developed and used to evaluate the functional form of Eq. (6-16) for a value of $\rho_r c_r / \rho c = 0.71$, appropriate for granite and 200°C water.

The numerical computer model is based on a finite element approach in which temperature is assumed to be linear over a finite distance. In the transient terms, temperature at a point in space is assumed to be linear over a finite interval of time. The model allows for material properties to vary from element to element. As a result, wellbore casings and annuli can be incorporated into the model. Also, fluid may be allowed to enter or leave the wellbore at any designated elevation. The computed curve for Eq. (6-16) is shown in Fig. 6-10. This curve is essentially a type curve, and is a thermal analog to the type curve developed by Ramey⁷ for pressure analysis of a single well in an infinite reservoir with wellbore storage.

All parameters, except temperature and time, in Eq. (6-16) are constant so if the experimental log ($\Delta T = T - T_0$) is plotted against log (t), the plot should have the same shape as the type curve. The data from the temperature logs taken in the GT-2 wellbore during a constant flow experiment with conditions satisfying Eq. (6-17) were plotted on log-log coordinates and the results are overlaid

Fig. 6-10.

Type curve for wellbore heat transmission with $\rho_r c_r / \rho c = 0.71$. A section of experimental data is overlaid on the curve to illustrate a curve shape match.

on the type curve of Fig. 6-10. A match point occurs with the actual time of 10 000 s corresponding to a dimensionless time of 1.4. For a wellbore radius of 0.087 m and a value of 2700 kg/m^3 for the rock density, ρ_r , and $1050 \text{ J/kg}\cdot\text{K}$ for the rock heat capacity, c_r , the calculated in situ thermal conductivity of rock is $3.0 \text{ W/m}\cdot\text{K}$ ($1.7 \text{ BTU/h}\cdot\text{ft}\cdot^\circ\text{F}$). This is in excellent agreement with the laboratory results reported by Sibbitt⁸ for core specimens taken from GT-2.

As a check, the temperature difference at 10 000 s is 2.8°C , and using

$$\rho = 950 \text{ kg/m}^3$$

$$c = 4184 \text{ J/kg}\cdot\text{K},$$

$$a^2 U = 1.9 \times 10^{-4} \text{ m}^2/\text{s},$$

$$\lambda_r = 3.0 \text{ W/m}\cdot\text{K}, \text{ and}$$

$$\Delta T (\text{dimensionless}) = 0.66,$$

a value of 0.032°C/m is calculated for an average temperature gradient dT/dZ , which is in excellent agreement with temperature log data in this region of the wellbore.

By assuming constant rock properties and a constant wellbore radius, the ratio of the 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, $\bar{G}$, at these depths and time as

$$\frac{U_2}{U_1} = \frac{T(z_2) - T_0(z_2)}{T(z_1) - T_0(z_1)} \frac{\bar{G}(z_2)}{\bar{G}(z_1)} \quad (6-18)$$

The gradient, $G = \partial T / \partial z$, is no longer required to be constant in Eq. (6-18), and in fact, the gradient to be used, $\bar{G}$, is an "effective average" gradient. For short time tests with insignificant wellbore heat storage ($1 < \alpha_r t / a^2 < 10$), a useful approximation for $\bar{G}$ is

$$\bar{G} = \sqrt{G(t) \cdot \frac{1}{t} \int_0^t G(\tau) d\tau} \quad (6-19)$$

The application of these techniques to determining wellbore-to-fracture connections by analyzing temperature logs taken under flowing conditions in wellbores is discussed in Sec. 5.1.

6.3. Thermodynamic and Economic Models of Energy Conversion Systems Associated with Hot Dry Rock Reservoirs*

Using a geothermal resource to supply heat to a power-generating cycle often involves a set of design criteria different from conventional fossil-fuel fired or nuclear generating cycles. Because conversion efficiencies range from 8 to 20% for geothermal resource temperatures of 100 - 300°C, and because costs associated with producing hot fluid at the surface frequently represent more than 60% of the total capital investment in the power plant, a premium is placed on designing and operating power conversion systems near their thermodynamic limiting efficiencies. In essence, when geothermal fluid production costs are high compared to equipment costs, thermodynamic and economic optima should coincide. The following discussion summarizes the salient features of a joint study by Oak Ridge

*In collaboration with S. L. Milora of Oak Ridge National Laboratory.

National Laboratory and Los Alamos Scientific Laboratory of geothermal power conversion systems made by Milora and Tester.⁹ The main effort was directed toward developing thermodynamic and economic design criteria applicable to generating electric power from low-temperature geothermal resources. Many of the concepts developed would also apply to other low-temperature resources, such as solar or ocean thermal.

Research and development activity in the geothermal power area has increased markedly in the past few years.⁹⁻¹⁶ Rankine or similar cycles have been used for power production with water as the working fluid, particularly where natural steam is available. For liquid-dominated systems, steam vapor can be created by flashing the geothermal fluid at the surface to a lower pressure. Then, the saturated steam phase can be used to drive a turbogenerator unit, with the unflashed liquid phase either reinjected or discarded. Binary-fluid cycles using nonaqueous working fluids are alternatives to single- and multiple-flashing systems now used in various parts of the world, for example, Cerro Prieto, Mexico, and Wairakei, New Zealand.¹¹ Binary-fluid cycles involve a primary heat exchange step where heat from the geothermal fluid is transferred to another working fluid. This fluid expands through a turbogenerator and then passes to a condenser/desuperheater for heat rejection to the environment. The cycle is completed by pumping the fluid up to the maximum cycle operating pressure.

Nonaqueous working fluids with large, low-temperature vapor densities would require smaller turbines than the low-pressure steam turbines used in flashing systems of the same power output. Flashing cycles are, of course, simpler because they do not require a primary heat exchanger. Models used in characterizing power cycle performance, in a thermodynamic and an economic sense, are developed and optimization procedures illustrated for several cases (for details see Ref. 9).

6.3.1. Thermodynamic Properties of Working Fluids. Accurate data on the thermodynamic properties of proposed fluids are required to calculate cycle performance. Heat capacity at constant pressure in the ideal gas state, C_p^* , vapor pressure, p^{sat} , pressure-volume-temperature (PVT) behavior, and liquid density at saturation, ρ_l^{sat} , are expressed with semi-empirical equations written in reduced form. For example, a modified form of the Martin-Hou equation of state with 21 parameters is used for calculating PVT properties.^{9,17,18} This equation is accurate for densities above the critical point, a requirement for supercritical Rankine cycle calculations. Derived properties such as entropy and

enthalpy are obtained by suitable differentiation and integration of the semi-empirical equations for C_p^* , p^{sat} , $P = f(T, v)$, and ρ_ℓ^{sat} . An equation rather than tabular format was preferred because many iterative calculations are routinely performed.

Seven working fluids in addition to water were examined. Refrigerants, R-22 (CHClF_2), R-600a (isobutane, $i\text{-C}_4\text{H}_{10}$), R-32 (CH_2F_2), R-717 (ammonia, NH_3), RC-318 (C_4F_8), R-114 ($\text{C}_2\text{Cl}_2\text{F}_4$), and R-115 (C_2ClF_5) were selected because they provided a range of properties, including critical temperature, T_c , and pressure, P_c , and molecular weight, M . All of these compounds have relatively high vapor densities at heat rejection temperatures as low as 20°C .

6.3.2. Power Cycle Performance Optimization. Detailed cycle calculations were performed to examine the effects of cycle operating pressure, heat rejection temperature, temperature differences in the primary heat exchanger, turbine and pump efficiencies, and geothermal fluid temperature. In each case a utilization efficiency, η_u , was determined that related the actual electrical work produced by the cycle to the maximum work (or availability) possible with specified geothermal source and heat rejection temperatures. Parametric effects were explored using computer computational techniques.⁹

For any given working fluid, there is an optimum set of operating conditions yielding a maximum η_u for a particular geothermal fluid and heat rejection temperatures. In screening potential working fluids, some knowledge of the magnitude of η_u and how it changes would be useful. Computer optimizations for the seven working fluids studied were conducted for geothermal fluid temperatures ranging from 100 to 300°C are shown in Fig. 6-11 (see Ref. 9 for details). At each point, cycle pressures were varied until an optimum was determined at that temperature. A characteristic maximum, η_u , which is different for each fluid but is generally between 60 and 70%, is observed at a particular resource temperature.

Because the calculations leading to Fig. 6-11 are complex and time consuming, a simpler technique for preliminary fluid evaluation was obtained by plotting the temperature of maximum η_u (T^*) minus the fluid's critical temperature, (T_c), as a function of the reduced, ideal gas state heat capacity, $C_p^*/R = (\gamma/\gamma-1)$, where $\gamma = C_p/C_v$ and R is the gas constant. The data for the seven fluids studied fit the empirical equation.

Fig. 6-11.
Geothermal utilization efficiency, η_u , as a
function of geothermal fluid temperature for
optimum thermodynamic operating conditions
(Ref. 9).

$$T^* - T_c = 790 / (C_p^* / R). \quad (6-20)$$

The quantity $(T^* - T_c)$ is effectively the degree of superheat above the critical temperature for optimum performance and can be explained by changes in properties associated with changes in molecular weight. Lower molecular weight compounds, for example, R-22 ($M = 86$) and R-717, ammonia ($M = 17$), have fewer molecular degrees of freedom resulting in lower values of C_p^* / R and higher values of superheat above the critical point. As molecular weight increases, more degrees of freedom exist, C_p^* / R increases, and $(T^* - T_c)$ decreases. An empirical procedure of this type should be valuable in a preliminary working fluid assessment because γ and T_c are commonly known properties of many compounds.

6.3.3. Power Generation Cost Optimization. In comparing flashing cycles to binary-fluid cycles, differences between the primary components, including geothermal wells, heat exchangers, condensers/desuperheaters, turbines, and pumps, are important economic factors. Power generation costs were determined using a factored estimate model of the major component costs.⁹ The total fixed capital investment, Φ , for a completed system is expressed as a function of the total equipment, Φ_E , and geothermal well cost, Φ_w :

$$\Phi = f_I[\Phi_E + \sum f_i \Phi_E] + f_I^*[\Phi_W + f_W \Phi_W]. \quad (6-21)$$

The fractions f_i of Φ_E represent direct costs associated with the constructional aspects of equipment installation. f_I covers the indirect costs such as engineering fees, contingency, and escalation during construction, f_W the direct costs for piping from the wellhead to the power plant, and f_I^* the indirect costs associated with discovery of the geothermal field, including land acquisition and surface exploration. Separate cost correlations were used for each component. Well costs were based on depth, diameter, and type of rock formation. Heat exchanger and condenser/desuperheater costs were calculated from required surface areas and existing manufacturing cost estimates. Turbine costs were based on a model developed by the Barber-Nichols Company of Arvada, CO.⁹ Turbine design parameters, blade pitch diameter, number of stages and exhaust ends in tandem units, blade tip speed, and stage pressure were used in the turbine cost equation. Pump costs were determined from manufacturers' estimates based on power rating and casing pressure.

In selecting nonaqueous working fluids for power cycle applications, turbine sizes should be small to reduce costs because of the economic tradeoff between the additional heat exchange surface area required for binary-fluid cycles and the much larger and more costly steam turbines required in flashing systems.

It is important to operate turbines at high efficiency. A similarity analysis of performance shows that turbine efficiency is controlled by two dimensionless numbers involving four parameters: (1) blade pitch diameter, (2) rotational speed, (3) stage enthalpy drop, and (4) volumetric gas flow rate.⁹ For operation at maximum turbine efficiency the relationship among these parameters is specified; therefore, turbine sizes and operating conditions and consequently costs can be estimated. For fluid screening purposes, a generalized figure of merit, ξ , which scales directly with turbine size was developed. The variable ξ is expressed as an explicit function of the fluid's molecular weight, M , critical pressure, P_c , and reduced vapor energy density, $h_{fg})_r/v_g)_r^{\text{sat}}$. The reduced latent heat is $h_{fg})_r = h_{fg}/RT_c$ and the reduced gas specific volume evaluated at the heat rejection temperature, T_o , if $v_g)_r = v_g/v_c$. Table 6-I presents values of ξ for water and the seven working fluids studied.⁹

TABLE 6-I
TURBINE SIZE FIGURE OF MERIT
 $T_0 = 26.7^\circ\text{C}$

Compound	Formula	$\xi^a = \frac{\sqrt{M}}{P_c} \left[\frac{v_g^{\text{sat}} r}{h_{fg} r} \right]_{T_0}$
R-717	NH ₃	0.177
R-32	CH ₂ F ₂	0.223
R-22	CHClF ₂	0.411
R-115	C ₂ ClF ₅	0.649
R-600a	C ₄ H ₁₀	0.881
RC-318	C ₄ F ₈	1.628
R-114	C ₂ Cl ₂ F ₄	2.246
Water	H ₂ O	30.71
$a(\text{g/gmole})^{1/2} \text{ bar}^{-1}$.		

Because of the complex relationships between economic factors, economic optima were first developed for specifically defined geothermal resources. A 100-MW(e) capacity was selected in the reference design cases. A 150°C liquid-dominated resource with an R-32 binary-fluid cycle and with a two-stage flashing cycle, and a 250°C hot dry rock resource with an R-717 (ammonia) binary-fluid cycle were considered initially. Well flow rates (45 kg/s for the 150°C resource and 136 kg/s for the 250°C resource), geothermal temperature gradients (50-60°C/km), well depths, and reservoir lifetime (≥ 20 yr) were

specified. Production and reinjection well costs were included. Economic optima were determined by varying the operating pressure of the binary-fluid cycles for specified heat exchange conditions. Flashing systems were optimized by varying stage pressure and temperature for specified heat rejection conditions (see Fig. 6-12).

Generating costs for hot dry rock systems are primarily controlled by three main variables: (1) fluid temperatures, which affect cycle efficiency and thus equipment costs; (2) well flow rates, which affect well efficiency (kW/well); and (3) geothermal temperature gradients, which affect well depth and cost for a given geothermal fluid temperature. For a defined set of resource and power plant conditions there should exist an optimum depth (or temperature) for drilling. A generalized cost model was developed to illustrate this hypothesis. In the model, installed generating cost is expressed parametrically as a function of well flow rates (45 - 225 kg/s), fluid temperatures (100 - 300°C), and temperature gradients (20 - 200°C/km) for a hot dry rock resource with a binary-fluid cycle for power production.

The model assumes a two-hole circulating, hot dry rock system with an equal number of production and reinjection wells. A net 100-MW(e) binary-fluid cycle was selected because it potentially represents an efficient conversion process for producing electricity. Purchased equipment costs (Φ_E) were calculated for

100 - 300°C geothermal resource temperature (T_{gf}) and several working fluids. Φ_E varied as a linearly decreasing function of temperature:⁹

$$\Phi_E (\$/kW) = 320.5 - 0.7040 T_{gf}, \quad (6-22)$$

where T_{gf} is expressed in °C. In addition, individual well costs (Φ_w^*) were approximated by an exponential function in depth z :

$$\Phi^* (\$/well) = 64.395 z \exp [3.88843 \times 10^{-4} z], \quad (6-23)$$

where z is expressed in meters. The depth can be calculated as a function of the average geothermal gradient ($\overline{\nabla T}$ in °C/km) and an average ambient crustal temperature ($\overline{T}_c = 15^\circ\text{C}$):

$$z = \frac{1000 (T_{gf} - 15)}{\overline{\nabla T}}. \quad (6-24)$$

By using average values for direct and indirect cost factors taken from Ref. 9; that is,

$$\begin{aligned} 1 + f_w &= 1.50 & f_I &= 1.70 \\ 1 + \Sigma f_i &= 1.63 & f_I^* &= 1.56 \end{aligned}$$

and assuming that 60% of the maximum possible power is produced from a resource temperature of T_{gf} to a heat rejection temperature $T_o = 26.7^\circ\text{C}$ (see Fig. 6-11), Eqs. (6-22) and (6-23) can be combined into Eq. (6-21) to give the total installed cost per kW as:⁹

Fig. 6-12. Approach to economic optimum cycle conditions. Cost per kWh and cost per installed kW as function of reduced cycle pressure. A 250°C hot dry rock geothermal resource with an ammonia Rankine cycle and a 150°C liquid-dominated resource with a R-32 Rankine cycle and a flashing cycle were studied (Ref. 9).

$$\Phi (\$/kW) = \frac{119.59 z \exp [3.8884 \times 10^{-4} z]}{\dot{m}_w \left[T_{gf} - 26.7 - 299.85 \ln \left(\frac{T_{gf} + 273.15}{299.85} \right) \right]} + 888.1 - 1.951 T_{gf}, \quad (6-25)$$

where $\dot{m}_w$ is the flow rate in kg/s per geothermal well. Figure 6-13 illustrates the parametric dependence at 113 kg/s.

Other approaches to geothermal power economics are being developed at the Battelle Northwest Laboratories^{19,20} and Lawrence Berkeley Laboratory²¹ and should be very useful for estimating purposes. However, economic factors for geothermal power development tend to be very site specific, and each case should be treated separately. Any cost estimate depends on the correlations used for each component, including downhole drilling costs as well as surface equipment.

6.4. Numerical Modeling of Fluid Flow in the GT-2/EE-1 System

A complete system model is intended to predict reservoir, surface plant, and fluid delivery behavior. Such a model will eventually incorporate heat extraction, thermal stress cracking, variable permeability, geochemical, and non-ideal geometry effects. To date, a lumped-parameter, isothermal system simulator, FRACFLO, has been developed. This simulator accounts for the following phenomena:

- Internal resistances to flow in the fracture.
- Possible resistances to flow between fractures, e.g., unfractured rock paths between fractures.
- Wellbore-to-fracture impedance (which can change in time).
- Fluid storage in wellbores.
- Fluid storage in the fractures due to compressibility of water in a fixed volume fracture, and also to inflation of fractures.
- Transient permeation of fluid into (and out from) the rock surrounding the fractures.

