HOT DRY ROCK GEOHERMAL ENERGY DEVELOPMENT PROJECT

ANNUAL REPORT FISCAL YEAR 1977

LASL HDR Project Staff

MASTER

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scientific laboratory**

of the University of California

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HOT DRY ROCK
GEOTHERMAL ENERGY
DEVELOPMENT PROJECT
ANNUAL REPORT
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by

LASL HDR Project Staff

ABSTRACT

The Los Alamos Scientific Laboratory has been investigating the feasibility of extracting geothermal energy from hot dry rock in the earth's crust. The concept being investigated involves drilling a deep hole, creating an artificial geothermal reservoir at the bottom of the hole by hydraulic fracturing, and then intersecting the fracture with a second borehole. At the beginning of FY77, the downhole system was complete, but the impedance to the flow of fluid was too high to proceed confidently with the planned energy extraction demonstration. Therefore, in FY77 work focused on an intensive investigation of the characteristics of the downhole system and on the development of the necessary tools and techniques for understanding and improving it.

This report covers results of Project work for the period July 1976 through September 1977.

EXECUTIVE SUMMARY (R. B. Duffield, Project Mgr.)

The Hot Dry Rock (HDR) geothermal energy extraction concept being investigated at the Los Alamos Scientific Laboratory (LASL) requires that a borehole be drilled into low-permeability, hot crystalline rock and that a large hydraulic fractured area be produced from the bottom of this borehole. A second borehole is then directionally drilled along a trajectory to intersect this fractured region. Pressurized water is pumped down one wellbore, circulated through the fractured area to recover heat from the rock, and returned through the second wellbore to the surface, where energy can be extracted by heat exchangers for generating electricity or direct heat applications.

The period covered by this report includes FY76TQ (July, August, and September, 1976) and FY77. During FY77 the HDR Project conducted a field test at the Fenton Hill, New Mexico site that demonstrated the principal features of this geothermal energy-extraction concept.

At the beginning of FY77, the status of the field work at Fenton Hill was as follows. The first borehole, GT-2, had been drilled to a depth of 2932 m (9619 ft) and a large hydraulic fracture had been produced near the bottom. The rock temperature of the fracture was about 200°C. The second borehole, EE-1, had been drilled nearby with the intent of intersecting the GT-2 fracture to form a system through which fluid could be circulated to extract heat. The desired low-impedance intersection was not made, primarily because the techniques and instrumentation available at that time did not give the accuracy required to determine the positions and orientations of one borehole with respect to the other, or of the target fracture with respect to the borehole being drilled. An attempt to fracture from the bottom of EE-1 did produce a large fracture and reduced the impedance considerably but did not result in a direct connection with the GT-2 fracture.

Experimental data strongly suggested that there were at least two major fractures at depth, one produced from each borehole, and that these fractures were parallel to one another and separated by a 9-m (30-ft)-thick section of granite. This overlapped, parallel fracture geometry permitted water to flow from one borehole to the other, but with an impedance to flow that was too high to allow a meaningful heat-extraction experiment to be performed.

In an attempt to produce the desired low-impedance heat transfer system, the following plan for FY77 was adopted:

1. Attempt to reduce the impedance of the existing system by a chemical leaching treatment. The leachant to be used was sodium carbonate solution, the object being to dissolve quartz from the formation in such a manner as to lower the resistance to flow. Success with this treatment would allow performance of the heat transfer experiment.

2. If the chemical treatment did not succeed, an attempt would be made to redrill from one of the two holes in the proper direction to make the desired, direct connection with the fracture at the bottom of the other borehole. Success in this attempt would allow loop operation to proceed.

This plan was followed in FY77. In November 1976, a sodium carbonate treatment was performed. A considerable amount of quartz was dissolved, but no reduction of impedance resulted. The major fraction of quartz dissolution was apparently localized to a relatively shallow penetration depth into the granite. Consequently, further chemical treatment would require an unacceptably large amount of carbonate solution.

Preparations were immediately begun to redrill. It was decided to redrill from GT-2 to intersect the fracture known to connect with EE-1 at 2758 m (9050 ft). While the contracts for drilling were being arranged, effort was intensified to develop and improve techniques for borehole and fracture mapping. If redrilling was to succeed, it was absolutely necessary that the drilling trajectory be established on the basis of accurate downhole mapping. By March 1977, considerable progress had been made in development and improvement of the necessary techniques. A series of acoustic, electrical, and flow experiments performed at Fenton Hill provided the basis for the redrilling program and enabled the trajectory of the new hole to be established.

Under contract, a commercial drilling rig (Noble Drilling Co.) was moved to the site and drilling began on April 6, 1977. By drilling along the planned trajectory (GT-2A) the target fracture was intersected at 2635 m (8645 ft) on May 5, 1977. The intersection was detected by pressurization of the target fracture. The point of intersection was directly above the EE-1 borehole-to-fracture connection. Flow experiments, however, soon indicated that the flow impedance of this new connection, though far lower than that of the previous connection, was not low enough to be satisfactory for a 10-MW heat-extraction experiment. This borehole, GT-2A, was cemented off and the hole was redrilled along a lower trajectory (GT-2B).

Intersection of GT-2B with the EE-1 fracture system was detected on May 28, 1977 at 2670 m (8760 ft). Flow testing demonstrated that the impedance was acceptable (~ 10 bar-s/liter or 10 psi/gpm) although a still lower value would have been desirable. The borehole GT-2B was cased to the surface and the rig released on July 7, 1977.