Because of limited knowledge of downhole fracture geometries, only preliminary models of the system have been generated. Figure 6-14 shows one of these models. Basically, the wellbores are treated as two separate lumped parameters, as are the two fractures. Pressure drops in the fractures themselves are assumed

Fig. 6-13.

Generalized cost model for geothermal systems. Generating costs expressed as a function of geothermal gradient, ∇T , and geothermal fluid temperature, T_{gf} , for a well flow rate $\dot{m}_w = 113 \text{ kg/s}$ (Ref. 9).

to be negligible compared with the pressure drop between the fractures and at the wellbore-to-fracture connections. Permeation of fluids through the rock is accounted for by numerically solving a one-dimensional hydraulic diffusion equation for each of the fractures.

Figure 6-15 shows the general agreement between predicted and experimental pressure-time response during flow Experiment 110. During this experiment water was pumped into EE-1 at

Fig. 6-14.

A preliminary flow model for the GT-2/EE-1 connected system. (Fracture orientation shown is distorted perspective.)

Fig. 6-15.

Pressure-versus-time behavior for Experiment 110.

a constant rate. After 2 h the GT-2 wellbore started to overflow at the surface and was then "shut in," accounting for the sudden increase in GT-2 pressure at this time.

After 3 h of pumping EE-1 was also "shut in" and its pressure started to decay as water from this fracture continued to permeate the surrounding rock and also to flow through an impedance to GT-2. Because of this flow the GT-2 pressure continued to rise for an additional 6 h, at which time the ever-diminishing supply of water from EE-1 was not sufficient to satisfy the permeation of water into the rock surrounding GT-2.

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7. DOWNHOLE INSTRUMENTATION AND EQUIPMENT DEVELOPMENT AND APPLICATION*

Although conventional oil drilling technology was used for much of the work on GT-2 and EE-1, the different rock formations and higher temperatures encountered in geothermal drilling required the development of new techniques and instrumentation.

GT-2 was drilled in three phases to a total depth of 2932 m (9619 ft).¹⁻³ (See Table 7-I.) Various logging and experimental operations accompanied each of the drilling phases. EE-1 was drilled in two phases to a current depth of 3064 m (10 053 ft).⁴ (See Table 7-II.) Each borehole progressed successively through volcanic tuff rock, sedimentary formations, and into Precambrian basement granitic rock (see Appendix B). In the first part of this section, the drilling operations and the directional surveys for these two boreholes are described briefly. The casing and cementing program is then presented, followed by a summary of downhole packer utilization.

TABLE 7-I
DRILLING OPERATIONS IN GT-2

<u>Phase</u>	<u>Starting Date</u>	<u>Final Depth</u>
I	Feb. 17, 1974	1937 m (6356 ft)
II	Aug. 30, 1974	2042 m (6701 ft)
III	Oct. 12, 1974	2932 m (9619 ft)

TABLE 7-II
DRILLING OPERATIONS IN EE-1

<u>Phase</u>	<u>Starting Date</u>	<u>Final Depth</u>
I	May 26, 1975	2099 m (6886 ft)
II	Aug. 31, 1975	3064 m (10 053 ft)

*In this section, unless otherwise noted, all depths are measured along the borehole from the top of the Kelly bushing of either the Calvert Western drilling platform (GT-2) or the Signal drilling platform (EE-1).

The second part of this section describes measurement-related activities in instrumentation and equipment development and application, including downhole tool orientation measurements, borehole acoustic detectors and sources, downhole temperature and pressure measurements, and other equipment and measurements associated with the borehole and geothermal reservoir system. Most of the results and interpretation of these measurements are discussed in other sections.

7.1. Drilling-Related Activities (D. W. Brown, R. A. Pettitt, D. L. Sims, F. G. West, D. J. Miles, J. M. Tatom, and W. D. Purtymun)

Drilling operations for GT-2 and EE-1 are fully described in Refs. 1-4, and only summaries of this work will be given here.

7.1.1. Standard and Coring Bit Drilling.

Drill Bit Performance, GT-2.* After the surface conductor casing was cemented in place, drilling began February 20, 1974, with a Smith Tool Company 31.1-cm-diam (12-1/4-in.), Type 3JS, steel-toothed tricone rock bit. The remaining 122 m (400 ft) of volcanic tuff rock was drilled rather easily in about 30 h.

Drill bits from three manufacturers, Smith Tool Company, Hughes Tool Company, and Dresser Security, were used in the sedimentary beds to drill the 31.1-cm-diam hole. Final depth of this section was 773 m (2535 ft), about 40 m (130 ft) into the granite. Smith 44.5-cm-diam (17-1/2-in.) bits were used as hole openers to 489 m (1605 ft). Caving of the sedimentary rock was a serious problem, and casing was inserted as soon as possible to save the hole.

The final casing size of the 27.3-cm-diam (10-3/4-in.) in the upper portion of the borehole dictated a maximum bit size of 24.4-cm-diam (9-5/8 in.) in the crystalline basement rock drilling. Hughes Tool Company supplied one bit, but because it was considered too soft for crystalline rock drilling, it was used only for reaming. Except for the bits used to drill cement and bridge plugs, and for coring, the only bits used to drill the crystalline rock were Smith Tool Company 9JS bits. These standard hard-rock mining bits were designed to drill the hardest, most abrasive ore-bearing rocks encountered in the mining industry (taconite, chert, granite, basalt, quartzite, and other hard metamorphic rocks). They were fitted with open, fluid-cooled and flushed, hardened bearings and were designed for air or mud circulation.

*See Refs. 1 and 3 for drilled footages and hours of use for each bit used.

In the initial runs in the basement rock, drilling was done with air as the circulating fluid. Air was considered superior to drilling liquids because air would not decrease the in-situ temperature of the rock as much as liquids, and the downhole temperature measurements would therefore be more accurate. Also, drilling in granite is generally faster with air. In addition, water had to be hauled to the site. Long runs with individual bits were not common. The longest run with a bit using air as the drilling medium drilled 72 m (237 ft) in 38 h, terminating at 866 m (2842 ft). Beginning at 1162 m (3814 ft), the drilled footage, the time in use, and the bit wear were recorded for two successive Smith 9JS bits, one used in an air-drilling mode and the other in a water-drilling mode. These results are shown in Table 7-III. As a result of the distinct advantage in footage and wear that was obtained with water drilling, a permanent conversion to water drilling was made.

As drilling progressed, the life of the Smith 9JS bits could be predicted. At 40 - 50 rpm and a bit loading of 17.2 - 19.1 Mg (38 000 - 42 000 lb), a bit could be expected to last about 60 h, after drilling nearly 91 m (300 ft). After this amount of drilling, the bit was usually about 0.6 cm (1/4 in.) under gauge, missing 15 - 25 buttons, and with the bottom reamers 0.2 - 0.3 cm (1/16 - 1/8 in.) under gauge (Fig. 7-1). During the last 10 - 12 h of bit operation, the drilling

TABLE 7-III
COMPARISON OF BIT PERFORMANCE
WITH AIR AND WATER DRILLING

	Air	Water
Drilled interval	61 m (199 ft)	78 m (237 ft)
Drilling time	39 h	42 h
Bit wear	0.6 cm (1/4 in.)	0.3 cm (1/8 in.)
Reamer wear	0.3 cm (1/8 in.)	0.2 cm (1/16 in.)
Drilling rate	1.6 m/h (5.1 ft/h)	1.9 m/h (6.1 ft/h)
Drill-string weight ^a	20 Mg (44 000 lb)	20.8 Mg (45 000 lb)
Drilling speed, rpm	40	44

^aWeight on the bit.

Fig. 7-1.
Smith 9JS tricone rock bit after
drilling about 60 h. Note missing
buttons.

rate was monitored closely. If the rate fell off significantly below the average 1.2 - 1.5 m/h (4 - 5 ft/h), or if the bit began to run rough or torque up, drilling was stopped and the bit pulled. Thus, maximum use was obtained from the bits while safeguarding against roller failure and disintegration in the hole. A summary of the major bit runs in GT-2 Phase I drilling is shown in Table 7-IV.

Phase I drilling was completed in June 1974 at 1937 m (6356 ft). Following the drilling, a series of hydrology experiments (Phase II operations) was performed (see Sec. 7.1.5.). An additional 105 m (345 ft) of drilling were completed during this testing phase to allow experiments to be conducted in this new region. On the basis of the results of the hydrology experiments and other measurements, it was decided to deepen the borehole to about 2930 m (9600 ft).

Phase III drilling began with a 25.1-cm-diam (9-7/8-in.) Smith Q9TJL mining bit and water as the drilling medium. Two successive drilling runs were made to 2281 m (7485 ft) using the Smith bits. Bit speed during these runs was 40 rpm, with the bit load varying from 17.2 to 18.2 Mg (38 000 to 40 000 lb).

At that time, additional Smith bits of the desired gauge were not available, and the remaining major portions of the drilling were done with 24.4-cm-diam (9-5/8-in.) Security H10J bits. Four major drilling runs were made with these bits; the longest run was 201 m (685 ft) in 81 h. The bit speed and weight were approximately those used with the Smith bits. When pulled, the Security bits showed a loss of gauge up to 0.3 cm (1/8 in.) and had one to six buttons missing.

TABLE 7-IV
SUMMARY OF MAJOR DRILLING RUNS IN GT-2, PHASE I

Drilled Depth	Drilled Interval	Drilling Time (h)	Rock Type ^a	Drilling Media	Bit Wear (Loss in diam)	Average Penetration Rate
870.8-959.2 m (2857-3147 ft)	88.4 m (290 ft)	27	Monzogranite gneiss, biotite-granodiorite gneiss	Air	--	3.2 m/h (10.7 ft/h)
969.9-1055.5 m (3182-3463 ft)	85.6 m (281 ft)	32-1/2	Monzogranite gneiss, biotite-granodiorite gneiss	Air	--	2.6 m/h (8.6 ft/h)
1162.5-1223.2 m (3814-4013 ft)	60.7 m (199 ft)	39	Monzogranite gneiss	Air	0.64 cm (1/4 in.)	1.6 m/h (5.1 ft/h)
1223.2-1301.5 m (4013-4270 ft)	78.3 m (257 ft)	42	Monzogranite gneiss, monzogranite	Water	0.32 cm (1/8 in.)	1.9 m/h (6.1 ft/h)
1304.2-1388.7 m (4279-4556 ft)	84.5 m (277 ft)	49-1/2	Monzogranite, monzogranite gneiss	Water	0.64 cm (1/4 in.)	1.7 m/h (5.6 ft/h)
1388.7-1473.7 m (4556-4835 ft)	85.0 m (279 ft)	60-1/2	Monzogranite gneiss, granodiorite gneiss	Water	0.64 cm (1/4 in.)	1.4 m/h (4.6 ft/h)
1499.9-1595.3 m (4921-5234 ft)	95.4 m (313 ft)	65	Monzogranite gneiss, biotite-granodiorite gneiss, biotite-tonalite gneiss	Water	0.64 cm (1/4 in.)	1.5 m/h (4.8 ft/h)
1597.2-1670 m (5240-5479 ft)	72.8 m (239 ft)	51	Monzogranite gneiss, biotite-granodiorite gneiss	Water	0.64 cm (1/4 in.)	1.42 m/h (4.7 ft/h)
1727.9-1822.4 m (5669-5979 ft)	94.5 m (310 ft)	55-1/2	Monzogranite gneiss, hornblende-biotite schist, amphibolite	Water	0.32 cm (1/8 in.)	1.7 m/h (5.6 ft/h)

^aRock types determined from drill cuttings and spectral gamma logs.

The life of the Security bits was surprisingly good, considering that the down-hole temperature was greater than 150°C. A summary of the major drilling runs in Phase III is shown in Table 7-V.

Coring, GT-2. The preliminary drilling program for GT-2 included a plan for obtaining intermittent cores in the sedimentary section and continuous cores in the crystalline section. The continuous wireline retrievable coring system used by the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) was to be used. Following the JOIDES design, Smith Tool Company manufactured 15 core bits, 24.4-cm-o.d. by 6.2-cm-i.d. (9-5/8 by 2-7/16 in.), with four carbide insert roller cutters to drill the hole and form the core (Fig. 7-2).

When used by the JOIDES Deep Sea Drilling Project, the inner core barrel is normally dropped from the surface with the borehole full of water. Because the initial plans called for drilling the granitic rocks in GT-2 with air, modifications to the placing and retrieving components of the coring assemblies were necessary. A system to orient the cores with respect to their placement in the undisturbed native rock was also incorporated.

TABLE 7-V

SUMMARY OF MAJOR DRILLING RUNS IN GT-2, PHASE III

Drilled Depth	Drilled Interval	Drilling Time (h)	Rock Type ^a	Bit Wear (Loss in diam)	Average Penetration Rate
2047.3-2164.7 m (6717-7102 ft)	117.4 m (385 ft)	48	Biotite-granodiorite gneiss, monzogranite gneiss, biotite-tonalite gneiss	0.32 cm (1/8 in.)	2.5 m/h (8.0 ft/h)
2166.2-2281.4 m (7107-7485 ft)	115.2m (378 ft)	67	Biotite-tonalite gneiss, biotite-granodiorite gneiss, monzogranite gneiss	0.32 cm (1/8 in.)	1.7 m/h (5.6 ft/h)
2281.4-2413.4 m (7485-7918 ft)	132.0 m (433 ft)	58.5	Granodiorite gneiss, monzogranite gneiss	0.16 cm (1/16 in.)	2.3 m/h (7.4 ft/h)
2413.7-2614.3 m (7919-8577 ft)	200.6 m (658 ft)	81	Monzogranite gneiss, biotite granodiorite	0.32 cm (1/8 in.)	2.5 m/h (8.1 ft/h)
2617.3-2695.0 m (8587-8842 ft)	77.7 m (255 ft)	30.75	Biotite granodiorite	none none	2.5 m/h (8.3 ft/h)
2695.0-2899.9 m (8842-9514 ft)	204.9 m (672 ft)	75	Biotite granodiorite	0.32 cm (1/8 in.)	2.7 m/h (9.0 ft/h)

^aRock types determined from drill cuttings and spectral gamma logs.

Many mechanical difficulties were encountered in fabricating and using the modified core orientation and wireline retrieval system. After the first three coring runs, the JOIDES bits were used in a conventional recovery mode, with no further attempt at wireline recovery.

When used as conventional bits, the JOIDES design at first provided less-than-satisfactory recovery. However, as was subsequently pointed out, the initial

Fig. 7.2.
Smith JOIDES core bit.

performance of these scaled-down JOIDES bits was on a par with the Deep Sea Drilling experience of about 25% core recovery in crystalline rocks.

Part way through the GT-2 coring program, the remaining core bits were returned to Smith for minor--but very important--modifications. The inner core-shaping carbide inserts were removed and replaced with the hardest available tungsten carbide inserts, and the core-accepting aperture just above the cones was enlarged slightly. The objective of these modifications was to help prevent premature jamming of the core in the core barrel caused by an oversized core diameter as the bit gradually wore down. These modifications, together with better near-bit stabilization, more than doubled the core recovery of this bit from about 30% to an average of 70% recovery. Beginning with run 12, the core recovery was comparable to conventional diamond bits. The coring operations are summarized in Table 7-VI, with the percent recovery of each core run, the type of bit, and rock formation shown.

After the initial coring operations failed to produce the desired amount of core recovery, diamond core bits were used. Standard commercial bits (Fig. 7-3), Christensen Diamond Products Company 24.4-cm-o.d. by 11.4-cm-i.d. (9-5/8 by 4-1/2 in.), were used for four coring runs. The first run with a diamond bit (Fig. 7-4) was drilled at a rate of 0.3 m/h (1 ft/h). This run produced 100% recovery (Fig. 7-5), but the bit life was only 3 m (10 ft). Modifications in the diamond placement increased footage in later uses. Coring with diamond bits was discontinued after recovery with the JOIDES bits improved.

Coring in Phase III progressed essentially as planned, after the temperature measurements were conducted at the end of each major drilling run. The coring operations are summarized in Table 7-VII, showing the percent recovery of each core run, the type of bit, and rock formation. Core runs 22 and 23 were made with the Christensen diamond bits. Penetration rates for these cores were 0.6 and 0.3 m/h (1.9 and 1.0 ft/h), respectively.

The next three cores were cut by the JOIDES-type bits. Penetration rates on these cores varied from 0.9 to 1.3 m/h (3 to 4.4 ft/h).

A core in the reduced-diameter bottom section of the hole was being drilled with a Christensen 20-cm-o.d. (7-7/8-in.) diamond bit when the tools and drill pipe became stuck. During the ensuing washover and milling operations, the bit and the core were ground up and not recovered. No further attempt was made to drill a bottomhole core until after EE-1 was drilled. After hydraulic fracturing of GT-2 a 0.3-m (1-ft) core was cut in the bottom of GT-2.

TABLE 7-VI

SUMMARY OF CORING RUNS IN GT-2, PHASE I

Core Run	Cored Interval, Depth	Recovery (%)	Core Bit ^{a,b}	Rock Type ^d
1	633.4-639.5 m (2078-2098 ft)	25 ^c	J	Clay w/limestone chips
2	635.2-688.2 m (2248-2258 ft)	50 ^c	J	Shale w/limestone chips
3	776.3-786.4 m (2547-2580 ft)	35	J	Leucocratic monzogranite gneiss
4	789.4-792.5 m (2590-2600 ft)	33	J	Leucocratic monzogranite gneiss
5	862.9-866.9 m (2831-2844 ft)	30	J	Leucocratic syenogranite gneiss
6	866.9-870.8 m (2844-2857 ft)	20	J	Leucocratic monzogranite gneiss
7	960.4-969.9 m (3151-3182 ft)	20	J	Biotite-granodiorite gneiss
8	1055.8-1059.5 m (3464-3476 ft)	17	J	Leucocratic monzogranite gneiss
9	1125.9-1129.3 m (3694-3705 ft)	100	C	Leucocratic monzogranite gneiss, granodiorite gneiss, pegmatite
10	1303.9-1306.1 m (4278-4285 ft)	85	C	Leucocratic monzogranite gneiss
11	1491.1-1492.6 m (4892-4897 ft)	100	C	Leucocratic monzogranite gneiss, leucocratic granodiorite gneiss, minor biotite-tonalite gneiss
12	1498.1-1499.9 m (4915-4921 ft)	100	J	Leucocratic monzogranite gneiss
13	1595.3-1597.1 m (5234-5240 ft)	38	J	Biotite-granodiorite gneiss tonalite gneiss
14	1672.4-1674 m (5487-5492 ft)	90	C	Leucocratic monzogranite gneiss, and thin folia of magnetite
15	1723.3-1725.2 m (5654-5660 ft)	92	J	Hornblende-biotite schist
16	1822.7-1824.5 m (5980-5986 ft)	100	J	Hornblende-biotite-plagioclase schist, amphibolite, granite gneiss, biotite-granodiorite gneiss
17	1874.5-1876.3 m (6150-6156 ft)	66	J	Leucocratic granite gneiss, granodiorite gneiss
18	1876.3-1878.2 m (6156-6162 ft)	100	J	Granodiorite gneiss
19	1933.7-1935.5 m (6344-6350 ft)	16	J	Leucocratic monzogranite gneiss
20	1935.5-1937.3 m (6350-6356 ft)	5	J	Chips of granite gneiss and schist

^aJ - JOIDES bit.^bC - Christensen Diamond Products Company bit.^cWireline core barrel retrieval.^dRock types for Cores No. 3 through 19 determined from petrographic examination of thin sections. Identification of Cores No. 1, 2, and 20 by hand-specimen examination.

Drill Bit Performance, EE-1.* Drilling through the volcanic tuff in EE-1 was accomplished in about 30 h with a 44.5-cm-diam (17.5-in.) Security S88 sealed-bearing tricone insert bit. Reaming of the hole to a depth of 178 m (584 ft) was accomplished in about 60 h with a 66-cm-diam (26-in.) Security hole-opening bit.

*See Ref. 4 for drilled footages and hours of use for each bit.

Fig. 7-3.
Christensen diamond core bit.

Fig. 7-4.
Retrieval of first diamond core
from GT-2. Note high-angle
fracture.

Fig. 7-5.
Section of GT-2 Core No. 9 showing
a quartz pegmatite dike.

Drilling in the sedimentary section was done with full-bore 44.5-cm-diam (17.5-in.) bits, instead of a pilot hole with a hole-opening bit. The expected lost-circulation problems in the limestone dictated a policy of drilling and setting casing as quickly as possible and making as few trips in and out of the hole as necessary.

Drill bits from two manufacturers were used in the sedimentary layers. A Hughes Tool Company OSC3A steel-toothed bit was used in the Permian beds with

TABLE 7-VII
SUMMARY OF CORING RUNS IN GT-2, PHASE III

Core Run	Cored Interval, Depth	Recovery (%)	Core Bit ^{a,b}	Rock Type ^c
21 ^d	2040.6-2042.5 m (6695-6701 ft)	0	J	---
22	2164.7-2165.3 m (7102-7104 ft)	100	C	biotite-tonalite gneiss, monzogranite gneiss
23	2413.4-2413.7 m (7918-7919 ft)	100	C	leucocratic monzogranite gneiss
24	2614.3-2617.3 m (8577-8587 ft)	70	J	biotite granodiorite, pegmatite
25	2901.4-2903.8 m (9519-9527 ft)	50	J	biotite granodiorite, monzogranite
26	2903.8-2906.9 m (9527-9537 ft)	50	J	biotite granodiorite

^aJ - JOIDES-type bit.

^bC - Christensen Diamond Products Company bit.

^cAll rock types determined from petrographic examination of thin sections.

^dPhase II core run.

good results, penetrating at an average rate of 3.7 m/h (12 ft/h). A run of 46 m (133 ft) in 13-3/4 h was made with open jets, and a subsequent run of 165 m (541 ft) in 43-3/4 h with 1.4-cm (18/32-in.) jets was made with the same bit. A Security S88 insert bit drilled in the Permian sediments at an average rate of 4.8 m/h (15.6 ft/h) but balled up with clay and was pulled after penetrating 37 m (121 ft).

Penetration rates in the Madera Limestone were considerably less than in the softer Permian sediments, and insert bits were used almost exclusively. The longest run was 137 m (450 ft) in 104 h with a Hughes Tool Company J44 bit.

A stiff bottomhole assembly was used in drilling the sedimentary beds to minimize hole drift and prevent doglegs. The assembly consisted of near-bit three-point reamers, a 3-m (10-ft) drill collar, a steel stabilizer with replaceable wear pads, a 9-m (30-ft) drill collar, and a rubber stabilizer. In the lower portion of the sedimentary section, a 4.1-m-long (13.3-ft) shock sub was inserted between the bit and the near-bit reamers.

Drilling in the 31.1-cm-diam (12-1/4-in.) section of the EE-1 hole (in the crystalline basement rock) was done with Smith Q9J and Security H-100 insert rock bits. Because of the Smith bit's intended use and carbide availability, it was fitted with somewhat softer tungsten carbide inserts than the Security bit. The Security H-100 bit was a more advanced, oil-field-type rock bit, fitted with pre-

lubricated and sealed roller bearings, and intended for mud or water circulation only.

These two types of bits were used exclusively for drilling the 31.1-cm-diam hole interval in EE-1 for two reasons:

- (1) These were the only types of 31.1-cm-diam hard-rock bits available.
- (2) There was a desire to compare the performance of two manufacturers' equivalent hard-rock bits.

A comparison of the performance of these two bits is shown in Table 7-VIII. A comparison of the different types of wear encountered in each bit type is shown in Fig. 7-6. Weight on the bit ranged from 27.2 to 31.7 Mg (60 000 to 70 000 lb) with a rotational speed of 40 - 50 rpm.

As can be seen from Table 7-VIII, the H-100 bits outperformed the Q9J bits in average rate of penetration and average bit life. The H-100 bits tended to drill 35% faster and lasted almost twice as long as the Q9J mining bits. The H-100 average bit performance of almost 49 m/day (160 ft/day), for a 31.1-cm hole in granite, is outstanding compared with typical oil-field drilling performance in hard rocks. Its longer life was due to the sealed bearings and the harder carbide inserts. As shown in Fig. 7-6, the inserts of the Q9J bit wore

TABLE 7-VIII
EE-1 31.1-CM DIAMETER ROCK BIT PERFORMANCE

Manufacturer and Type	Depth Drilled [m(ft)]	Time Elapsed (h)	Penetration Rate		Depth Out [m(ft)]
			[m/h (ft/h)]	[m/day overall (ft/day)]	
Smith Q9J	108 (354)	71	1.5 (5.0)	34.4 (113)	848.9 (2785)
Smith Q9J	103 (338)	57	1.8 (5.9)	39.0 (128)	951.9 (3123)
Security H-100	198 (650)	107-1/2	1.8 (6.0)	41.4 (136)	1149.1 (3770)
Smith Q9J	119 (391)	73-3/4	1.6 (5.3)	35.1 (115)	1269.2 (4164)
Security H-100	229 (752)	96-3/4	2.4 (7.8)	52.1 (171)	1498.4 (4916)
Smith Q9J	107 (350)	68	1.5 (5.1)	33.2 (109)	1605.1 (5266)
Security H-100	250 (821)	107	2.3 (7.7)	51.2 (168)	1855.3 (6087)
Smith Bit, <u>Average</u>	109 (358)	67	1.6 (5.3)	35.4 (116)	
Security Bit, <u>Average</u>	226 (741)	104	2.2 (7.2)	48.2 (158)	

smooth and the bit just stopped "digging" sooner than the H-100 bit. The few broken carbide inserts in the H-100 bit (because of its harder, more brittle grade of tungsten carbide) did not slow the bit appreciably, and the sealed bearings increased its life for many more hours.

Drilling the 24.5-cm-diam (9-7/8-in.) section of the hole below 1957 m (6420 ft) was done almost exclusively with Security H10 JP bits.

Coring, EE-1. Two coring runs were made in EE-1; a summary of the runs is given in Table 7-IX. The first run was made with a Smith Tool Company modified JOIDES bit, described above. The second coring run was made with a 24.4-cm-o.d. by 15.2-cm-i.d. (9-5/8 by 6-in.) diamond bit manufactured by American Coldset Corporation.

Problems and Areas for Improvement. Two problems of oil-field-type hard-rock bits when used to drill hot granitic rocks are excessive gauge wear and bearing seal failure. However, based on the recent EE-1 drilling experience, neither of these problems can be considered major for drilling in basement crystalline rocks up to about 200°C.

Fig. 7-6.
Comparison of Smith Q9J bit and Security H-100 bit after use in EE-1.

TABLE 7-IX
SUMMARY OF CORING RUNS, EE-1

Core Run	Core Interval, Depth	Recovery	Core Bit	Rock Type ^c
1	2095 - 2099 m (6874 - 6886 ft)	25%	J ^a	Leucocratic monzogranite gneiss
2	3011 - 3012 m (9877 - 9881 ft)	17%	ACC ^b	Leucocratic granodiorite

^aJOIDES-type bit.

^bAmerican Coldset Corporation bit.

^cRock types determined from petrographic examination of thin sections.

As a point of reference, the three 31.1-cm-diam (12-1/4-in.) Security H-100 carbide-insert rock bits with sealed roller bearings had a remarkable average bit life of over 100 h each at penetration rates varying from 1.8 to 2.7 m/h (6 to 9 ft/h).

Gauge wear is the more significant hard-rock bit problem and the contributing cause of the near-bit reamer roller cutter wear. However, the bits used in the EE-1 drilling program were generally standard oil-field-type liquid-circulation bits that were designed primarily to drill the very hardest sedimentary rocks, but not particularly granite. The possibly more suitable air-percussion hard-rock mining bits were not used (except where necessary because of availability) because water had been chosen as the circulating medium, which from our experience is the more desirable medium.

A bit could probably be designed particularly for drilling very hard crystalline rocks by using more and harder tungsten-carbide gauge buttons. However, the bit manufacturers would have to be convinced that there was a sufficient market for such a specialized bit.

Bearing seal failure has not become a problem at hole temperatures up to 200°C. Of the three Security H-100 bits mentioned earlier, the bearings were only slightly more worn out than the carbide compacts when the bits were pulled. On a scale of 1 (new) to 10 (completely worn out), these three bits were graded 6, 6, 6 for carbide compact wear and 7, 7, 8 for bearing wear. At hole temperatures above 200°C, however, seal failure may become a problem.

Abnormal reamer roller cutter wear is probably the direct result of bit gauge wear, as experienced during the drilling of EE-1. For EE-1, all the roller cutters except the three rollers directly above the bit were the smooth-wear pad type (carbide faced), which worked well.

7.1.2. Directional Drilling. During drilling operations below 1120 m (3700 ft) in EE-1 the inclination of the hole had gradually increased to about 6° from vertical. This deviation placed the bottom of the hole on the northwest side of the fracture, which was initially believed to extend northeast from the bottom of GT-2. (See Sec. 7.1.5.) To intercept the fracture, the hole had to be angled back to the southwest. However, information from the last fracture and impression packer tests in EE-1 at about 1966 m (6450 ft) indicated that the fracture in GT-2 was more likely oriented in a NW-SE direction rather than the previously indicated NE-SW direction. Because of the relative uncertainty of

the position of the GT-2 fracture, the decision was made to drill EE-1 so that it would pass directly below the bottom of GT-2, thus having a good probability of intersecting the fracture regardless of its orientation. Arrangements were made to conduct directional drilling operations using a Dyna-Drill assembly.

The Dyna-Drill has many advantages not offered by other equipment or methods. Because it incorporates its own downhole motor, Dyna-Drill does not require the drill pipe to be rotated as in conventional rotary drilling. The positive displacement motor is powered by the drilling fluid, air, or gas used in normal drilling operations.

The power generating source of the Dyna-Drill is a multi-stage Moyno-pump used as a motor. This specially designed motor consists of a rotor and a stator, a rubber-like element molded with a spiral passageway having an oblate cross section.

Rotation occurs when drilling fluid is forced under pressure into the cavities between rotor and stator. The upper end of the rotor is unattached and exposed to the flow of drilling fluid. The lower end of the rotor is attached to a connecting rod, which in turn is connected to the drive shaft. The connecting rod converts eccentric rotation of the rotor to concentric rotation of the drive shaft. The lower end of the drive shaft is designed to accommodate the drill bit.

With the Dyna-Drill, programmed directional drilling is achieved by including a bent section in the nonrotating drilling assembly near the drill bit. As the drill and nonrotating bent assembly advance, a continuing gradual arc of hole curvature is created because the Dyna-Drill carries its own bending force along as it drills. (See Fig. 7-7.)

The first Dyna-Drill run, on August 31, started at 2099 m (6886 ft). Figure 7-8 shows the path taken in the subsequent directional drilling. (Note that depths in the figure are measured from the casing flange, about 4-1/2 m (15 ft) below the Kelly bushing.) The Scientific Drilling Controls device was used for directing and checking the course. On September 10, an Eastman-Whipstock magnetic multishot survey was made from 2040 - 2740 m (6700 - 8990 ft).

A series of seismic experiments (see Sec. 4.2.1) conducted on September 20 between the two holes indicated that at 2764 m (9070 ft), the holes were about 16 m (52 ft) apart horizontally. At that time, the decision was made to drill directly under the bottom of GT-2 at 2995 m (9825 ft) at a 10 - 11° angle of inclination.

Fig. 7-7.
Directional drilling with
Dyna-Drill assembly.

Fig. 7-8.
Path taken during drilling of EE-1. Depths are
measured from the casing flange, near ground level.

Another series of seismic ranging experiments was conducted between the holes from September 24 to October 1. The position of EE-1 at 2914 m (9560 ft) was determined to be about 8 m (26 ft) away from GT-2 and nearly due west.

When directional drilling was resumed on October 1, the azimuth of the hole was turned to N77°E. The fracture in GT-2 was kept inflated by hydraulic pressure ranging from 98 to 101 bar (1420 to 1470 psi). It was expected that when EE-1 intersected the fracture, a decrease in the GT-2 pressure would occur. At 2954 m (9690 ft), a fluid loss of 1.6 m³/min (10 bbl/min) occurred in EE-1, with no corresponding change in pumping pressure in GT-2. Temperature and SP electric logs run by G0-International the next day located a break in the casing at 82 m (270 ft). Remedial cementing operations were performed by Halliburton Oil Well Cementing Service on October 4 and 5. Directional drilling was resumed with GT-2 again being pressurized.

On October 7, the stator blades in the Dyna-Drill assembly sheared off, having been softened by exposure to the heat in the hole. While a new directional drilling tool was being sent, drilling continued with a conventional assembly to 3011 m (9877 ft). At that depth, a 1.1-m (3.6-ft) coring run was made. Drilling with the new Dyna-Drill assembly began on October 11. Drilling was terminated the next day at a final depth of 3065 m (10 053 ft).

The usual bit rotational speed for standard drilling was 40 rpm; for directional drilling the bit speed was 250 rpm. Although this increased rotational speed greatly improved the penetration rate, the bit life was drastically reduced. The highest penetration rate achieved was 11.6 m/h (38 ft/h) for a 2 h-period of directional drilling starting at 2977 m (9766 ft). The longest bit run was 34.4 m (113 ft) in 5 h. (Compare standard bit run results in Table 7-VIII.)

7.1.3. Borehole Directional Surveys. To connect at depth the EE-1 borehole and the hydraulic fracture formed near the bottom of GT-2--and thus to establish a circulating flow loop---the relative positions of the two holes had to be determined. Two commercial methods, magnetic and gyroscopic, were available for performing the required borehole directional surveys.

Although gyroscopic surveys are free of the effects of magnetic anomalies that might be expected in the basement crystalline complex, they were then limited to a maximum hole temperature of about 150°C (300°F), corresponding to a depth of about 1830 m (6000 ft). The two commercially available gyroscopic surveys had no heat shielding or heat sinking in their gyroscopic tools. The

magnetic surveying tools are heat shielded and capable of operating at hole temperatures of about 200°C (390°F) for up to 2 h.

As a consequence, magnetic surveys were to be used as the primary method of determining the relative hole locations. Gyroscopic surveys were to be used to about 2000 m to assess the possible effect of magnetic anomalies in the Precambrian section. Unfortunately, the results of these comparative surveys were inconclusive, at least for GT-2.