The necessary work to install the components of the surface plant of the energy-extraction loop had been in progress and the system approached completion in September 1977. By using some temporary components, such as circulation pumps, it was possible to begin operation in September. During a 96-h run the extracted power reached 3.2 MW(thermal) and the surface fluid temperature reached 130°C. This test demonstrated for the first time that heat could be extracted from hot dry rock at depth and transported to the surface by a manmade system. The rate of water loss decreased continuously during the run, reaching 1.25 liters/s (~ 20 gpm) after 96 h; indications are that the steady-state loss rate will be less than 0.6 liters/s (10 gpm). No induced seismicity was observed during the test. The fluid geochemistry was also encouraging, with total dissolved solids levels at about 400 ppm for the recirculated water.

The scientific and technical work performed during this period is covered in this report under the task categories of: HDR resource assessment and site selection, instrumentation and equipment development, drilling and fracturing, reservoir engineering, energy extraction system, and environmental studies. Highlights of the accomplishments under each of these task areas were as follows:

HDR Resource Assessment and Site Selection

- A report prepared by the Hot Dry Rock Assessment Panel (HDRAP) was published.
- A report characterizing the petrology and geochemistry of the Fenton Hill reservoir was published.
- A summary report on exploration methods for HDR resources was published.

Instrumentation and Equipment Development

- Improvements were made to the mechanical design of the detonator-geophone package that was developed earlier for acoustic borehole ranging and orientation measurements. Results of tests using these instruments played a vital role in establishing the redrilling plans.
- Several new or improved instruments were developed by LASL and used at Fenton Hill, for example,

High-temperature borehole fluid sampler
High-temperature downhole fluid injector
High-temperature cable-head assembly

Thermopile probe for temperature logging
Vacuum-insulated enclosure to protect downhole electronics from hostile borehole environment. (The vessel was fabricated by Mechanics Research Inc.)

- Improved heat-shielded gyrosurvey tools were developed and used successfully at Fenton Hill. (Eastman Whipstock and Sperry-Sun performed this work under service contracts with LASL.)
- A high-temperature acoustic test and calibration facility was designed and fabricated by M/RAD Corp. under contract to LASL. It will test instruments from 5 Hz to 9 kHz at temperatures to 275°C.
- An instrument sonde test stand has been designed and partially fabricated to check out subassemblies and downhole sondes under simulated downhole conditions.

Drilling and Fracturing

- Redrilling of GT-2 was accomplished successfully.
- In the GT-2 redrilling, some experience was gained in sidetracking a hole in granite.
- A high-temperature open-hole packer was developed by Lynes United Services for LASL and performed well downhole at a temperature of 180°C.

Reservoir Engineering

- A technique (and associated instrumentation) was developed to measure by acoustic means the distance between two boreholes and to determine the directional orientation of one borehole with respect to another. This technique was used successfully several times at downhole temperatures to 200°C.
- A technique was developed to observe the attenuation of the shear component of acoustic waves passing through an inflated fluid-filled fracture. This technique was useful in planning the redrilling operation.
- Investigation of the microseismic signals generated during the inflation of a fracture continued. It was possible to establish the locus of the source of the signals. This information was used in planning the redrilling operation.
- A technique was developed to measure the residence-time distribution of fluid in a downhole reservoir by injection of a dye tracer (sodium-fluorescein). By this technique, a volume and a residence-time distribution were measured for the Fenton Hill fracture system.
- The chemical interaction of water and sodium carbonate solutions with hot granite was examined in detail to assist in planning and interpreting the chemical leaching experiment and to anticipate geochemical effects from the Fenton Hill loop operation.
- A reservoir model was developed to describe the flow of fluid into the reservoir with pressure-dependent formation permeability and porosity.
- Methods of interpreting geophysical logs taken in the Fenton Hill wellbores were refined to describe a geometric fracture-wellbore model of the redrilled GT-2B/EE-1 system.

Energy Extraction System

- The surface plant for the 10-MW(t) energy extraction system at Fenton Hill was completed by using some components that will not be part of the permanent system. The system performed satisfactorily during the 96-h run in September 1977.
- Procurement and other steps were taken to complete the loop in final form in preparation for sustained operation during FY78.

Environmental Studies

- No events related to HDR Project activities have been detected by the seismic network.
- A technique to reduce the fluoride concentration of the geothermal fluid by using activated alumina was laboratory and field tested.
- Base-line data on weather and biology at the Fenton Hill site are being collected. To date no adverse environmental impact has resulted from HDR Project activities.

It is significant that the redrilling of GT-2 resulted in a system with characteristics that will allow sustained operation of a heat-extraction loop at Fenton Hill. In the development of energy extraction methods for HDR reservoirs, however, work must continue on techniques and instrumentation that can be used to produce larger, more efficient HDR systems. This includes:

- The ability to map, from one borehole, a fracture produced near the bottom of that borehole.
- Improved accuracy in directional drilling in hot formations.
- A better understanding of the downhole flow impedance and how it can be reduced.
- Development of better and more reliable instrumentation for use in hot boreholes.
- A better understanding of how large fractures are formed in crystalline rock in response to hydraulic pressure exerted from boreholes.

In addition, it is imperative that assessment of other potential sites be accelerated in preparation for the creation of new HDR reservoirs and the construction of energy extraction systems. A major effort on work in these areas is planned for FY78 and beyond.