In summary, the following directional hole surveys were run:

GT-2

Eastman magnetic survey, 806 - 1776 m (2642 - 5828 ft)

Eastman magnetic survey, 794 - 2938 m (2604 - 9638 ft)

Sperry-Sun gyroscopic surveys, surface to 1830 m (6000 ft)

EE-1

Eastman tool magnetic single-shot directional surveys while drilling, surface to 3064 m (10 053 ft) (run over entire drilling program)

Eastman magnetic survey, 2042 - 2740 m (6700 - 8990 ft)

Two Eastman gyroscopic surveys, surface to 2042 m (6700 ft)

Sperry-Sun gyroscopic survey, surface to 1957 m (6420 ft)*

Magnetic (surface readout) directional surveys while directional drilling: Scientific Drilling Controls tool and field computer system (EYE system).

A comparison of the three GT-2 surveys at two different depths is given in Table 7-X. As shown in this table, the variation between the Sperry-Sun gyroscopic and the Eastman magnetic surveys run in 1975 is of the same order as the variation between the two Eastman magnetic surveys run over a year apart. In any case, the uncertainty in hole location at 1776 m is about 4 m, and probably would be almost 7 m at 3 km.

Table 7-XI shows a comparison between the Eastman single-shot magnetic surveys (while drilling) and the better Eastman gyroscopic survey (smaller precession error) at two depths. The most significant aspect of the EE-1 survey comparison shown in the table is the consistent angular change between the two surveys. At these two depths--and throughout the two survey traces from the Precambrian surface to 2042 m--the hole coordinates obtained in the gyroscopic survey are rotated about 7.4° counterclockwise from those obtained in the magnetic survey. This

* Results from this survey were rejected because they were erratic and differed greatly from the corresponding magnetic survey.

TABLE 7-X
COMPARISON OF BOREHOLE DIRECTIONAL SURVEYS IN GT-2

	<u>Borehole Inclination Angle</u>	<u>North-South Coordinate (m)</u>	<u>East-West Coordinate (m)</u>
<u>At 1222 m (4008 ft)</u>			
Eastman, magnetic, 7-3-74	2°15'	N 12.0	W 18.5
Sperry-Sun, gyro, 8-12-75	2°0'	N 11.5	W 15.5
Eastman, magnetic, 9-20-75	2°15'	N 12.9	W 16.8
Average	2°10'	N 12.1	W 16.9
<u>Average 1776 m (5828 ft)</u>			
Eastman, magnetic, 7-3-74	4°30'	N 22.4	W 48.5
Sperry-Sun, gyro, 8-12-75	4°15'	N 26.3	W 41.6
Eastman, magnetic, 9-20-75	4°30'	N 24.4	W 45.0
Average	4°25'	N 24.4	W 45.0

TABLE 7-XI
COMPARISON OF EASTMAN MAGNETIC AND GYROSCOPIC
SURVEYS IN EE-1

	<u>Borehole Inclination Angle</u>	<u>North-South Coordinate (m)</u>	<u>East-West Coordinate (m)</u>
<u>At 1401 m (4595 ft)</u>			
Magnetic single-shot	4°30'	N 26.6	W 40.3
Gyroscopic survey	4°15'	N 23.4	W 40.6
Difference, magnetic to gyroscopic	- 15'	- 3.2	+ 0.3
<u>At 2042 m (6700 ft)</u>			
Magnetic single-shot	6°0'	N 49.1	W103.9
Gyroscopic survey	5°45'	N 36.2	W105.0
Difference, magnetic to gyroscopic	- 15'	- 12.9	+ 1.1

angular correction may be a function of depth (i.e., temperature) or elapsed time (i.e., precession error) or it may indicate an actual magnetic shift within the Precambrian section.

That the sense of rotation of the magnetic field in the Precambrian is the same as that noted in core studies may not be a coincidence. In a recent study of GT-2 Precambrian core samples Robert L. DuBois, professor at the University of Oklahoma,* determined a consistent rotation of the paleomagnetic field by an average of about 53° in a counterclockwise direction. Even if the actual effect of this paleomagnetic field is only a few percent of its measured declination, an apparent rotation of 7.4° might be mainly due to this effect.

If this magnetic-to-gyroscopic correction is valid, it would indicate that at 2926 m (9600 ft) the EE-1 borehole is about 8 m (26 ft) east of the GT-2 borehole rather than only about 2 m SW of the GT-2 borehole as indicated by the magnetic surveys. To obtain improved borehole coordinates as a function of depth, one or more surveys to full depth with a gyroscope operating in a controlled environment (Dewar package) are planned for the summer of 1976.

7.1.4. Casing.

GT-2. The conductor casing consisted of 20 m (65 ft) of 51-cm-o.d. (20-in.) line pipe. The backfill concrete was furnished by a local ready-mix supplier.

The 34-cm-o.d. (13-3/8-in.) surface casing was set at 488 m (1600 ft). A Baker cement shoe was installed at the bottom, and a Baker float collar at 4795 m (1573 ft). Cementing of the casing was performed by the Farmington, NM, station of Dowell, a division of Dow Chemical Company.

The next string, of 27.3-cm o.d. (10-3/4 in.), was set at 773 m (2535 ft). A Baker cement shoe was installed at the bottom, and a Baker float collar at 733 m (2404 ft). Cementing of the string was performed by Dowell. This completed the casing installation associated with Phase I drilling. Hydrology and fracture experiments were then conducted, as described in Sec. 7.1.5.

During the Phase II operations, the failure of packers to operate successfully in the open hole led to the decision to install a cemented liner and polished bore receptacle (PBR). This operation is discussed in Sec. 7.1.5. At

* Report submitted to Los Alamos Scientific Laboratory with regard to core samples sent to the University of Oklahoma for paleomagnetic work; May 5, 1976.

the termination of the experiments in this phase, the cemented liner was removed by washover operations.

At the end of the Phase III drilling operation, a 185-m-long (608-ft) section of 20-cm-diam (7-7/8-in.) steel liner with a PBR assembly at the top was installed and cemented in the hole at a bottom depth of 2920 m (9581 ft).

EE-1. The conductor casing consisted of 3 m (10 ft) of 76 cm-diam (30 in.) corrugated metal pipe. The backfill concrete was furnished by a local ready-mix supplier.

During the drilling of the volcanic rock, considerable leakage of drilling fluid occurred around the conductor casing and up the mouse and rat holes. This was attributed to the short length of the conductor casing. A deeper string of conductor casing would probably have effected a better seal.

After the hole was reamed, a string of 50.8-cm-o.d. (20-in.) line pipe was set at 181 m (595 ft). A Baker cement shoe was installed at the bottom of the casing. Cementing of the casing was performed by the Farmington, NM, branch of Byron Jackson, Inc. (See Fig. 7-9.) A wooden plug was run down the casing after the cement was displaced from the casing by pumping in water.

Intermediate casing of 34-cm o.d. (13-3/8 in.) was set at a depth of 741 m (2431 ft). A Baker cement shoe was installed at the bottom of the casing with Baker float collars at 728 m (2390 ft) and 703 m (2307 ft). Cementing was again done by Byron Jackson, Inc.

Considerable trouble was encountered in cementing this casing, which extended through a severe lost-circulation zone at 719 m (2359 ft). The cementing of the casing was to be accomplished in three stages. During the first- and second-stage cementing operation, the lost-circulation zone apparently took the cement slurry as fast as it could be pumped in, and when the plugs were started down the casing was empty. The Baker plugs and/or stage collars that were used were probably not strong enough to withstand the force of the plugs

Fig. 7-9.
Cementing truck hookup during cementing of EE-1 casing.

hitting the empty stage collars with a full column of displacement water above them. As a result, they broke apart, letting the displacement water leak by and wash out the cement slurry below. Mud containing 30-50% lost circulation materials was pumped through the upper stage collar until circulation was established, and the third-stage cementing was carried out. No cement came to the surface, so cementing of the upper section of casing was completed by injecting cement through a pipe extending down the annulus between the inner and outer casings. The bottom of the casing was later successfully cemented by injecting through open-ended drill pipe.

The deep string, consisting of 27.3-cm-o.d. (10-3/4-in.) casing, was set at 1957 m (6420 ft). To prevent the malfunction of the displacement plugs and stage collars as occurred in the intermediate casing cement operation, two float collars (a Baker below and a Halliburton above) were installed at the bottom and an aluminum plug landing baffle was inserted one casing joint up from the bottom. A Halliburton cast aluminum plug designed to withstand high landing pressures was also used. Cementing was performed by Halliburton Oil Well Cementing Company, Farmington, NM.

Before placing the final casing, a taper mill and reamer assembly was run in the hole to ream the casing at the 64- to 81-m (210- to 265-ft) depth where a break had previously been cemented. The final string of casing was then set at a bottom depth of 2925 m (9599 ft). The string consisted of 304 m (999 ft) of 19.4-cm-o.d. (7-5/8-in.) casing on the bottom, with the remainder being 2627 m (8617 ft) of 2.9-cm-o.d. (8-5/8-in.) casing. A Halliburton float shoe was installed on the bottom of the string with a Halliburton float collar and baffle plate inserted two casing joints up. Halliburton Oil Well Cementing Company cemented this casing.

No apparent difficulties were encountered in cementing these last two strings of casing.

7.1.5. Packers. The use of downhole packers in hydrology and fracturing experiments is outlined in this section. Reservoir properties determined from these experiments are discussed in Sec. 5.1.

Hydrology Experiments. When the drilling to 1937 m (6356 ft) in GT-2 had been completed and the associated logging operations carried out, a set of measurements using drill-stem-testing techniques was begun to determine the pre-fracturing permeability of the Precambrian rock below the casing. These tests

were to determine the permeability of the exposed basement rock at various intervals in the hole. Because the successful operation of a two-hole hot dry rock geothermal energy system largely depends on the impermeable quality (water-tightness) of the basement rock, the least permeable sections of the hole had to be found to conduct the fracture experiments.

Hydrology testing began on July 17, 1974, and continued until August 4, when it was essentially completed. About 16 tests were conducted in the 792- to 884-m (2600- to 2900-ft) and 1433- to 1890-m (4700- to 6200-ft) regions of the hole. Packer spacings ranged from 27 to 124 m (90 to 408 ft). On September 8, after the hole had been deepened to 2042 m (6701 ft), a hydrology test was conducted below 1981 m (6500 ft).

All packers used in the hydrology tests were from the Johnston Division of Schlumberger Limited. The usual procedure was to use a straddle packer assembly consisting of two packer elements, spaced 3 m (10 ft) apart, set above a hook-wall anchor at the lower end of the pipe string, and another similar two-packer assembly inserted in the pipe string at the selected spacing interval.

Sections of the hole to be tested were chosen on the basis of geophysical log data. The caliper log very effectively determined depths in the hole that were closest to bit-gauge diameter, where the anchors and packers would have the best chance of seating.

For the two tests of the bottom section of the hole, a string of drill collars was made to rest on the bottom of the hole with the packer assembly inserted in the string for positioning at the top of the test zone.

After the packer assembly had been set in a predetermined zone, the drill pipe was partially filled with water to prevent possible steam blowoffs during the flow tests. The main control valve in the multiflow evaluator (MFE) system of the Johnston packers was then opened to allow water inflow from the formation. (This control valve is opened and closed by up-and-down motion of the drill stem.) Flow tests lasting 2 - 4 h were normally conducted. At the end of a series of flow tests, a 2.5-liter (0.66-gal) sample of formation fluid (or drill-hole fluid) was trapped in the MFE sampler chamber and brought to the surface for analysis.

When the flow test was completed at each zone, the MFE valve was closed and an 8- to 12-h pressure test was conducted. During this time the pore-fluid pressure in the rock isolated by the packer assembly was obtained. Pressures were recorded on a metal chart by a diamond-tipped stylus at the end of a Bourdon tube within a section of the packer assembly.

After a series of tests had been completed at a specified depth, the assembly was pulled up the hole and set at the next higher zone to be tested. Normally, two separate flow tests and shut-in pressure tests were made at different depths before the packer assembly was withdrawn.

After the second flow and shut-in pressure test, the MFE valve was opened and the drill pipe filled with water to the surface. The decrease in water level in the pipe was observed for up to 4 h to measure the rate at which the formation accepted water. Then the drill pipe was pressurized at 14 - 28 bar (200 - 400 psi) above surface hydrostatic, and the rate of injection into the formation was again observed for 4 h.

The hydrology tests indicated that the granitic rock was relatively impermeable and would be able to contain pressurized water with acceptably low leak-off rates. Those sections of the hole that gave the appearance of being "tight" on the geophysical logs were zones of low permeability (in the microdarcy range).

In the early stages of the hydrology testing, tool malfunctions, leaking drill pipe, and fittings plugged by drill cuttings presented difficulties. Once these problems were corrected, testing progressed more smoothly.

A procedure was developed to seat the packer assembly in the casing at about 610 m (2000 ft) and to cycle the MFE valve several times to determine if it was working properly. Because it normally took 3 - 5 h to lower the packer assembly to the test zone, determining correct packer operation early saved much time.

A useful feature of the Johnston straddle packer assembly was the packer by-pass principle. A tube through the packer assembly provides continuous communication of fluid from above the top packer to below the bottom packer during a test. This feature gives an immediate indication of the surface if the bottom packer fails or otherwise becomes inoperative. However, this feature also allowed the total hole depth (except for the packed-off interval) to be subjected to the hydrostatic water pressure in the annular space between the drill pipe and the borehole wall. Although the granitic rock accepted small amounts of water over large sections of its depth, the drop in the annulus water level could be easily measured.

Another procedure, developed to check for proper function of the packer assembly, used this continuous drop in the annulus water level. After the packer was seated, the annulus level was measured with the MFE valve open and closed. If the water-level drop decreased or remained the same after the valve was closed, the assembly was assumed to be functioning properly. If the rate of drop

increased, as occasionally happened when the valve was supposedly closed, it was taken as an indication that the assembly was not operating properly, and the packers were immediately pulled for inspection.

The diameter of the packer elements used in the first few tests was 21.6 cm (8-1/2 in.), but after difficulty in trying to seat this size, a 23.2-cm-diam size (9-1/8 in.) proved to be more satisfactory. The rubber packer elements were often torn and ruptured from being seated against and dragged across the irregular borehole walls. (See Fig. 7-10.) At least one element in the assembly usually needed to be replaced at the end of each test, but because of the double packer configuration very little leakage past the elements occurred during this stage of the testing.

Initially, 21.6-cm-diam hook-wall anchor assemblies expandable to 27.6 cm (10-7/8 in.) were used but were found to be too small for reliable seating in the hole. A 27.3-cm-diam (10-3/4-in.) anchor assembly expandable to 30.5 cm (12 in.) was then tried and proved satisfactory. During the first hydrology tests, the replaceable shoes of the hook-wall anchors were made of plain-carbon steel. No great difficulty was experienced in seating these anchors. However, when these shoes became worn and were replaced by the packer service company with carbide-steel shoes, seating of the anchors became very difficult. Four or five attempts were usually required before these anchors would seat. The carbide-steel anchor shoes may have been too hard for the rock, and the borehole-wall surfaces in contact with the anchor shoes may have spalled off under contact pressures. When softer steel shoes were again used, the anchors were seated on the first try.

Fig. 7-10.

Double packer assembly after withdrawal from GT-2. The lower packer element has ruptured, but the upper element is still usable.

Fracture Experiments--Open Hole. Fracture experiments began August 5, 1974, and were conducted in six zones in the open hole existing at that time. The approximate depths of the zones are

Zone 1	843- 873 m	(2765-2865 ft)
Zone 2	793- 817 m	(2600-2680 ft)
Zone 3	1442-1487 m	(4730-4880 ft)
Zone 4	1487-1530 m	(4880-5020 ft)
Zone 5	1620-1644 m	(5314-5394 ft)
Zone 6	1407-1571 m	(4617-5153 ft)

These zones were selected from the logs as being the least fractured areas of the hole being closest to bit-gauge size. The results of the hydrology testing in these zones further indicated that they were relatively impermeable.

Johnston packers, which had been used for all the hydrology experiments, were used for most of the fracture experiments. Testing with the Johnston packer assemblies continued until August 25, except for a few days when Brown Oil Tool inflatable packers were tried.

The Johnston packers were used in a straddle packer configuration, two packers below and two above the test zone. Most of the Johnston packer elements were made of 90-durometer hardness rubber, but for the last few tests, elements made of softer elements of 70-durometer hardness were used.

All zones were pressurized at flow rates varying from 4 to 76 liter/min (1 to 20 gpm). Pressures of 34 - 68 bar (500 - 1000 psi) were usually reached before leakage occurred around the packers. During the first fracture experiments, seismic noises from the leakage were thought to be breakdown or fracture extension signals. These signals were later recognized as resulting from leakage, when the observation was made that the annulus water level always rose rapidly at the same time. By using the softer rubber packer elements, a pressure of 110 bar (1600 psi) was obtained before leakage occurred. Drill-stem weights on the packers ranged from 36.3 to 68 Mg (80 000 to 150 000 lb), but leakage still occurred.

A Brown Oil Tool impression packer was used in Zone 4 but no impressions of fractures were obtained. On August 20 and 21, several pressurization tests were made in Zone 5 with the Brown inflatable packers in a straddle packer configuration. These tests were also unsuccessful; the packers either burst when inflated or leaked.

From August 26 through 30, and on September 2, Lynes packer elements were used for pressurization tests in Zones 5 and 6. Pressures of 90 bar (1300 psi) were obtained before leakage occurred. Maximum internal-seating pressures for the Lynes packers ranged to 61 bar (880 psi).