1. INTRODUCTION AND HISTORY (G. J. Nunz, Alternate Project Mgr.)

1.1. Background

With the exhaustion of fossil energy sources already all too clearly in sight, the nation's need to develop its nonfossil energy resources has become increasingly critical. Prominent among these alternative energy sources are the enormous subterranean reservoirs of geothermal energy, which offer the promise of "clean" and virtually inexhaustible power (Fig. 1-1) at competitive price. The overwhelming contributor to the geothermal resource base of the US is the geographically distributed hot dry rock (HDR), whose heat content, to a depth of 10 km, is estimated to be about 32 million quads.* Approximately 40% of this - about 13 million quads - occurs at temperatures greater than 150°C. If it is assumed that 2% of the supra-150°C resource base can be economically exploited, then at the present annual rate of energy consumption in the US, this resource could potentially supply the nation's nontransportation energy needs for more than 2200 yr. Development for nonelectric utilization of that portion of the resource base whose temperatures are below 150°C would also significantly impact the nation's energy economy.

Given this realization, the Los Alamos Scientific Laboratory (LASL) has focused its effort in the geothermal energy field on the as yet unexploited hot dry rock segment of the geothermal resource base. Although the characterization and extraction technologies for HDR reservoirs require more development than for hydrothermal and, perhaps, than for geopressured reservoirs, it is LASL's contention that commercial power from hot dry rock is much nearer realization than is generally believed and that the payoff from its present ongoing HDR Project can be substantial in the mid-term time frame.

1.2. Synopsis of the Project Pre-FY77

The LASL Hot Dry Rock Geothermal Energy Development (HDR) Project began in 1970 with the concept (subsequently patented by the Atomic Energy Commission) of a hot dry rock energy extraction system. This system is based on the use of hydraulic fracturing to produce the connected subterranean flow passages and large heat-transfer surface required for prolonged extraction of

* 1 quad of energy = 1 quadrillion (10^{15}) Btu = 334 megawatt-centuries.

Fig. 1-1.
Comparison of resource bases (note logarithmic scale).

heat at a usefully high rate from deeply buried hot rock. In FY71, under U.S. Atomic Energy Commission (AEC) sponsorship, evaluations were conducted of the state of knowledge in the areas of geology, geophysics, and geochemistry related to dry rock geothermal reservoirs, and of the state of the art in drilling, hydraulic fracturing, and other techniques associated with the development and exploitation of this resource.

In FY72, geologic, geophysical, and hydrologic measurements were taken in preparation for selecting a site. A locale on the Jemez Plateau, a geothermally interesting area of comparatively recent vulcanism west of Los Alamos, New Mexico, was ultimately chosen and a 785-m (2575-ft) -deep exploratory hole (GT-1) drilled there. Through FY73, the Project conducted a protracted series of pressurization and depressurization experiments on downhole hydraulically produced fractures to measure rock surface fracture energies, compressive stresses, and permeabilities. These results were encouraging with regard to the existence of a suitable hot dry rock resource, the probability of successful drilling and hydraulic fracturing operations, and the probability of

subsequently establishing a suitable pressurized-water circulation loop without excessive loss of the heat transport fluid. It was deemed necessary, however, to confirm these observations at another location and to make similar measurements at greater depths and under conditions of higher temperature and pressure.

In late FY74, drilling began on a second borehole (GT-2), at a location about 24 km (1.5 mi) south of the exploratory hole (GT-1). Borehole GT-2 was completed during the first half of FY75, to a total depth of 2928 m (9607 ft). The temperature at the bottom of the hole was measured to be 197°C. Tests made before completion of the drilling determined that the permeability of the granitic basement rock was extremely low. Hydraulic fractures were produced, the largest of which had a calculated radius of about 215 m (700 ft). When this fracture was inflated with water and then deflated, almost 90% of the injected water was returned, confirming the competence of the basement rock. Further encouragement, derived from a series of reservoir engineering tests, led to the decision to proceed with the drilling of a second operational borehole and the subsequent establishment of a circulation system connecting GT-2 and this new borehole.

Late in FY75 - with Project sponsorship transferred to the Energy Research and Development Administration (ERDA), Division of Geothermal Energy (DGE) - Drilling of the third borehole (EE-1) began. Hydraulic fractures were created near the bottom of GT-2 and borehole EE-1 was directionally drilled in an attempt to intersect a GT-2 target fracture. EE-1 was completed in the first part of FY76. A flow connection between the two holes was indeed established through the subterranean system in the 2745- to 3050-m (9000- to 10 000-ft) -depth range; however, the impedance to fluid flow through this system was found to be far too great to permit a sustained water circulation rate high enough for a convincing energy extraction demonstration. It was therefore decided to proceed in FY77, with an intensive investigation of the character of the downhole system and with the concomitant development of the necessary tools and techniques for understanding and improving it.

1.3. Objectives and Plans for FY77

Failure to achieve the expected low-impedance subterranean connection in FY76 was the primary motivation in shaping the FY77 planning. It was recognized that the major part of the problem lay in the lack of understanding of the downhole geometry - both that of the wellbores themselves and that of the fractures hydraulically produced therefrom in the contiguous rock. LASL therefore resolved

to mount a multifaceted attack on the reservoir geometry problem in FY77. The specific objectives for the year were

- (a) to study, by a variety of approaches, the reservoir geometry;
- (b) given the attainment of an adequate understanding from the results of (a), to take necessary remedial steps to improve the connection; and
- (c) assuming reasonable success in (b), to complete the installation of surface equipment and proceed with the activation of an energy extraction loop.