In 1973, a system had been conceived to fracture in the open hole using a straddle packer configuration; an impression packer that could be actuated on command from the surface was to be located between the two end packages. This system would take a "picture" of the fracture in its inflated condition. In April 1974 this packer configuration was ordered from Brown Oil Tool. They specified that their packers should be run in casing unless the hole was very smooth. At the time of delivery in August 1974, the hole was found to be very rough and irregular. Great difficulty was experienced in seating from packers designed for open hole, and as a consequence the Brown packer array was not used.

The bottom of the hole was tested for permeability using a packer assembly consisting of three Johnston elements at the top of a 62-m (203-ft) section of drill collars. A 1-h flow test indicated zero inflow at the 1981- to 2042-m (6498- to 6701-ft) zone. A subsequent 7-h shut-in test indicated that a water pressure of nearly 140 bar (2000 psi) was acting on the formation at the test zone. Several fracture impressions were noted on the lower packer element, about 15 cm (6 in.) apart, dipping 70°.

Fracture Experiments--Cemented Liner. Because of the failure of the packers to hold satisfactorily in the open hole, a cemented liner had to be used to conduct meaningful fracture experiments. Arrangements were made with Halliburton Oil Well Cementing Company to cement a steel liner and polished bore receptable (PBR) in the hole.

The liner and PBR assembly, consisting of 64 m (210 ft) of 16.4-cm-i.d. (6.46-in.) casing, was set with its bottom end at 1981 m (6501 ft) on September 10 and was cemented in place. The top 1.1 m (3.5 ft) of the assembly was made of a flared, machined inner-surface section into which the PBR mandrel on the end of the pipe string would seat. After the cement had set, the cement plug was drilled out and the sand washed out of the bottom of the hole. On September 13, the PBR mandrel assembly was seated with a 63.5-Mg (140 000-lb) drill-string weight.

The following week, a series of pressurization tests was conducted in the zone between the lower end of the liner and the bottom of the hole at 2042 m. Pressures up to 172 bar (2500 psi) and flow injection rates of 454 liter/min (120 gpm) were obtained using the high-volume truck-mounted pump. The downhole

instrumentation cable pack-off assembly on top of the pipe string leaked continuously and finally ruptured. To repair this assembly, the pipe string had to be raised, which required breaking the PBR seal. Pumping began again after the PBR seal was reset. During this pumping, temperature measurements in the bottom of the hole below the liner section indicated that a fracture had been created or that an existing crack had been opened.

As the pumping continued, the annulus water level above the PBR began to rise. When the assembly was pulled out of the hole for inspection, the nylon chevron seals in the PBR mandrel were found to have been damaged during the reseating operations. (See Fig. 7-11.) Because the seals were so severely damaged, a packer had to be seated in the liner for further pressurization tests. On September 21, a Baker Oil Tool packer was set at 1928 m (6325 ft). During the next 2 days, a Schlumberger spinner logging tool (Fig. 7-12) was used to test for water flow into the fracture during pressurization experiments. During the 20

Fig. 7-11.
Damaged chevron seals on the PBR
mandrel.

Fig. 7-12.
Schlumberger spinner logging tool being
examined on drill rig catwalk. The rate
of water flow through the tool is mea-
sured by the rotational speed of a set
of blades in the section of the tool
resting on the support.

spinner runs made, increasing volumes of water, up to 17 m^3 (4600 gal) in a maximum single injection, were pumped into the fracture at pressures of about 172 bar (2500 psi) and flow rates of 450 - 680 liter/min (120 - 180 gpm). A later interpretation of the spinner logs indicated the existence of two fractures, between approximate depths of 1990 - 1993 m (6529 - 6540 ft) and 1999 - 2002 m (6559 - 6568 ft).

From September 25 through 27, the fracture system in the bottom of the hole was extended by pumping increased amounts of water into it. Quantities of 42, 76, and 136 m^3 (11 000, 20 000, and 36 000 gal) were injected separately at maximum pressures of 172 bar and maximum flow rates of 610 liter/min (160 gpm). After venting the system, about half the injected water was usually recovered.

On September 28, a sand-fracture experiment was conducted to prop open the cracks. The Western Co. pumped in 17 m^3 of a cross-linked polymer gel and 4.3 Mg (9500 lb) of sand (7500 lb of No. 20-40 sand and 2000 lb of No. 10-20 sand). Maximum pumping pressure was 203 bar (2950 psi) at a flow rate of 1440 liter/min (380 gpm). The pressure was monitored during controlled repressurization, vent, and shut-in experiments until September 30. (See later parts of this section for a discussion of packer impressions of these fractures.)

On September 30, the cemented liner was perforated by GO-International Inc. in preparation for additional fracture experiments. Eighty perforations were made in the 1942- to 1945-m (6370- to 6380-ft) interval. A Johnston straddle packer assembly was lowered into the hole to enclose the 1934- to 1948-m (6345- to 6390-ft) region.

When the zone was pressurized with the Western pump, the pressure rose to 128 bar (1850 psi), but continuous flow up the annulus indicated the packer was leaking. The Johnston packers were pulled and the Baker packer was set in the liner above the perforated zone at a depth of 1929 m (6330 ft). Water was pumped in the hole for an hour at a maximum pressure of 134 bar (1950 psi). The system was shut in for 15 min, then vented. About 92% of the 7.6 m^3 (2012 gal) of injected water was recovered.

On October 2, the Baker packer was set below the perforated zone to determine if there was a connection from below the liner to the perforations. Pumping continued for 2 h at 121 liter/min (32 gpm). The pressure rose to 151 bar (2185 psi), but no connection to the annulus above the packer was observed. The system was vented, and within 5 h about 85% of the water was recovered.

The Baker packer was pulled out of the hole, and the tool string was assembled with a bridge plug on the bottom. The plug was set at 1960 m (6342 ft) and the Baker packer at 1929 m (6328 ft), thus enclosing the perforations. Pressurization at a flow rate of 477 liter/min (126 gpm) was initiated and the pressure rose immediately to 246 bar (3570 psi). Pumping continued until 10.3 m³ (2730 gal) of water had been injected. The system was then shut in and the pressure decay was observed.

Early October 3, the bridge plug and packer assembly were loosened and then lowered to set the packer at 1957 m (6422 ft). The bottom section of the hole was pressurized to 152 bar (2200 psi) at a flow rate of 238 liter/min (63 gpm). At that pressure, a short but rapid rise in the annulus water level was observed, followed by a smaller, steady discharge of 11.4 liter/min (3 gpm) out the flow line. Presumably two separate cracks, offset from each other but separated by unfractured rock, existed in the lower section of the hole and at the perforated zone. The rise in the annulus level could therefore have been water that was ejected through the perforations from the upper fracture when the lower one was expanded by pumping.

Impression Packers. On November 5 and 6, two Brown Oil Tool impression packer assemblies were set in GT-2 at 1992 and 2011 m (6536 and 6554 ft), where sand-propped fractures had been opened during Phase II fracturing experiments. Each time the packers ruptured during initial pressurization (Fig. 7-13). Very faint impressions of doubtful significance were obtained.

On November 18, two Lynes packers were assembled and set at 1992 m. Some trouble was experienced in inflating them, and the possibility that one had ruptured was considered. However, the packers were left in the hole for 10 h. When withdrawn, both packers were found to have been inflated and discernible impressions had been obtained, but the packers had been inadvertently set 27 m (90 ft) too high. Two days later, a second set of Lynes packers was assembled and set at the correct depth. After they had been inflated for 10 min at 83 bar (1200 psi), the packers burst. The impressions obtained were slightly better than those from previous attempts.

A steel casing with a PBR assembly at the top was run in the hole on December 13 and cemented in place. The bottom of this liner was landed on the borehole shelf at the bottom of the 24.4-cm-diam (9-5/8-in) hole at 2920 m (9581 ft). After the liner had been cemented in place, two Lynes impression packers were assembled and spaced up on the drill string to be centered at 1990 and 2001 m

(6529 and 6566 ft). The packers were pressurized to 70 bar (1000 psi) and left in place for 6 h. Two good impressions were obtained of fractures that were nearly vertical and oriented to an approximate northeast-southwest direction (Fig. 7-14). Good fracture impressions were sometimes obtained on the standard packer assemblies, as occurred on August 27, 1974, with a Lynes packer.

Casing Packer. On December 18, an attempt was made to insert an Otis casing packer (equipped with a plug-type valve) near the bottom of the liner emplaced a few days before. The packer seated prematurely at 2802 m (9193 ft). However, because it could be used for experiments at that depth, the packer was left at that location. A PBR mandrel was then seated in the polished-bore receptacle at the top of the liner, with a string of 11.4-cm-o.d. (4-1/2-in.) tubing extending to the surface. Pressure tests indicated that the PBR seal was tight but that the plug valve in the Otis packer might be leaking.

During subsequent experiments, the Otis packer was found to be leaking around the outside. Removal of this packer began on June 15, 1975. A 17.1-cm-diam (6-3/4-in.) mill was run down the hole on 7.3-cm-diam (2-7/8-in.) drill tubing and a tight spot was encountered in the casing at 2750 m (9025 ft). This was passed without difficulty, but after drilling for 0.5 m (1.5 ft) on the packer,

Fig. 7-13.
Ruptured impression packer from 1992 m (6536 ft) in GT-2.

Fig. 7-14.
Lynes packers showing impressions of fractures in GT-2 at 1990 and 2001 m (6529 and 6566 ft).

the mill balled up and milling operations were suspended for several days. Eventually, on June 23, the slips on the Otis packer were drilled out and the assembly was pushed to the bottom of the hole. The packer was later removed by fishing operations and additional drilling with a washover bit to permit an attempt to obtain a core at the bottom of GT-2 for fracture orientation determination.

Additional Fracture and Pressurization Experiments, GT-2. Between the time that the Otis packer assembly was pushed to the bottom of the hole and its removal, numerous fracture and pressurization experiments were conducted in GT-2 using a Baker straddle packer assembly in the cemented liner. During July and August, the Baker assembly was set across perforations in the casing at various depths between 2790 and 2910 m (1950 and 9550 ft) and the isolated intervals were pressurized. In about a third of these tests, the packers leaked or ruptured.

After the Otis packer had been retrieved from the bottom of the hole, the PBR mandrel was reinserted at the top of the casing on 11.5-cm-o.d. (4-1/2-in.) tubing, thus ending the use of packers in GT-2.

Packer Usage in EE-1. On August 23, 1975, a Lynes inflatable packer was set in EE-1 at 1975 m (6480 ft), 18 m (60 ft) below the bottom of the existing casing in preparation for experiments to detect acoustic signals associated with fracture initiation and extension. Inflation of the packer was accomplished with an initial pressure of 100 bar (1500 psi) by the Haskell pump in the LASL trailer. The inflation pressure was gradually increased to about 13 bar (200 psi) above the hole pumping pressure. The Kobe pump was used to pressurize the interval between the packer and the bottom of the casing. Maximum flow into the interval was 34 liter/min (9.1 gpm) with about 3000 liter (800 gal) being injected. Definite fracture initiation (breakdown) occurred at 130 bar (1900 psi). An SP electric log later indicated the fracture had been formed between 1962 - 1967 m (6437 - 6454 ft).

The system was then vented, the Lynes packer was allowed to deflate, and pumping was resumed to pressurize the entire hole below the casing. The packer was then moved down 73 m (240 ft) and reset. The system was again pressurized to a maximum of 95 bar (1370 psi), with about 1900 liter (500 gal) injected. The Lynes packer performed exceptionally well under these conditions.

On August 27, a 1.5-m-long (5-ft) Lynes inflatable impression packer was centered at 1964 m (6443 ft) and inflated with the LASL Haskell pump. The interval between the packer and the top of a cement plug at 1975 m (6480 ft) was

pressurized with the Kobe pump at a flow rate of 34 liter/min (9 gpm). The previously made fracture opened at a pressure of 128 bar (1850 psi); after 5 min, the pressure decreased to 119 bar (1730 psi), then increased to 134 bar (1950 psi) after an hour of pumping.

The impression packer was set at a pressure of 170 bar (2500 psi) for 45 min. During this time, part of the fracture was evidently sealed off because the flow rate through the Kobe pump decreased substantially. When the packer was pulled, the soft rubber liner remained in the hole. No impressions were obtained. The following day an oriented Lynes impression packer assembly was run down the hole and set in the hydraulic fracture zone at a pressure of 160 bar (2300 psi) for 4 h, while the fracture was being pumped at 140 bar (2000 psi). The packer assembly consisted of two 1.5-m (5-ft) elements, spaced 1.8 m (6 ft) apart with the elements centered at 1962 and 1966 m (6438 and 6449 ft). Definite impressions of the hydraulic fracture were obtained and indicated that the fracture was oriented in a NW-SE direction.

On October 14, after EE-1 had been drilled to final depth, an attempt was made to create an intersection with the GT-2 fracture by producing a connecting fracture in EE-1. This work is discussed in Sec. 3.2.4. From the results, it was concluded that a low-order connection between GT-2 and EE-1 had been established.

Another Lynes inflatable packer was run down to be set at about 2987 m (9800 ft). Trouble was experienced in getting the packer past 2930 m (9600 ft), and it could not be seated. When the packer was pulled from the hole it was badly torn. A bit was then run in, and the hole was reamed from 2917 to 3023 m (9570 to 9918 ft), then circulated for 3 h.

On October 17, another Lynes packer was run down EE-1 to 2994 m (9822 ft) in an effort to fracture below that depth. Attempts to inflate the packer were unsuccessful, and when the drill pipe was pulled, the entire packer assembly was left in the hole. The following day another packer was run in, but it could not be lowered below 2828 m (9278 ft). When it was pulled, the bottom third of the assembly remained in the hole. A bit was installed on the drill pipe and both packers were pushed down the hole to 3055 m (10 022 ft). On October 20, another Lynes packer was successfully set at 2984 m (9791 ft). The Western pump truck was used to pump through the packer; at 230 bar (3300 psi) the annulus level began to rise, indicating a leak around the packer. There was no apparent fracturing of the rock at that pressure. This was a surprising result, because

this pressure far exceeded the expected minimum earth stress. The packer by-pass valve was opened with the wire-line, and the hole was circulated.

The following day, another Lynes packer was run in. It prematurely seated at about 244 m (800 ft) and was pulled. The hole was then prepared for the final string of casing, the casing was set, and no further attempt was made to hydraulically fracture at the bottom of EE-1.

7.2. Measurement-Related Activities (B. R. Dennis, J. H. Hill, J. R. Archuleta, C. F. Fink, E. L. Stephani, B. E. Todd, E. H. Horton, D. M. Yates, R. L. Housel, W. L. Sibbitt, J. C. Skalski, and P. J. Chavez)

7.2.1. Orientation in the Borehole. Many downhole operations, for example, obtaining oriented borehole cores or using impression packers, require appropriate orientation techniques and equipment. The success of fracture-mapping and borehole ranging techniques depends on the determination of the compass orientation of the downhole acoustic sonde. A multishot directional survey instrument (Eastman Whipstock) was used to determine the acoustic package orientation in the borehole. This orientation system works successfully at borehole temperatures up to 200°C but is limited in operation to not more than 2 h at this temperature. The borehole instrument consists of a camera, an instrument watch (timing device) to activate the camera periodically, a battery section, disc trap, and angle unit. The angle unit combines a magnetic compass and an angle indicator to show inclination from vertical. From a previous borehole survey that measured the inclination and direction of the borehole as a function of depth, the relationships at any depth between the magnetic compass direction and the plumb bob inclinations (relative to sonde markings) determine the orientation of the sonde. The disc trap allows daylight loading and unloading of film without a camera bag. High-temperature capability is provided by a heat shield that protects the instruments and film.

Another method of determining the compass orientation of the downhole tri-axial geophone package uses acoustic sources positioned at predetermined surface locations. A Dynoseis system was used as the surface acoustic source, and acoustic signals were generated by firing an explosive mixture (electrically) to actuate a piston and couple a 95-kJ impulse into the ground (Fig. 7-15). This repeatable acoustic source could be deployed at any position relative to the borehole. A well-defined timing signal was also provided when the impact mechanism actuated a microswitch when striking the ground. The accurate timing signal

was necessary to facilitate signal averaging techniques to extract the coherent acoustic signatures from the noise. A previous velocity survey of the GT-2 borehole, conducted by a service company (Birdwell), provided a seismic map of the geological structure in the volcanics.

A digital processing oscilloscope (Tektronix 7704A) and processor (Tektronix P7001) was programmed to algebraically add all signals received in a window triggered by the Dynoseis timing signal. The data in Fig. 7-16 describe the results of averaging the signals recorded by the downhole geophones at about 910 m (3000 ft) in the GT-2 borehole. A series of 25 impulses were generated at the surface. A high-gain differential amplifier used for conditioning the low-level signals in the instrument trailer was set to a gain of 50 (34 dB). The coherent acoustic signal is enhanced proportionally to the number of impulses recorded, whereas the random noise enhancement is proportional to the square root of the number of impulses. The data shown in Fig. 7-17 were recorded at about 1520 m (5000 ft) in the GT-2 borehole. This time 50 impulses were recorded, and the differential amplifier gain was set to 200 (46 dB). No useful signals were recorded at 2130 m (7000 ft). However, a known porous zone at 2070 m (6800 ft) may have decoupled the acoustic signals.

This method of orientation has practical limitations as borehole depth increases. More impulses are required for sufficient enhancement of the detected signals as the first motions, imperative to determining orientation, become increasingly more difficult to interpret (compare Figs. 7-16 and -17).