In consonance with objective (a), attention was to be turned first to the wellbore geometry. Statistical analysis of wellbore survey errors, which used the nominal stepwise accuracies, predicted that such surveys should have overall accuracies of a few meters at 3-km depth. In these cased holes, however, where only gyrocompass-type survey instruments can be used, the temperatures at depth (2.4 km) exceeded the capability of the instrumentation then commercially available and resulted in much larger errors. A redundant approach was planned to maximize the probability of being able to define accurately the wellbore positions in a timely manner: (1) contracts to industry to perform more accurate surveys by upgrading the temperature capability of their existing instruments, and (2) LASL-internal development of acoustic- and magnetic-ranging techniques. It was also recognized that the tools being developed for acoustic ranging were potentially adaptable to fracture mapping as well, based upon the shear-wave attenuation property of a liquid-filled fracture. Hence, such "shear-shadowing" experiments were planned and conducted.

Success achieved in these endeavors (see Sec. 5.) permitted progression to objective (b), remedial work. The first approach to reducing the interwellbore impedance was chemical attack on the silica content of the intervening rock. A leaching experiment was conducted, but was unsuccessful. As the reservoir geometry became better understood through a series of experiments, the need for redrilling was manifest. A comprehensive workover redrilling program was planned and executed to the limit of available funds, resulting in a usable, albeit not optimal, downhole connection (see Sec. 4.).

Work subsequently proceeded toward objective (c), culminating in activation of the loop near the end of the fiscal year (see Sec. 6.). The time-sequencing of the year's major activities, formatted to the stated objectives, is shown in Fig. 1-2.

REFERENCE

1. D. F. White and D. L. Williams, Eds., "Assessment of Geothermal Resources of the United States-1975," Geological Survey Circular 726 (1975).

Fig. 1-2.
Time-sequencing of major Project activities in FY77.

2. HOT DRY ROCK RESOURCE ASSESSMENT AND SITE SELECTION (B. M. Crowe; A. C. Eddy; J. Eichelberger, D. T. Gambill; G. Heiken; P. R. Kintzinger; A. W. Laughlin, Task Mgr.; G. W. Linn; M. C. Smith; J. W. Tester; F. G. West)

2.1. Introduction

Before we can fully develop and use the energy stored in hot dry rocks, techniques must be developed for locating the thermal reservoirs and for extracting the energy. In addition, reliable, quantitative estimates of the magnitude of the useful resource base must be made, for without them potential users may question the longevity of this energy source. During FY76A and FY77 considerable effort was expended on these tasks.

Within LASL's Geosciences Division, major efforts were directed toward the preparation of the first report of the Hot Dry Rock Assessment Panel (HDRAP).¹ This report summarizes the criteria used for the selection of the Fenton Hill, Marysville, and Coso sites as case history studies, and reviews the present state of geologic knowledge at each of these sites. It examines the available exploration and assessment techniques, as well as the rationale for HDR resource base assessment, and also recommends several other regions that appear to have high potential as HDR sites.

A workshop on "Exploration Methods for Hot Dry Rock" was held at LASL in June 1976, funded by the ERDA Division of Physical Research. The panel report,² which examined the geophysical and geological methods that could be used to locate large- and small-scale target areas, is directly applicable to the Hot Dry Rock Geothermal Energy Development Program.

Within the area of resource assessment, primary attention was given to the Fenton Hill site. The existing program to characterize this site was expanded, drawing upon additional non-DGE funding. The objective of this program is the development of a model of the total geothermal system within the Jemez Mountains, relating the Fenton Hill HDR site to the hydrothermal system under development by Union Oil on the Baca Location. In addition, a reevaluation of the United States Geological Survey (USGS) estimate³ of the magnitude of the total HDR resource base was begun in FY77 and will continue into FY78.

2.2. Site Selection

2.2.1. Hot Dry Rock Assessment Panel (HDRAP)

During the summer of 1975, the Hot Dry Rock Assessment Panel was organized by ERDA-DGE to assist the Division in coordinating HDR activities such as collecting and analyzing technical information, contributing to the

development of a reservoir characterization rationale, assisting in site location, and reviewing plans, programs, and reports on assessment and exploration. Panel membership included representatives from DGE, USGS, ERDA National Laboratories, and the academic community. Three members of the LASL Geosciences Division served on the Panel during the past year.

The major product of the Panel in FY77 was the first HDRAP Report;¹ LASL contributed significantly in its preparation and editing. The objectives of the report were to:

- (1) Define what is meant by hot dry rock, the HDR geothermal resource base, and some related terminology.

- (2) Describe and summarize the present status of HDR exploration and evaluation, including summaries of sites explored to date.

- (3) Review the techniques and criteria that may be used in exploring for specific HDR systems.

- (4) Describe the exploration status and the characteristics of known sites that have been explored for HDR in terms of their physical properties.

- (5) Recommend directions for future research to improve the knowledge of the magnitude of the US HDR geothermal resource base.

- (6) Recommend a rational approach for selection of future US HDR regional sites.

- (7) Recommend a list of potential HDR regional geothermal sites based on available data.

Included in the report are summaries of the geology at the Fenton Hill, New Mexico; Marysville, Montana; and Coso, California, sites and the rationales used to select these sites. None of these sites was chosen primarily for resource assessment. LASL selected the Fenton Hill site to test a particular energy extraction technique; the Marysville site was chosen to test a blind thermal anomaly that exhibited extremely high heat flows; and the Coso site was selected to evaluate slim-hole drilling as an HDR exploration tool. Consequently, the Panel spent considerable time examining rationales for future HDR resource assessment. A plan recommended by the Panel entails locating a geothermal system by using a variety of geological, geophysical, and geochemical techniques and then eliminating that portion of the system that might be expected to be dominated by hydrothermal fluids. The remainder of the system would then have potential for HDR.

The report includes descriptions of four areas recommended by the Panel as prime future HDR sites: Long Valley, California; San Francisco Peaks, Arizona; Medicine Lake Highland, California; and Mt. Shasta, California. Because of the large amount of work performed by the USGS, the Mono/Long Valley known geothermal resource area (KGRA) was ranked number one for future assessment. Short descriptions were presented of 12 other areas that appear to be likely candidate sites.

2.2.2. HDR Exploration Workshop

The report² of a panel meeting on exploration methods for hot dry rock, held in Los Alamos on June 22, 1976, was also issued this year. The meeting was funded by the ERDA Division of Physical Research.

The panel consensus was that patterns of geologic conditions and geophysical parameters could be used to characterize areas of hot dry rock. Possibly hot dry rock can be located by using one element of the pattern, though the probability for success, of course, will be enhanced by using a complete suite of available methods. Hot dry rock lies near one end of a range of geothermal possibilities; at the other end are fluid-dominated, high-temperature systems, and both have particular patterns of characteristics.

Of the geophysical methods considered by the panel, geoelectromagnetic methods such as magnetotellurics show the most promise and versatility. The large range--up to 6 orders of magnitude--in electrical conductivity allows for a more unique delineation of geologic environments, especially at great depth. Because the electrical conductivities of fluids and rocks are partially dependent on temperature, a spatial mapping of the deep isotherms is feasible. Various parameters affecting the transmission of seismic waves have likewise been shown to be temperature dependent, thus allowing another mapping of isotherms. The new Aiken method⁴ of making Bouguer gravity corrections will provide a means of mapping the distribution of rock types in the crust that may have a high radiogenic heat generation and high thermal conductivity. The correlation of heat flow and emplacement of silicic and mafic rocks has been noted in various areas. The coincidence of various geophysical anomalies in areas of thermal enhancement is further evidence of the deep-seated nature of the thermal source.

Exploration strategies begin at a reconnaissance scale of about 1000 km, proceed to an exploration scale of about 100 km, and to a 10-km site-selection scale. The intent is to select a site in an area that demonstrates evidence for regional thermal enhancement and yet is not a "wet" system.

The panel strongly recommended a field application of the geological and geophysical methods to evaluate their potential in hot dry rock exploration.

2.2.3. Possibility of Satisfying a Portion of LASL's Energy Requirements with Geothermal Energy

During 1977, ERDA Headquarters directed the National Laboratories to convert from natural gas to some alternate energy source. In response to this directive, an informal committee was established at LASL to determine which of the alternative energy sources, or combinations thereof, would optimally replace LASL's natural gas usage. The committee's charter includes detailed investigation of the possibility of satisfying some portion of the Laboratory's energy requirement with geothermal energy. Both hydrothermal and HDR systems are being considered.

The existence of regional and local geothermal heat sources has been well documented for the Los Alamos area. Reiter et al.⁵ and Decker and Smithson⁶ have shown that the Rio Grande Rift is a zone of abnormally high heat flow. Superimposed on this regional high is a local heat source associated with formation of the Valles Caldera. LASL and Union Oil have demonstrated the existence of geothermal systems reasonably close to the Laboratory.

With a nearby heat source proven, the next step is to evaluate the geology of the area to determine if thermal energy has been transported to a site beneath the Laboratory and, if so, whether it can be extracted economically.

The Pajarito fault zone is the major structural feature exposed at the surface in the area. However, from new gravity data, a graben, which trends NE-SW beneath the middle of the Pajarito Plateau (Fig. 2-1), is hypothesized. The gravity low by which the graben was detected corresponds very closely with a magnetic low.

Seismic data for the area are available only for three shallow reflection lines. The deepest penetration of these three lines was 460 m (1500 ft). Recent and historic seismic data suggest a maximum probable 100-yr event of magnitude 5.5 for the Los Alamos vicinity.

Geothermal gradient data for this area are available for only one shallow well, DT-5A on Frijoles Mesa, which showed a gradient of 23.1°C/km. More limited temperature data are available for 22 wells in or near the area of interest.

The aquifer in the Santa Fe Group is 335 m (1100 ft) below the surface of the western edge of the Pajarito Plateau. The aquifer is recharged in the Jemez Mountains and flows east to the Rio Grande River. Another, deeper aquifer may

Fig. 2-1.

Geologic cross section and gravity and magnetic profiles along a NW-SE line across LASL technical areas.

be present in the Magdalena Group. The cavernous and, hence, permeable nature of this unit was demonstrated at the Fenton Hill site.

In a discussion by the committee of the compiled data, a suggestion was made that Los Alamos Canyon may be a surface expression of a fault terminating the north end of the proposed graben. This fault could serve as a conduit for the transport of thermal water away from the caldera. Magnetotelluric and seismic studies to determine the existence of the fault and the graben were proposed. The final proposal made was to drill a 3050-m (10 000-ft) well into basement rock at a prime location to derive more geologic data related to heat flow and hydrology.

2.3. Resource-Base Assessment

2.3.1. Magnitude of the HDR Resource Base

The most widely accepted source of information on the magnitude of the hydrothermal geothermal energy resource base of the United States is USGS Circular 726.³ Data from this publication are the basis of the estimates of the resource base and producible energy published in the ERDA "Definition Report"⁷ and subsequent ERDA documents. White and Williams³ consider the hot dry rock

resource base under two separate headings: "igneous-related geothermal systems," and systems based on "conductive transport of heat" from the earth's interior. The total resource base is, of course, the sum of the two.

The igneous-related hot dry rock resource base is estimated by White and Williams to be about 48 000 quads of heat in the "crystallized parts and hot margins" of the 48 best known volcanic systems in the US. They quadruple this estimate to about 190 000 quads to account for other systems not recognized or included in their tabulations. LASL's estimate of the heat content of the same igneous-related hot dry rock resource base is about 400 000 quads. This number includes the energy obtained by cooling the rock to 150°C and not the 300°C used by the USGS. This additional cooling would at least double the USGS estimate of 190 000 quads.