A plumb bob orientation device that could be read out at the surface (eliminating the temperature-sensitive film) was designed to operate continuously at 200°C. The plumb bob is a high-density (18-g/cm³) half cylinder, axially mounted in bearings and coupled to a low-friction cosine (360°C) potentiometer. Inclination of the axis beyond a critical angle causes the off-center mass to rotate to a lower position. Initial check out of this device in the laboratory at ambient

Fig. 7-15.

Dynoseis truck used to produce acoustic signals for detection in the GT-2 borehole.

Fig. 7-16.

Dynoseis-produced signal measured at about 910 m (3000 ft) in the GT-2 borehole. Top: Signal produced after first impulse. Bottom: Signal produced after 25th impulse. Note enhancement of the signal (beginning at about 330 ms) from the signal averaging technique.

Fig. 7-17.

Dynoseis-produced signal measured at about 1520 m (5000 ft) in the GT-2 borehole. Top: Signal produced after first impulse. Bottom: Signal produced after 50th impulse. Note signal enhancement at about 440 ms.

temperature indicated that angles greater than 2° of dip could be determined. The device was tested in the GT-2 borehole and the readout was compared with the directional survey instrument (Eastman Whipstock) run at the same time. The correlation of data recorded by the survey instrument and the plumb bob was poor, probably because of temperature effects on the plumb bob bearing. A modification in the design of this plumb bob should eliminate system friction.

When the downhole controlled environment (Dewar) is available, a system using sensitive inclinometers, mounted in an orthogonal configuration, will be able to output a dc voltage directly proportional to the sine of the angle of tilt. The system will provide orientation of downhole instrument packages if a borehole survey has been made.

7.2.2. Downhole Acoustic Signal Detectors. A downhole triaxial-geophone package is usually used to detect acoustic signals from discrete fracturing events as the hydraulic fracture is extended. Signals 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.

Initial attempts to use acoustic methods in the boreholes used high-temperature geophones^{*} mounted in a cradle assembly in a multipurpose instrumentation package (Fig. 7-18). Coupling into the uncased (open) wall depended on the vertical tilt of about 5° of the wellbore and the total length of the downhole sonde allowing at least one point of contact. Early tests revealed several problems with this first assembly. The geophone output was inadequate to drive the long signal lines for the microseismic events, and additional gain downhole was required. A more positive coupling of the sonde to the borehole wall was necessary for increased response to the microseismic events generated during fracture extension.

Geometrical constraints imposed on the outside dimensions of the downhole sonde severely restricted the space available for instrumentation because of the borehole diameter and high pressures encountered during pressurization experiments. Pressures up to 620 bars (9000 psi) are possible at depths of 3000 m (10 000 ft) with a 280-bar (4000-psi) hydrostatic head and a 340-bar (5000-psi) overpressure capability. The high pressure combined with the high temperature affected exposed components such as O-ring seals and electrical feedthroughs.

^{*} Walker-Hall-Sears of Houston, TX, Model Z-3 modified for high temperature. Coil resistance, 730 ohms; natural frequency, 6 Hz; intrinsic sensitivity, 3 V/cm/s; damping, 76% of critical.

The downhole geophone package is shown in Fig. 7-19. The figure shows 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, heat treated to insure a 8374-bar (120 000-psi) yield strength. The entire package is 3.7 m (12 ft) long with a maximum diameter of 9.2 cm (3-5/8 in.). The assembled package weighs 54 kg (120 lbs). (See Appendix C for detailed drawing 81Y210110.)

Figure 7-20 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 rate of motion is further reduced by a lead-screw mechanism. The motor has a rated torque of 21 N·m (15.5 lb·ft) and is specified for continuous operation at 125°C. The motor was tested for

Fig. 7-18.
Multipurpose instrumentation package. Pressure housing (A), mule shoe (B), geophone cradle (C), water sampler (D), pressure transducer (E), and cable-head subassembly (F).

Fig. 7-19.
Downhole geophone package, 9.2-cm diam (3-5/8 in.).

intermittent duty (several hours) at 200°C and has operated satisfactorily downhole. Total travel time of the arm from the fully extracted position, enclosed in the sonde housing, to the fully extended position of 23 cm (9 in.) is about 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 890 N (200 lb). The actuating linkage includes a shear pin to release the extended arm downhole should the motor fail.

Figure 7-21, a diagram of the downhole geophone sonde, shows the arrangement of the geophones, Dewar and amplifier package, and actuating motor. The Viton O-ring seals are specified to meet the borehole pressure and temperature requirements. However, this elastomer tends to become brittle when exposed to the downhole environment for several hours and must be replaced for each insertion.

To increase output-signal strength and improve signal-to-noise ratio downhole, an operational-amplifier circuit as shown in Fig. 7-22 was used. The Harris 2620 operational amplifier was tested at 200°C for several 24-h periods and operated continuously with only slight degradation in specifications. Four geophones were arranged in series for each orthogonal set and in parallel with a high-temperature resistance equal to the geophone-coil resistance.

Fig. 7-20.
Cricket arm coupling system.

Fig. 7-21.
Schematic of downhole geophone sonde.

Fig. 7-22.
High-temperature downhole operational amplifier and associated frequency response.

Polarities of first motions were carefully observed for each geophone during fabrication of the cradle assembly (Fig. 7-17) to insure enhancement. This configuration allowed for an additional factor of 2 gain and increased the reliability of the geophone package. The frequency response curves shown in Fig. 7-21 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 a second serious limitation on the downhole amplifier array because only seven conductors were available for

^{*} Cable electrical parameters were measured at 280 ohms per conductor, 100 megaohms conductor to armor, 0.54 μ F capacitance per conductor pair, and 5.75 mH inductance per pair.

wiring the triaxial package, as shown in Fig. 7-23. 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 at least 12 h in the 200°C environment. A Burr Brown M3670 differential amplifier is shown schematically in Fig. 7-24. The amplifier and associated battery pack were potted with a Dow Corning silicone-rubber epoxy and housed in an ice-filled glass Dewar (Fig. 7-25). Providing the dc power for amplifier operation downhole 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, thereby reducing dc drift during downhole operations. The gain of this amplifier was set to 1000, and the response is shown in Fig. 7-24, Curve A. Curve B describes the response of the amplifier driving the instrument cable. Figure 7-26 shows the geophone cradle and Dewar package ready for insertion in

Fig. 7-23.
Operational amplifier wiring diagram.

the pressure housing. An additional refinement, added later, was to encapsulate the amplifier and battery pack in a solid brass tube (Fig. 7-27) with an O-ring seal at the cap. This system permitted a larger volume of ice in the Dewar, extending the downhole lifetime several hours.

Signals from the geophones were conditioned through a differential amplifier in a surface recording facility 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. See Sec. 4 for an analysis of geophone data.

7.2.3. Downhole Acoustic Source. Successful fracture mapping and borehole ranging experiments were conducted in the GT-2 and EE-1 boreholes with downhole acoustic sources. Several measurements to detect the fracture were made with a high-temperature, high-pressure Primacord explosive providing the acoustic source at predetermined depths in the borehole. The intensity of the acoustic signals varied considerably (including numerous misfires) because the explosive material was degraded by the hostile environment. For this reason analysis of the recorded data was inconsistent.

With the development of the downhole acoustic geophone package, including the high-gain amplifiers and the wideband tape recorder in the instrument trailer, acoustic signals generated by firing only detonators in the adjacent borehole could be recorded. A series of 10 detonators could be fired in sequence for each trip in and out of the borehole. The detonators, supplied by a service company, also were degraded in time for the hostile environment, and numerous misfires occurred. The service company firing signals were not reliable for timing purposes and caused errors in the data analysis. A LASL-designed firing unit was fabricated to provide a surface timing pulse and allow for installation of a high-temperature geophone in the detonator sonde for an additional downhole firing signal. The detonators were coated with a high-temperature Dow-Corning RTV silastic to extend their operational lifetime in the borehole. With this configuration, because of the conductor limitation of the logging cable, only three detonators could be fired in sequence, the minimum required for each ranging position. A ranging experiment involving several depths in the borehole would not be practical if a round trip were made to load the downhole detonator package for each depth.

Fig. 7-24.

Downhole differential amplifier and its associated frequency response.

Fig. 7-26.

Geophone cradle and Dewar package ready for insertion in the pressure housing.

Fig. 7-25.

Disassembled downhole Dewar package showing the three potted differential amplifiers and their battery packs.

Fig. 7-27.

Slim-line amplifier package with plug-in battery pack and 0-ring sealed brass tube.

Two alternative approaches were taken to provide a reliable, repeatable downhole acoustic source. First, a contract was negotiated with Reynolds, Inc., to design and construct a system that would include a downhole firing unit capable of sequentially firing up to 12 detonators. This unit will use a high-temperature detonator that has been tested at temperatures greater than 200°C and pressures up to 620 bars (9000 psi) without degradation for up to 12 h. A power supply and control unit will be used at the surface to charge the downhole firing unit and switch the detonator array. A timing signal will be generated by a high-temperature geophone assembled in the downhole firing unit. This unit is scheduled to be shipped from Reynolds in late July.

The second approach, to design a mechanical acoustic source, was started in December 1975. The unit has been fabricated and tested (see Appendix C, drawing 18Y210121) and has been used as the downhole acoustic source for several ranging experiments. The power to actuate the source is derived from the conversion of electrical energy to mechanical energy (spring). An electrical motor enclosed in a downhole sonde is powered from the surface. The motor extends an arm forcing the package against the wall of the casing much like the geophone package. The motor continues to run and cocks a symmetric beam spring through a toggle linkage (Fig. 7-28). As the toggle goes over center, the stored energy of 542 J (400 ft-lb) released drives a hammer against an anvil that is rigidly coupled to the extended arm. The impulse is thereby coupled through the arm and into the casing wall. The cocking mechanism may be actuated as often as desired. A high-temperature geophone is also mounted in the downhole sonde to provide a zero signal. This zero time has routinely been measured at $\pm 10^{-4}$ s.

7.2.4. Borehole Temperature Measurements. The drilling program initiated for GT-2 allowed for extensive coring in the Precambrian granitic rock followed by in situ temperature measurements. Because of the high cost of a drilling rig and crew, the time at depth required to extrapolate an accurate bottomhole temperature had to be minimized. Continuous logs of the entire boreholes were required to detect geological anomalies, such as the present aquifers in the granite zones, and to measure major temperature departures from previous logs caused by hydraulic fracturing and flow experiments.

The probes used for measuring borehole temperatures have thermistors for the sensing device. A thermistor is a semiconductor that behaves as a temperature sensitive electrical resistance. Thermistors have a very high negative

temperature coefficient of resistance, which provides a high degree of resolution not available in other temperature transducers. The resistance of a thermistor as a function of temperature change is nonlinear and varies for different types of thermistors; therefore, each thermistor must be carefully calibrated.

Two different temperature recording systems were used in the GT-2 and EE-1 boreholes. Accurate temperature measurements, such as bottomhole temperature, were recorded by reading the resistance of a thermistor probe with a digital ohm converter that has a six-digit readout and a $\pm 0.02\%$ full-scale accuracy. These digital resistance measurements were corrected for line resistance and thermal effects of the logging cable. The resistance data were converted to temperature using a linearization equation computed for each probe (Fig. 7-29). In the second system, a dc-excited Wheatstone bridge network, with the thermistor in one arm, was used to continuously log the borehole. The Wheatstone bridge output signal was recorded on a strip-chart recorder that had the chart speed controlled by the logging cable hoist. An accuracy of at least 4% was maintained by restricting temperature intervals to 50°C and by calculating bridge resistance and excitation voltage, which minimized the nonlinear characteristics of the thermistor (Fig. 7-30). The thermistor resistance was high (100 k ohms) in the cooler regions of the borehole, and the bridge network presented a high output impedance to the recording equipment. This high impedance of the transducer source resulted in poor signal-to-noise ratio, which decreased the resolution of the measuring system. For semiquantitative measurement, however, this system is adequate and very reliable.

Fig. 7-28.
Downhole mechanical acoustic source.

Fig. 7-29.
 Temperature vs resistance for thermistor probe 612-1.
 The solid line results from the equation shown.
 Measured data points are shown by circles.

LASL is developing a thermopile transducer that uses an ice bath (Dewar) for a reference junction. (See Appendix C, detailed drawing 81Y210128.) Because this thermopile transducer is approximately linear for the complete borehole temperature range (0 - 200°C) and is a low source impedance, temperature measurement accuracy can be greatly improved. Also, the fast thermal response time (about 1 ms) of the thermopile will enhance the capability to detect borehole geological

anomalies and borehole temperature departures caused by hydraulic fracturing and flow experiments. The amount of time the thermopile will maintain its accuracy depends on the duration of the ice bath, which is now about 12 h.

7.2.5. Downhole Pressure Measurements. During fracturing experiments in GT-2, a downhole pressure gauge was instrumented to provide data related to fracture-initiation (breakdown) pressure, fracture-extension pressure, and fluid leak-off rates. The pressure transducer was installed in a high-pressure housing (see Appendix C, detailed drawing 81Y210049) and was lowered into the pressurized zone through the drill string by way of the logging cable. The transducer used a strain-gauge bridge sensor calibrated to 520 bars (7500 psi) and specified to be compensated over a temperature range of 50 - 200°C. The pressure transducers were to be calibrated in an autoclave facility by the manufacturer, as required in the LASL specifications, to insure proper operation throughout the temperature and pressure range.

The gauge was installed in the downhole sonde and lowered into the GT-2 borehole. Just before reaching the region of interest in the borehole, a large negative shift in the transducer output was observed. The sonde was recovered and the transducer recalibrated by LASL personnel. The results of this calibration are shown in Fig. 7-31. The additional negative shift at the 520-bar level and 200°C temperature confirmed that the strain-gauge elements were creeping on the pressure-sensitive diaphragm. The gauges were returned to the manufacturer for repair. No further attempts at downhole pressure measurements have been made, but such measurements would be desirable in future experiments.

Fig. 7-30.
Voltage across thermistor, as a function of its temperature, when used in a Wheatstone bridge circuit.

7.2.6. Downhole Water Sampler and Bailer. A commercial water sample device, to obtain a fluid sample at the bottom of boreholes during flow tests, was purchased. The sampler was specified by the manufacturer to operate at 315°C (600°F) and 1380 bars (20 000 psi). The water sampler, a self-contained unit with an internal clock and actuating solenoid, could be run in the borehole on a wire line or attached to a downhole instrument sonde. The device was laboratory tested at equivalent downhole pressure and then used in a GT-2 experiment. It failed to operate and was returned to the manufacturer for repair. It was later used in an EE-1 experiment and again failed. A new LASL-designed water sampler is being fabricated (see Appendix C, drawing 81Y210123).

A 7.6-liter (2-gal) bailer was designed and fabricated to inject a concentrated sodium-fluorescein dye into the hydraulic fracture in EE-1. The dye was successfully injected at 2740 m (9000 ft) for the residence time experiment (No. 119). A large-volume bailer is being designed for future experiments.

7.2.7. Cables and Cable Heads. The most severe limitations to the use of instrumentation in a geothermal well are those associated with the high-temperature and high-pressure effects on currently available commercial armored logging cable and associated cable-head assemblies. LASL is using a commercially available standard high-temperature logging cable to field downhole experiments at the Fenton Hill site. This cable is made of seven "Tefzel" insulated conductors wrapped to form a core and then covered with a nylon braid for seating the outer steel-wire armor. The conductors are not twisted in pairs nor shielded to reduce electromagnetic and electrostatic (common mode) noise as prescribed by good instrumentation practices. The electrical parameters of this cable measured over the 5790-m (19 000-ft) length are a capacitance of 0.54 μF per conductor pair and a 5.75-mH inductance per shorted pair. These electrical properties severely

Fig. 7-31.
Calibration of commercial downhole pressure transducer at two different temperatures.

limit frequency response and signal-to-noise characteristics of a downhole measuring system. Plans call for procurement of a special armored cable with much better electrical characteristics.

The armored cable is terminated in a cable-head assembly designed specifically for well-logging operations. Commercial head assemblies use a short bridle and torpedo to make easy disconnections in the field (Fig. 7-32). The wire armor from the bridle is terminated in the cable head over a steel cone basket that secures the armor inside the head housing. A torsion bar couples the cone basket to the head assembly and is machined to break at a specified tension. This design allows for the logging cable to be retrieved from the wellbore if a tool becomes lodged downhole. The fishing bell housing will accept a fishing tool to retrieve the head assembly and associated sonde left in the borehole. High-temperature cable heads use ceramic feedthroughs for electrical connections and Viton O-rings for pressure seals. After the head and torpedo are assembled in the field, they are filled with a high-temperature silicone grease to prevent moisture from intruding up the cable conductors. Once moisture has entered the insulated conductors, the insulation resistance breaks down, resulting in a low impedance to ground. The cable must then be reheaded above the moisture level, resulting in the loss from several feet to a few thousand feet of cable.

The high-temperature heads and torpedo assemblies used by most commercial logging services are adequate to brief applications where borehole temperatures do not exceed 150°C. For long-term measurements in a geothermal borehole, as required by LASL, cable-head assembly problems have caused considerable delays. The combination of hydrostatic pressure and high temperature exhibited by the fluid in the borehole was detrimental to the cable-head assembly. The commercial head assembly had to be modified with the fishing-bell configuration and torsion-bar design intact. The first improvement was to eliminate the torpedo and terminate the cable directly in the head assemblies. The silicone grease was replaced with a high-temperature Dow

Fig. 7-32.
Dresser-Atlas cable-head assembly. Fishing bell housing (A), bridle (B), torpedo section (C), and cable-head assembly (D).