The USGS estimate of the total heat content of conductive systems not directly associated with volcanism is about 32 000 000 quads, in this case above a reference temperature of 15°C, and to a depth of 10 km. This total is the sum of the individual estimates of heat stored beneath the Sierra Nevada, Eastern, and Basin and Range Provinces of the conterminous 48 states, plus similar regions in Alaska and Hawaii.

Estimates of the hot dry rock resource base can also be made by use of a straightforward methodology to calculate the energy stored as heat in a specified volume of rock. In our estimates, the volume is defined by the geographic surface area of the US (including Alaska and Hawaii) to a depth of 10 km and only rock temperatures initially above 150°C are considered, with a reference temperature of 50°C defined as the minimum useful temperature. The total heat content Q can then be expressed as:

$$Q = \sum A_i \left[\int_{Z(T=150^\circ\text{C})}^{Z=10 \text{ km}} \rho C_p (\nabla T_i \cdot Z + T^* - 50) dZ \right], \quad (2-1)$$

where

Z = depth, km

T = rock temperature, °C

A_i = surface area having a characteristic regional gradient of ∇T_i

T^* = ambient surface crustal temperature $\approx 15^\circ\text{C}$

ρ = rock density, kg/m³

C_p = rock heat capacity, J/kg °C
 ∇T_i = geothermal temperature, °C/km.

A preliminary estimate for Q results if one assumes an average gradient $\overline{\nabla T}$ for the entire US land area ($9.36 \times 10^6 \text{ km}^2$ or $3.62 \times 10^6 \text{ mi}^2$) of 25°C/km , an average $\overline{C_p}$ of $772 \text{ J/kg}^\circ\text{C}$, and an average density $\overline{\rho}$ of 2500 kg/m^3 . Equation (2-1) then simplifies to

$$Q \text{ [in quads, } 10^{18} \text{ J (} 10^{15} \text{ BTU)]} = \overline{\rho} \overline{C_p} 10^{-9} \int_{5.4}^{10} (25Z-35) dZ \quad (2-2)$$

$$A = \sum A_i = 9.36 \times 10^6 \text{ km}^2.$$

With these more conservative assumptions as to the useful temperature range, the 32×10^6 -quad USGS estimate is reduced to

$$Q = 13 \times 10^6 \text{ quads.}$$

See Fig. 1-1 for a comparison of resource base estimates for several alternative energy sources. The magnitude of the hot dry rock resource base is sufficiently large to place it in the inexhaustible category with fusion and solar.

A more detailed quantitative approach to the distribution of gradients and rock properties across the US is being developed, which should provide an improved estimate of Q. In addition, the methodology for calculating the potentially useful fraction of the HDR resource base for electric and nonelectric applications is being reassessed. Results from this study will be reported later.

In "Scenario I," ERDA⁷ assumes an "extraction recovery" of 2% and a "conversion efficiency" of 8% for heat to electricity from hot dry rock energy systems. With these assumptions, the 13×10^6 -quad hot dry rock resource base calculated above represents 260,000 quads of producible heat and 7×10^6 megawatt-centuries of producible electrical energy. Estimates of any extraction recovery percentage are obviously preliminary and subject to change during evaluation and refinement of hot dry rock extraction technology.

2.3.2. Jemez Mountains Geothermal System

2.3.2.1. General Discussion. LASL and Union Oil have clearly demonstrated the existence of two types of geothermal systems within the Jemez Mountains: hot dry rock and liquid-dominated hydrothermal. The extreme youthfulness of igneous activity within this area makes it seem likely that a third type of system, magma, may also be present. As a result of this variety of

geothermal systems, the assessment program was expanded to characterize the heat sources and reservoir rocks of the total geothermal system within the Jemez Mountains.

Support for this work is not restricted to DOE-DGE, but is spread through several divisions because certain portions of the work satisfy dual requirements. Although most of the work reported here was accomplished in FY77, certain earlier portions not previously reported are also included.

2.3.2.2. Reconnaissance-Scale Geophysical Surveys

Gravity map of northern New Mexico. A residual Bouguer gravity anomaly map of northern New Mexico at a scale of 1:500 000 was made by Carlos Aiken et al.⁸ for LASL. In this map, shown in Fig. 2-2, residual Bouguer gravity anomaly values have been generated by the use of a regional elevation datum in which a local regional elevation, rather than sea level, is used for the reduction datum.

Comparison of the residual anomalies with other geophysical data such as seismic and heat-flow data, and geological information indicate possible correlations that suggest mantle and crustal temperature variations.

The residual map of northern New Mexico is more easily interpreted than the classic sea-level datum, Bouguer gravity anomaly maps. A prominent residual Bouguer gravity anomaly high 130 - 160 km wide extends from south of the map boundary into Colorado and apparently outlines the presence of high-density rocks along the Rio Grande Rift. Previously, the rift had not been well delineated by a distinct gravity anomaly.

The San Juan Basin and Zuni Uplift are also well delineated, by a gravity low and high, respectively, as are numerous other local structures. Regionally the area consists of a broad gravity low extending southwestward from the San Juan Basin, a high over

Fig. 2-2.
Residual Bouguer gravity anomaly map of northern New Mexico (Ref. 8).
Contour interval = 5 milligals.

the Rio Grande Rift intersecting with a northwest-trending high extending from 106° longitude, 36° latitude, into Colorado through 107° longitude, 37° 30' latitude. Los Alamos lies almost at the intersection of these anomalies.

Work is continuing on the analysis of gravity data for southern New Mexico. Possible correlations with other geophysical and geologic information are being examined in more detail in an effort to better determine the geothermal potential of the area.

Heat flow. The Fenton Hill site lies near the western margin of the Rio Grande Rift, a zone of high regional heat flow (Refs. 5 and 6) where measured heat-flow values exceed 2 HFU. Superimposed on this regional high is a local heat source associated with formation of the Valles Caldera. Potter⁹ and Reiter et al.¹⁰ measured high geothermal gradients in seven shallow holes around the periphery of the caldera. These holes, which penetrated to depths of 30 m, indicated that the heat flow was highest on the west side of the caldera. Because geothermal gradients in shallow drill holes are readily perturbed by the local hydrology, four additional holes were drilled to depths of 152 - 229 m. Holes A, B, and C, (Fig. 2-3) forming an arc 2.4 km outside the western caldera ring fault, indicated heat flows of 5.1 - 5.9 HFU, increasing to the north. A decrease in heat flow with radial distance from the caldera was shown by drill hole D, where the heat flow was 2.2 HFU, 6.4 km from the ring fault. This value is approximately equal to the average Rift value.

Even the deeper heat-flow holes, A, B, C, and D, were perturbed by the local hydrology and did not give reliable values for the conductive heat flow. In GT-1, the gradient in the Paleozoic sedimentary rocks was 129°C/km in contrast to 45°C/km in the Precambrian rocks. An abrupt change in gradient occurs in the lower Madera Limestone near the contact with the underlying Sandia Formation. Warm water moving outward from the ring fault through the permeable Madera Limestone is apparently disturbing the gradient in the overlying sedimentary and volcanic rocks. A similar effect was observed in GT-2.¹³

The relative effects of the Rift and the Valles Caldera upon the heat flow at Fenton Hill can be evaluated from data now available, by use of an expanded form of the reduced heat-flow equation of Birch, Roy, and Decker.¹⁴

The expanded equation is:

$$Q = Q^* + Ad + R + C_c + C_H,$$

where

- Q = measured heat flow
- Q^* = heat flow from lower crust and mantle
- A = heat generation in radioactive layer
- d = thickness of radioactive crustal layer
- R = heat-flow contribution from Rio Grande Rift
- C_C = conductive heat-flow contribution from Valles Caldera
- C_H = hydrologic heat-flow contribution from Valles Caldera.

If we assume that the Rio Grande Rift is comparable to the Basin and Range Province, Q^* is 1.4 HFU and d is 10 km (Ref. 15). For the Rift itself the C_C and C_H terms are equal to zero and Q is assumed to be ~ 2.2 HFU. This value of Q was taken from the measured heat-flow value in drill hole D, which also agrees with the results of Reiter et al.⁵ for the Rift. The value of Ad for the Rift is assumed to be 0.4 HFU, which is the product of d (10 km) and the value of A measured in the Precambrian rocks of Fenton Hill. With these estimates the term R is approximately equal to 0.4 HFU.

The term C_H for the Fenton Hill site can be estimated from the difference in heat-flow values between the Cenozoic and Paleozoic volcanic and sedimentary rocks and the Precambrian metamorphic and igneous rocks. Values in the shallower holes cluster around 5.5 HFU, whereas the calculated value in the Precambrian rocks is 3.7 HFU. The difference, 1.8 HFU, is due to hydrologic effects from the Valles Caldera heat source, that is, C_H .

The values for Q^* , Ad , C_H , and R can now be substituted into the expanded equation for the Fenton Hill site.

$$5.5 = Q^* + Ad + C_C + C_H + R$$

$$5.5 = C_C + 4.0$$

$$C_C = 1.5 \text{ HFU.}$$

Fig. 2-3.

Geologic map of the Fenton Hill site showing location of LASL deep drill holes GT-1 and GT-2 and heat-flow holes A, B, C, and D. Geology modified from Refs. 11 and 12.

Thus, it seems likely that the conductive and hydrologic contributions of the Valles Caldera are roughly equivalent. Their sum is the dominant factor in determining the heat flow of the Fenton Hill site.

2.3.2.3. Exploration-Scale Geophysical Surveys. Recent geophysical surveys in the Jemez Mountain area have included magnetotelluric resistivity depth probing by John Hermance of Brown University, deep resistivity (dipole-dipole and roving dipole) mapping done by George Jiracek of the University of New Mexico (UNM), and seismic reflection and refraction surveys.

Seismic reflection surveys. Results of the two reflection seismic surveys are shown and correlated in Fig. 2-4, which is a structure of the top of the Precambrian near Fenton Hill. It is interesting to note a northeast trend of major fracture patterns in the LASL geothermal area. This northeasterly trend was also indicated by resistivity lows mapped by G. Jiracek.¹⁶ The results of the reflection surveys are summarized in a forthcoming report titled "Seismic Survey of Barley Canyon in Jemez Mountains, New Mexico."¹⁷

Seismic refraction survey. In the fall of 1976, a large high-explosive shot was detonated at White Sands, New Mexico. With the cooperation of K. Aki of the Massachusetts Institute of Technology (MIT), and the permission of Union Oil and the landowner, P. Dunigan, four portable seismometers were placed in a north-south line across the Valles Caldera (Baca Location No. 1). The data are still being analyzed; however, seismic delays were observed at several stations, possibly indicative of a buried magma chamber.