Corning RTV potting compound to seal the entire cable head, thus preventing the high-pressure borehole fluid (water) from intruding into the conductor. The RTV was later discovered to expand and contract with temperature variations, resulting in abrasion of conductor insulation in contact with sharp metal edges in the head assembly (such as the wire basket). The expansion from high temperature also resulted in a tensile force large enough to damage the torsion bar. All metal surfaces in contact with the conductors were therefore smoothed where possible, and a high-temperature heat-shrink tubing was inserted over the insulation. The head was heated during the curing of the RTV, and excess compound from the expansion was removed from the housing. A compression ring was installed over the torsion bar to prevent damage from compressional stresses. Figure 7-33 shows the modified cable-head components and fishing bell housing. Placement of the potting compound is shown in Fig. 7-34. The modified cable head has increased the reliability of downhole measurements. Cable integrity during experiments in the GT-2 and EE-1 boreholes has been maintained for durations exceeding 24 h.

Use of cable-head assemblies in deeper boreholes with temperatures of 250°C will require additional development, including testing of components and potting

Fig. 7-33
Modified Dresser-Atlas cable head, showing components and housing. Fishing bell housing (A), compression ring (B), steel cone basket (C), torsion bar (D), wire basket (E), ceramic feedthroughs (F), and O-rings (G).

Fig. 7-34.
Disassembled (modified) cable head, after downhole use, showing potting compound in place. Fishing bell housing (A), potting compound (B), wire basket (C), and O-rings (D).

compounds. Use of metal seals in place of the Viton O-rings will be required. The logging cable now used at the field site will not meet higher temperature specifications, and a new insulating material may be required.

7.2.8. Casing Depth Measurement. Reference points near the bottom of the GT-2 and EE-1 wellbores are desirable for correcting the exact location (depth) of a downhole instrument package, for example, for ranging and fracture-mapping experiments. The downhole cable depths as read by the footage counter in the cable hoist units do not agree with the casing tally. This error can be attributed to the cable measuring head, cable stretch, and thermal effects. The bottomhole depth from other logging services also varies. Locating the bottom of the hole by reading the weight indicator on the cable measuring head depends on the operator and the sedimentation and is not a repeatable measurement. To calibrate the cable hoist footage counter, the bottom of the casing in the GT-2 and EE-1 wellbores was determined using the SP probe. (See Appendix C, drawing 81Y210127.) The SP probe was used as one arm in an ac-excited (1-Hz) Wheatstone bridge circuit. The bridge circuit was then used to measure the resistance between the SP probe and the wellbore casing. The change in resistance when the SP probe exits the casing (resistance is now measured between the probe and the open-hole wall) is well defined, as shown in Fig. 7-35. The bottom of the casing in GT-2 was measured at 2921 ± 0.6 m (9584 ± 2 ft), and the bottom of the casing in EE-1 was measured at 2929 ± 0.6 m (9608 ± 2 ft) as recorded by the cable hoist footage counter. These depths were measured along the boreholes from the top of the wellhead of the respective boreholes.

7.2.9. Controlled Environment. A controlled environment for downhole instrumentation was necessary when a differential amplifier and auxiliary battery power supply had to be included in the downhole geophone package. Laboratory Dewars (glass) were tested and incorporated into the downhole instrument sonde. The demand for larger Dewars to house more electronic equipment has continued to grow. A large Dewar has been ordered from a commercial firm (Minnesota Valley Engineering). This Dewar will supplement a large prototype Dewar assembly being fabricated for the downhole acoustic detection package (geophones) and will include the inclinometer orientation device (see Appendix C, drawing 81Y210130).

Fig. 7-35.
SP probe ac bridge circuit and recorded signals
at the bottom of the casing in GT-2 and in EE-1.

7.3. Logging Operations (F. G. West and P. R. Kintzinger)

7.3.1. Borehole Logging. During the drilling of EE-1 several logs or suites of logs were run. These logs included full-wave sonic, spectral gamma, bulk density, electric (resistivity and SP), caliper, and neutron activation. The results permitted determination of the condition of the borehole, lithology, permeability, rock competency, natural fracture zones, and the integrity of cement around the casing. The use of a particular log was based on experience from drilling GT-2.

Logging in EE-1 was performed in several steps. The sedimentary section was logged to determine lithology, hole condition, and the integrity of the casing cement job. When the hole was drilled to 1958 m (6424 ft), logs were run to determine hole condition, lithology, permeability, rock competency, and occurrence of fractures. After the casing was set and the hole was deepened to 2097 m (6880 ft), logs were run to determine permeability, rock competency, fracture zones, and the integrity of the casing cement. After experiments were completed at this level, the hole was deepened to 2917 m (9571 ft). Logs were run to determine the condition of the borehole, permeability, lithology, rock competency, and fracture zones. Upon deepening of the hole to 3064 m (10 053 ft), logs were run to determine the lithology, rock competency, fracture zones, and the integrity of the casing cement.

Logging operations on EE-1 were more efficient than those of GT-2, and all objectives were achieved. Experience from GT-2 allowed logs to be deleted that appear to have limited usefulness in a crystalline rock environment. Also, better lines of communication and working relationships with the service companies had been established. However, several equipment failures occurred. As experienced in GT-2 logging, the incidence of failures tended to increase with increased hole temperature. In fact, the bottomhole temperature of $\sim 200^{\circ}\text{C}$ (400°F) appears to be near the practical limit of most existing commercial logging equipment.

The USGS used GT-2 in June 1975 to field test their new high-temperature (200°C) logging tools, in particular, the borehole televiewer. Failure of the tool drive motor delayed a complete test. Current plans include a test of the tool by logging the bottom section of the EE-1 in mid-1976.

From the logging of EE-1, it is concluded, as it was from the GT-2 logging,⁵ that the most useful log for project purposes is the full-wave sonic log, and the most useful log for lithologic determination is the spectral gamma log.

Logs of the crystalline section of rock are being used to interpret the geology in the holes and of the area. The logs indicate little lithologic correlation between EE-1 and GT-2 in the 730- to 1830-m (2400- to 6000-ft) interval, although the hole separation is only 77 m (252 ft) on the surface. The only correlations are for two fracture zones and two dikes, which were probably emplaced along fracture zones. Although some lateral variation is expected, the lack of correlation in this section of the hole is thought to be the result of high dip angles. This conclusion is based in part on the geologic conditions and relationships observed in local areas of crystalline rock outcrop. Because

the correlations in this section provide only two points on the plane, only an apparent minimum angle of dip can be computed. The apparent minimum dip of the fracture at 974 m (3195 ft, GT-2 depth) is 5° and of the fracture at 1291 m (4237 ft) is 9° . The apparent dip of the dike at 1179 m (3868 ft) is 23° and of the dike at 1295 m (4250 ft) is 8° .

Some change in the general character of the rock occurs at a major fracture zone at 1830 m (6000 ft, GT-2 depth), which has an apparent dip of 7° . The shift in rock character coupled with an apparent low-angle fracture zone suggests a Precambrian age relative lateral movement between these two sections of rock. Correlations tend to increase with increased depth below the fracture zone at 1830 m. Also, the intensity of fracturing decreases and the competency of the rock appears to increase below this fracture zone. Using the spectral gamma log, the existence of healed fracture zones in the lower part of the holes can be inferred. One small fracture zone appears at 2544 m (8345 ft) and has an apparent dip of 9° . In EE-1 at a depth of 2989 m (9808 ft) a small fracture is seen, but is not found in GT-2.

The ability to evaluate general levels of rock competency and hence the relative permeability, was tested in the selection of intervals for hydrologic testing in GT-2. In EE-1 this ability was again tested at 2080 m (6825 ft), when a moderately weak and permeable zone was thought to exist. Fluid injection at relatively low levels of pressure confirmed the existence of this zone.

As was found in the GT-2 logging, the caliper log of EE-1 correlated well with the full-wave sonic, electric, and drilling time logs. The electric and full-wave sonic logs gave good indications of permeable fracture zones. Incompetent rock zones were clearly shown on the full-wave sonic log. The elastic properties of the rock were computed using the bulk density and full-wave sonic logs. The bulk density and spectral gamma logs gave an indication as to the rock lithology, whether the rock is mafic or silicic.

Work on problem areas in the interpretation of these logs is under way. The electric dip log is being studied for some insight as to why the log results do not agree with the preliminary results obtained from the borehole televiewer. The excellent electrical response of the fractures suggests that the dip log should be a very useful tool for fracture detection and orientation. The correlation of rock type with the spectral gamma log and density log is being refined. The neutron activation (pulsed 14-MeV neutrons) log run in EE-1 is also being correlated with rock type.

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8. INDUSTRIAL LIAISON AND SUBCONTRACTING

8.1. Introduction

Many of the field operations conducted at Fenton Hill this past year were subcontracted with appropriate industrial firms. The major subcontract was, of course, the drilling of EE-1. Additional major industrial support was obtained through a contracted workover drill rig to perform the experiments conducted in GT-2. These major contracts required a close day-to-day liaison with personnel of the firms involved. Contacts were also required with the various supporting firms and individuals needed to carry out minor drilling operations, such as packer handling and casing, and the hydraulic fracturing experiments. Additional subcontracts were arranged in many other areas of work; some representative cases are discussed later in this section.

8.2. Liaison Activities

The unique nature of HDR geothermal energy extraction technology under development requires that the concepts, problems, and results be communicated widely throughout the geothermal and related industries. If the developing technology is to be effectively transferred to the private sector it will have to be available for review and judgment of technical details and ultimate economic viability. Information dissemination was achieved by distribution of technical reports, presentations at technical and scientific meetings, informal correspondence and discussion, and the use of displays at technical and trade association meetings. Briefings and tours were also conducted for many visitors to LASL, and exchange visits were made by LASL staff to industry installations. Additionally, technical personnel of numerous firms were consulted on potential solutions to problems encountered during the course of the project.

In summary, the aim of the industrial liaison activities for the HDR project is to:

- Establish and maintain a general awareness of the HDR project progress, plans, and problems on a national scale.
- Solicit advice and consultation.
- Locate sources of special expertise, instrumentation, equipment, and services.

- Keep abreast of private sector progress, problems, and opinions in geothermal development.

8.3. Drilling Technology and Equipment

The drilling program for EE-1 was modified as the result of a review of the GT-2 experience by a technical panel composed of drilling contracting firms, drilling equipment companies, and drilling technology specialists. The major recommendations of this panel were included in the EE-1 drilling specifications, equipment selection, strategy, and operations. This review approach will be followed before any future drilling programs are undertaken.

Special drill collars and drill bits were needed for the hard rock encountered in geothermal drilling. Interactions with Smith Industries, Inc. have been especially helpful. The downhole assembly design (DrillCo, Div.) and the four-cone (JOIDES) coring bit were major contributions by Smith Industries to the project. Subsequent discussions on directional drilling and improved penetration rate have also been very valuable.

The high-temperature open-hole packer problem has been pursued with the Lynes United Testers, Inc. Discussions with Baker Oil Tools, Inc. were instituted in an effort to define whether an alternative approach of a packer system employing an advanced, easily removable cemented-in liner (scab) is possible.

8.4. Downhole Instrumentation and Measurements

8.4.1. Dresser Atlas. Several well logging systems to lower various experimental instrumentation packages into the hostile environment of the borehole had to be purchased so that special experiments could be conducted in GT-2. Commercial service companies were employed to run various logs in the hot boreholes, but for long-term experimental work, it was necessary to have the capability to handle the instrumentation and associated electronics in house.

In early May 1973 several companies that manufactured well logging equipment and provided well logging services were visited. Most of those companies were somewhat hesitant to support this program because of the lack of a large market. However, the management of Dresser Atlas decided that the program was not only a very interesting one but also that the use of logging services in hostile boreholes may provide a near-future market.

Dresser Atlas has since supported this program not only with well logging equipment and services but also with help in several advanced technology areas. In return LASL has cooperated with Dresser Atlas in the development of a

high-temperature cable head that will endure the high-temperature and high-pressure environment of a geothermal well for several hours. LASL has encouraged Dresser Atlas in its development of logging techniques for geothermal wells. A mutual interest and an open exchange of information has been established.

8.4.2. Walker-Hall-Sears. During the initial hydraulic fracturing experiments in the GT-2 wellbore at 2040 m (6700 ft) acoustic techniques were proving to be a useful fracture-mapping tool. A sensitive triaxial geophone array that would operate in the hostile environment was required. A set of specifications were submitted to several geophone manufacturers for a high-temperature geophone. Walker-Hall-Sears, Inc. expressed an enthusiastic interest in developing a geophone to meet our requirements. Several problems were encountered with the high-temperature geophones when first used in the wellbore at a depth of 2930 m (9600 ft) and temperature approaching 200°C, and further development of the high-temperature geophone required special materials and tools. Because Walker-Hall-Sears is a relatively small company, it was not in a position to invest in the necessary tools and materials for the few geophones to be purchased by LASL. Therefore, a cooperative development program was initiated whereby LASL would provide the materials and tools, along with operating personnel, and an exchange of techniques. Information obtained during the development of the 200°C geophone may be useful for future development of a geophone for temperatures up to 275°C.

8.4.3. Reynolds Industries. Several acoustic ranging experiments were conducted in the GT-2/EE-1 wellbores (see Sec. 4.2). A primary explosive (lead azide) was detonated to provide an acoustic source in one borehole, and a downhole geophone package was used as a detector in the other borehole. At 2740 m (9000 ft) degradation of the explosive charge was excessive, and 50% of the detonators failed or misfired.

To employ a reliable high-temperature detonator in the geothermal borehole environment, an exploding bridgewire initiation is required. This firing mechanism also requires the rapid application of a relatively large amount of energy. Owing to the electrical restrictions of the armored logging cable, an exploding-bridgewire-type detonator would require a downhole firing unit programmed from a surface control system.

Reynolds Industries, a specialist in the design and manufacture of electrical connectors and ordnance components and a supplier of many special detonator systems for the LASL weapons systems, was awarded a contract to design and

manufacture a downhole firing unit that would be reliable at 200°C. Reynolds will supply LASL with a complete explosive package including the high-temperature detonators, downhole firing unit, and surface control system.

9. CONCLUSIONS

The major achievements of the HDR project have been summarized in Sec. 1. These include

- successful conventional and directional drilling in hard crystalline rock to depths of about 3 km (10 000 ft) and temperatures of about 200°C (390°F)
- successful production of hydraulic fractures in the crystalline rock
- establishment of a downhole connection between the two boreholes
- identification and field testing of instrumentation that uses acoustic methods for mapping hydraulic fractures and for distance ranging between wellbores
- measurement of reservoir properties by pressure-flow temperature logging and fluid residence time distribution studies
- modeling of fluid flow and heat transfer in downhole systems.

Although much work remains to be done to achieve the final goal of demonstrating the technical and economic feasibility of energy extraction from hot dry rock, the results to date are encouraging.

In the performance of the hot dry rock project, several major problem areas have arisen that will require additional attention. These deal primarily with the development of downhole equipment and techniques for characterizing fracture geometry. The identified needs are as follows, in approximate order of priority in an operational program.

1. Develop more accurate and reliable methods of surveying boreholes. To achieve the optimum downhole intersection, directional drilling of the second borehole is required, and this can be performed satisfactorily only if the relative positions of the two boreholes are accurately known as well as the orientation and size of the target fracture. Of particular importance is the development of detonator and mechanical acoustic sources for borehole-ranging measurements and of suitable environmentally protected or hardened gyroscope, magnetic, and plumb-bob orientation devices. Directional drilling and guidance systems are marginal at present bottomhole temperatures, and significant improvement in this type of equipment will be needed when directionally drilling in deeper, hotter rock.

2. Develop reliable alternative methods of mapping hydraulic fractures. This mapping is required to achieve the optimum intersection of a fracture by the second borehole and to permit suitable fluid flow and heat transfer modeling to estimate the energy extraction capability of the reservoir. Experience so far

has been restricted largely to monitoring downhole acoustic signals in one borehole while extending or inflating fractures originating from the second borehole, although SP, IP, temperature, spinner, and radioactive tracer logs have been used to define the location and/or vertical extent of the fracture intersection with the borehole. Surface seismic detection methods have thus far failed to provide useful information. In addition to the improvement and extension of the present techniques, further investigations should be made in the development of techniques such as (1) rf-induced magnetic induction, (2) downhole radar ranging, (3) acoustic reflection and refraction, (4) use of an inclinometer installed in the borehole during fracture inflation, and (5) displacement or strain measurements performed in the adjacent borehole during fracture inflation. Particular attention should be paid to fracture-mapping techniques in which instrumentation is used in the borehole from which the fracture originates.

3. Assure reliable operation of packers for hydraulic fracturing of basement rock at 200°C and higher. The experience to date with various open- (uncased-) hole packers (see Sec. 7.1.5) suggests that the best chance of achieving capability for high temperature (up to 300°C) and high pressure differential (up to 350 bar) operation is through the redesign and improvement of existing inflatable packer systems. Experience with the alternative, large compression-set rubber and mechanical packers, shows a significantly lower capability for such a system. Another option should be investigated, i.e., development of a packer system that uses an advanced, easily-removable, cemented-in liner.

Although work must continue on other problems, those listed above now appear crucial in the preparation of a well-defined two-borehole hot dry rock reservoir. Once a suitable downhole connection has been made, the next series of questions can be pursued, such as the indicated useful life of the reservoir, and the nature of the chemical, thermal, and mechanical performance of the heat extraction system.

The LASL program plan anticipates a substantial effort in each of the problem areas outlined above, as well as in other important areas. Attempts to reduce further the impedance of the present downhole system will be made in the fall of 1976, by techniques such as selective chemical leaching, fracture propping with particles, or fracture extension. If the impedance can be reduced sufficiently from its present value, the 10- to 20-MW(t) surface heat exchanger will be installed and operated, and based on the performance of this system a decision will be made whether or not to proceed with a 100-MW(t) system.

If the impedance of the present connection is not decreased sufficiently, present plans are to directionally redrill from within GT-2 (or EE-1) to intersect an existing fracture near the bottom of EE-1 (or GT-2). This redrilling operation requires a high degree of confidence in fracture maps, borehole surveys, and directional drilling capability. Pressure-flow testing would then determine the impedance of this new system, and, if it were sufficiently low, the surface heat exchanger would be installed.

Successful formation and operation of a 10-MW(t) reservoir and the associated surface heat exchanger, and of a follow-up 100-MW(t) system, will provide data basic to the design and construction of a small-scale electrical generating plant, and will provide essential information to assess the commercial feasibility of hot dry rock geothermal power systems.

APPENDIX A

MAJOR FIELD EXPERIMENTS CONDUCTED AFTER ESTABLISHMENT OF GT-2/EE-1 CONNECTION

Experiment No.	Date Executed	Experiment Description	Remarks
101	11/6/75	Background temperature log in GT-2.	Temperature anomalies at about 2800 and 2880 m (9200 and 9450 ft). Bottom-hole temperature constant at 197°C.
	11/7/75	Temperature log in GT-2, pumping GT-2 at 34 liter/min (9 gpm).	Same as November 6, 1975.
102	11/12/75	Same as November 6 and 7.	Same as November 6 and 7. Measured outflow at EE-1 of 8.3 liter/min (2.2 gpm).
103	11/19 and 11/20/75	Background temperature logs in GT-2 with Kuster water sampler.	Same as November 6 and 7. Water sample taken at 2750 m (9000 ft). Water sampler failed.
104	12/2/75	Background temperature log in EE-1.	No anomalies noted. Bottom-hole temperature was 205.5°C.
105	12/3 and 12/4/75	Temperature log in GT-2 while pumping EE-1 at 34 liter/min (9 gpm).	Input EE-1: 51 500 liter (13 600 gal). Outflow GT-2: 40 500 liter (10 680 gal). 75% of outflow from GT-2 occurs at 2800 m, 25% occurs at 2880 m.
106	12/23 and 12/24/75	Flow from EE-1 to GT-2 at 130 liter/min (34 gpm), temperature in EE-1 at finish.	Input EE-1: 43 900 liter (11 600 gal). Outflow GT-2: 26 500 liter (7000 gal) at 33 liter/min (8.8 gpm). No change in temperature data.
107	1/8/76	Seismic background in EE-1 with new slimhole geophone package.	Cable head leaked, amplifiers became wet, locking arm failed.
108	1/20/76	Checkout plump-bob orienting device (PBOD) with Eastman multishot.	No reliable readings with PBOD; needs modification.

<u>Experiment No.</u>	<u>Date Executed</u>	<u>Experiment Description</u>	<u>Remarks</u>
109	1/21 and 1/22/76	Induced-potential and self-potential logs in EE-1, while pumping EE-1; electrode in GT-2.	Electrode not functional. S-P probe would not pass 2990 m (9820 ft); both need modification.
109	2/11/76	Repeat of January 22 Expt. Induced-potential and self-potential logs in EE-1, while pumping EE-1; electrode in GT-2.	Logs showed bottom of casing in EE-1 at 2930 m (9600 ft) and indicated presence of a conductive zone below the casing at the 2978- to 2981-m (9770- to 9780-ft) depth.
109A	1/23/76	Pump 22 700 liter (6000 gal) at 130 liter/min (34 gpm) into EE-1 with GT-2 shut in. Rapid vent of both holes.	Input EE-1: 22 700 liter (6000 gal). Recovery EE-1: 12 860 liter (3400 gal). Recovery GT-2: 3090 liter (817 gal).
110	1/13/76	Pump 22 700 liter at 130 liter/min into EE-1 with GT-2 shut in. Measure pressure decay for 20 h, then vent.	Input EE-1: 22 700 liter, Recovery EE-1: 1500 liter (397 gal). Recovery GT-2: 3310 liter (875 gal).
111	3/16,17, 18,19/76	Determine volume of fracture system by pumping into EE-1 at various pressure levels; GT-2 shut in.	Total EE-1 input, 102 200 liter (27 000 gal). Maximum pressure in EE-1, 91 bar (1320 psi); in GT-2, 65 bar (950 psi). Final pressure 53 h after shut in: EE-1, 49 bar (705 psi); GT-2, 50 bar (730 psi).
112	1/29/76	Reverse of Expt. 110.	Input GT-2: 22 700 liter. Recovery GT-2: 6110 liter (1614 gal). Recovery EE-1: 1760 liter (464 gal).
113	1/27/76	Reverse of Expt. 109A.	Input GT-2: 22 700 liter. Recovery GT-2: 12 340 liter (3260 gal). Recovery EE-1: 2180 liter (576 gal).

<u>Experiment No.</u>	<u>Date Executed</u>	<u>Experiment Description</u>	<u>Remarks</u>
114	2/4,5,6,7/76.	Determine flow rate potential of GT-2/EE-1 connection with both holes pressurized to keep the fractures inflated.	Both holes pressurized in steps to about 90 bar (1300 psi). GT-2 vented at rate of 55-75 liter/min while maintaining pressure in EE-1. GT-2 pressure dropped at rate of 1.7 bar/h (25 psi/h). Total input both holes, 240 200 liter (63 470 gal). Total recovery both holes, 149 600 liter (39 520 gal). S3 measured in GT-2 at 85 bar (1240 psi).
115	3/23,24/76	Conduct residence time analysis of the fracture system using sodium-fluorescein dye tracer techniques. Pump into EE-1 at a constant pressure 90 bar (1300 psi).	Injected 227 400 liter (60 080 gal) in EE-1 with 380 liter (100 gal) dye. Recovered 63% of dye from GT-2. Substantial dispersion occurred in fracture.
116	3/20,21/76	Spectral gamma log in EE-1; iodine tracer logs in GT-2 and EE-1; cement bond log in GT-2, all by Dresser Atlas.	Good logs obtained; EE-1 fracture extends from 2930 to 2950 m (9610 to 9690 ft), oriented N54W. GT-2 fracture input at point where OTIS packer previously milled out.
117	3/3,4,5/76	Map fracture in EE-1 through analysis of seismic signals; geophones in GT-2, flowing 635 liter/min (168 gpm) into EE-1.	Orientation of the geophone package achieved. Many discrete seismic signals from different azimuths and horizons obtained.
118	4/8,9/76	Preliminary downhole test of mechanical signal source.	Geophone was inoperative; replaced. Dewar failed; replaced.
118A	4/22/76	Rerun.	Arm could not be activated; repaired cable head.
118A	4/26/76	Rerun.	Test successful; good seismic signals recorded at all settings.

Experiment No.	Date Executed	Experiment Description	Remarks
119	4/27,28, 29/76	Conduct residence time analysis of the deflated fracture system using sodium-fluorescein dye. Pump into EE-1 at a constant pressure of 49 bar (700 psi).	Injected 119 400 liter (31 540 gal) into EE-1 with 6.8 liter (1.8 gal) concentrated dye. First dye appeared in GT-2 about 9450 liter (2500 gal) after maximum short-circuit time. Recovered 91% of total injection.
120	5/11,12, 13,14/76	Maintain GT-2 outflow of 38 liter/min (10 gpm) while pumping into EE-1 at constant pressure of 93 bar (1350 psi); confirm minimum earth stress value.	Steady-state pressurized circulating flow established; overall fracture system flow impedance, 28 bar/liter/s (26 psi/gpm). Total injection: 691 600 liter (182 730 gal). Recovery on May 26: 551 700 liter (145 750 gal); 79.8%.
121	4/19/76	Measure characteristics of GT-2 fracture and time constant for flow between GT-2 and EE-1. Pump into GT-2 with EE-1 vented; maintain pressure at 48 bar (700 psi) for 4 h; shut in GT-2 and monitor pressure decay.	Fracture characteristics essentially unchanged from previous experiments; flow impedance still large; flow time estimated at 10 min or less.
122	5/6/76	Map EE-1 fracture by inflating it and recording acoustic signals in GT-2 at three different depths. Measure impedance with a series of stepped flow tests.	Pressure response noted in GT-2 about 70 s after start of pumping in EE-1. Many problems with late contractor arrival, lightning strikes, power outages, faulty geophone. Experiment terminated early.
122A	5/10/76	Continuation of Expt. 122; pumped into EE-1 at flow rates from 795 liter/min (210 gpm) to 80 liter/min (21 gpm) with GT-2 vented.	Total injection: 156 600 liter (41 380 gal). Pressure rise in GT-2 leveled at 76 bar (1102 psi) for 1 h; repeated and confirmed Expt. 117.

<u>Experiment No.</u>	<u>Date Executed</u>	<u>Experiment Description</u>	<u>Remarks</u>
125	6/2/76	Measure values of $A \sqrt{k}$ for EE-1, GT-2, and combined system. Pump 160 liter/min (43 gpm) into each hole separately and simultaneously; measure pressure response.	Total injection: 14 650 liter (3870 gal). $A \sqrt{k}$ value for GT-2 and EE-1 remained essentially unchanged. During combined flow into both holes, 60% went into EE-1, 40% into GT-2.
126	5/27/76	Assess performance and characteristics of mechanical seismic source (wallbanger).	Acoustic signals obtained at all tested depths in EE-1.
127	6/16,17/76	Ranging experiment to determine depths to specific horizons in each hole, and to calculate relative positions of the two holes.	Equivalent horizons between the two holes determined within ± 1 m (3 ft); preliminary value of minimum GT-2/EE-1 hole spacing at -200 m (-650 ft) sea level elevation is about 14 m (46 ft).
129A	6/22,23,24/76	Obtain additional micro-seismic data for further mapping of EE-1 fracture. Pump into EE-1, with geophone package and Sperry-Sun orienting device in GT-2.	Two failures of the armature springs in the locking arm motor occurred, but a sufficient number of acoustic signals for mapping the EE-1 fracture were obtained.
129B	6/29/76	Continuation of Expt. 129.	Additional signals were observed during inflation of the EE-1 fracture; no equipment problems. Total injection: 190 500 liter (50 320 gal).
131	6/7-13/76	Calibrate lengths of logging cables on GT-2 and EE-1 cable hoists.	Cables now marked to determine precise depths ± 0.6 m (2 ft) in each hole.

APPENDIX B
LITHOLOGIC LOG OF GT-2

APPENDIX C
DETAILED DRAWINGS OF DOWNHOLE EQUIPMENT

MAT'L = STEEL TUBING
2 1/2 O.D. x .500 WALL
BREAK SHARP EDGES 1/32 x 45°

MAT'L = STEEL
BREAK SHARP EDGES 1/32 x 45°

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54

EL 4340
16-304)

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FABRICATION & ASSY STEPS :

1. MACHINE PARTS 301, 401, 402, 403, AND 404.
301, 502, AND 503
2. ASSEMBLE 401 AND 403 THEN WELD.
3. ASSEMBLE AND WELD 402 AND 401.
(MUST BE VACUUM TIGHT)
4. SILVER PLATE OUTER SURFACE OF 401 & 402.
5. SILVER PLATE INNER SURFACE OF 301.
6. INSPECT PLATING.
7. INSERT INNER CAN ASSY IN OUTER SHELL. (301)
 - a. GUIDE PIN 502 MUST BE IN PLACE.
 - b. WELD UPPER JOINT. (MUST BE VACUUM TIGHT)
(DO NOT REMOVE GUIDE PIN 502)
8. INSTALL SETSCREW PINS #404. 4 REQ'D.
 - a. SCREW IN UNTILL TOUCHING 401 THEN TIGHTEN 1/8 TURN.
 - b. WELD OVER SETSCREW
(MUST WITHSTAND 10,000 PSI EXTERNAL PRESSURE)
9. a. REMOVE GUIDE PIN 502.
b. WELD VACUUM FLANGE W/RING IN PLACE.

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Los Alamos, New Mexico 87545

TOLERANCES UNLESS OTHERWISE NOTED FRACTIONS DECIMALS ANGLES .0005 .0005 .0005			
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APPENDIX D

AIR-COOLED HEAT EXCHANGER DESIGN DETAILS

Air-cooled heat exchangers were selected for the energy extraction system because of the lack of water at the Fenton Hill site and for simplicity of heat disposal at the surface. The coolers chosen force air upward through rows of finned tubing. Each tube is 2.5-cm i.d. (1 in.) with 0.32-cm-thick (0.125-in.) walls, and the fins are aluminum. Two fans, each rated at 24 kW (30 hp) and 220 m³ (142 000 cfm) air volume are mounted in each module of two tube bundles. Motorized exit louvers and manually adjustable-pitch fans provide air flow control. The tubes in each bundle are arranged in twelve passes in six rows and are roll-sealed into welded box headers at each end. Each tube is accessible for inspection and cleaning of the water side through individual header plugs. Each bundle can be isolated from the flowing system by valving. This feature allows for cleaning or repairing while continuing the experiment.

Detailed analysis was made to determine the stress level of the heat exchanger tubes during operation. Results showed that the stress level in the tubes of the first hot pass far exceeded that specified in the American Society of Mechanical Engineers pressure vessel code. Additional stress calculations made at LASL led to a minor design modification that will reduce the stress level within the tube bundle to within specified limits.

Figures D-1 through D-4 provide views of the heat exchanger components during assembly and Fig. D-5 shows an assembled module. The manufacturer of the modules was Yuba Heat Transfer Corporation, Tulsa, Oklahoma.

Fig. D-1. Moving a finned tube from the basket to assembly into the headers to form the tube bundle. Tube supports/spacers are installed as last step in finning operation.

Fig. D-2. Placing tube into headers.

Fig. D-3. Two tube bundles in the left background are under hydrostatic test; tubes are partially installed in foreground unit.

Fig. D-4. Tube-to-tube sheet joint is accomplished by rolling (expanding) tube end into grooved hole in tube sheet. The expanding roller is torque-controlled to assure desired seal.

Fig. D-5. Assembled module, showing two tube bundles and fan housings, on trailer for shipment. Unit is 3.6 m (12 ft) wide by 11.3 m (37 ft) long and will mount on 2.1-m (7-ft) columns for total height of about 4.9 m (16 ft). (Trailer load was 4.4 m (14 ft 6 in.) high).

APPENDIX E
PUBLICATIONS AND PRESENTATIONS

Publications

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GLOSSARY

- annular space - the space around a pipe suspended in a borehole; the outer wall may be either open hole or casing.
- borehole televiewer log - maps fractures by use of a sonar-type system.
- blowout preventer - a device attached above the casing that can be closed to shut off the hole if a blowout occurs.
- borehole - the drilled hole or wellbore.
- caliper log - a test to determine the diameter of the wellbore or internal diameter of the casing drill pipe, or tubing.
- Christmas tree - the assembly of valves, pipes, and fittings used to control the flow from the casing head.
- competent rock - area of low-permeability rock. (If fractures are present they are sealed.)
- density log - gives an indication of the lithology and the elastic constants (mafic rocks are more dense than silicic rocks); confirms low-potassium (mafic rock) and high-potassium (silicic rock) interpretations. Low-density zones may reflect fracture zones that generally correlate with a distinctive low-velocity signature on the full-wave sonic log.
- doglegs - sharp changes of direction or elbows in the wellbore.
- dry hole - any well that does not produce commercial quantities.
- electric-resistivity log - a test used to confirm zones that are interpreted as fracture zones on the caliper or full-wave sonic logs.
- fishing - operation of retrieving items from the hole.
- full-wave sonic log - a test that estimates rock competency by recording the velocity of sound waves through the rock.
- geophone - a seismic detector that is located on or in the ground (trade name).
- hole - the wellbore or borehole.

hot leg	- the wellbore that returns hot water or other fluid to the surface for energy extraction.
impression packer	- a rubber device that expands to obtain an impression of the wellbore.
inclinometer	- an instrument used to determine if the wellbore is proceeding in a vertical orientation at any point (trade name).
Kelly	- the heavy square or hexagonal steel pipe that goes through the rotary table and turns the drill string.
liner	- any string of casing below the surface.
log	- the processing of recording information about the borehole by various means.
mouse or rat holes	- shallow bores in which the Kelly joint and joints of drill pipe are temporarily suspended while making a connection; rat hole also refers to a hole of reduced size in the bottom of a wellbore.
near-bit reamer	- a reaming device that fits just above the drill bit.
neutron activation log	- a test used to determine the general composition of rocks for geochemical processes and hydraulic fracturing operations.
packer	- a device lowered into the wellbore that expands to produce a watertight joint against the casing or borehole.
reaming	- the process of enlarging a borehole.
rotary table	- the geared rotating table that propels the Kelly and drill stem.
slim hole	- generally an exploratory hole less than 4 in. in diameter.
spectral gamma log	- measures the potassium, uranium, and thorium radioactivity, as well as the total level of radioactivity emitted by crystalline rock.
spinner survey	- a test to determine positions where fluid leaves or enters a wellbore by measuring flow velocities.
straddle packer	- an assembly used to isolate sections of a wellbore, usually for drill-stem testing or hydraulic fracture.
sonde	- a cylindrical downhole container and the measurement instrumentation within.

sub

- a short threaded adapter used to connect parts of the drill string that cannot be screwed together because of differences in size or design.

TD

- terminal depth.

trip

- hoisting the drill pipe out of a borehole or running it back into the hole.