Magnetotelluric survey. The variation of electrical conductivity with depth can be mapped by using the natural transients in the magnetic and telluric fields. This variation of conductivity at shallow depths is due primarily to variations in the water content of the rocks; at greater depths, however, where little water is normally present, the variation of conductivity is in response to the temperature of the rock. Thus, magnetotelluric surveys can possibly map the spatial variation of water content and temperature.

The field-work portion of the magnetotelluric survey by John Hermance was performed during the summer of 1977; data are being analyzed. Figure 2-5 shows the locations of the magnetotelluric stations. The work is being performed in cooperation with the USGS, which is funding a regional profile that includes the Fenton Hill site and Valles Caldera. The site-specific work funded by LASL will therefore be set in the regional context established by the USGS work.

Fig. 2-4.

Structure map of top of Precambrian near LASL geothermal project (scale 1:82025).

Electrical resistivity measurements. George Jiracek (University of New Mexico) has been actively involved for several years in measuring the electrical resistivity of crustal rocks near the Fenton Hill site. His resistivity stations are shown in Fig. 2-6. Results of this work are presented in Ref. 16. Jiracek's results show a northeasterly trend of resistivity lows, which may be related to the northeasterly trend of fault zones indicated by the reflection seismic surveys of the area.

Fig. 2-5.
Location map - geophysical surveys in Jemez Mountains (scale 1:631800).

Fig. 2-6.
Location map—reflection seismic surveys and University
of New Mexico resistivity survey (scale 1:82025).

2.3.2.4. Geologic Investigations

Basement xenoliths in Bandelier Tuff. The character of the crystalline basement is a critical factor in assessing the hot dry rock geothermal resource within a given region. However, in volcanic fields, where hot rock at shallow depth is most likely to occur, the basement is commonly concealed by thick accumulations of lava. For example, the basement under the Cascade Range is exposed only at its northern end. Only one small Precambrian horst occurs within the Jemez volcanic field. In such cases, xenoliths (foreign

rock fragments in lava) brought up by the volcanic eruptions can provide valuable samples of the basement reservoir before deep drilling.

A study of Precambrian (basement) xenoliths in the Bandelier Tuff, Jemez Mountains, was conducted to gain information about the basement under the Jemez Mountains, and to compare these samples with core from the GT-2 hole at Fenton Hill. The study was funded by the LASL New Research Initiatives Program. The tuff was chosen for study because it is rich in xenoliths and because it was erupted from vents near Fenton Hill. Sites where samples were collected for this study are shown in Fig. 2-7.

Despite the abundance of xenoliths in the tuff, basement xenoliths are rare. In the lower member of the tuff, 90% of the xenoliths are older volcanic rocks, 10% are Paleozoic sediments, and only trace amounts are Precambrian rocks. The large volume of xenolithic material in the lower member and the volume distribution of xenolith types requires substantial flaring of the vent near the surface (Fig. 2-8). Two lines of evidence support the view that the xenoliths were torn from vent and magma-chamber walls during the eruption: (1) in almost all cases there is marked disequilibrium between xenolith and host, and (2) xenoliths are scarce or absent from products of subsequent quiet eruptions of similar magma. Thus, the xenoliths are largely unmodified samples of the basement from the vicinity of the hot dry rock reservoir. In all, we found 22 Precambrian xenoliths, mostly from the lower member of the tuff. All of these xenoliths came from nonwelded zones of the tuff, so modification after eruption is most unlikely.

Although some Precambrian xenoliths are quite similar to the GT-2 core, others differ markedly in composition, deformation, and chemical alteration. Figure 2-9 compares the frequency distribution of compositions for xenoliths and core samples. Most of the core is granitic, consisting of > 80% quartz and feldspar. Xenoliths show a bimodal distribution, one peak corresponding to granitic composition and one at about 50% quartz plus feldspar, corresponding to a gabbroic composition. Hence, gabbros appear to be a much more important component of the crust in the vicinity of the magma chamber than near the surface.

Many of the Precambrian xenoliths exhibit severe deformation textures suggestive of shearing at relatively high but subsolidus temperatures. This is indicated by deformation and recrystallization of biotite, quartz, and feldspar, often grading into veins of these finely granulated minerals. Such textures may be produced in the basement near the rising magma body or by shearing along the incipient ring fracture zone before eruption. Similar textures were observed

Fig. 2-7.

Location map of Bandelier Tuff (shaded area) 12 sampling sites for study of Precambrian xenoliths.

Fig. 2-8.

Schematic radial cross section through the ring fracture zone, showing material (shaded) which must be removed from vent walls to account for the volume and distribution of xenolithic material in the Bandelier Tuff.

Fig. 2-9.

Frequency distribution of compositions (volume % quartz and feldspar) for basement xenoliths and GT-2 core samples.

within 10 m of a granite ring dike in northern New Hampshire, an eroded analogue of the Valles Caldera. In contrast, fracturing in the core samples appears more brittle, and fractures are more commonly sealed with deposits from fluids rather than locally derived granulated minerals.

Chemical alteration of primary phases in many of the Precambrian xenoliths is far more advanced and of a higher metamorphic grade than in the GT-2 core. Alteration is characterized by formation of biotite, aluminum-poor amphibole (actinolite), and other magnesium-iron silicates at the expense of hornblende. Biotite occurs as fine-grained masses; actinolite, augite, and epidote occur in veins and as ragged clots. A notable feature of the biotite and actinolite is their high fluorine content (Figs. 2-10 and -11). Alteration of hornblende to biotite requires addition of substantial amounts of K^+ , OH^- , and F^- . The potassium might be locally derived from alkali feldspar; however, OH^- and F^- were probably derived from the adjacent magma body. No major phases which could accept OH^- and F^- were present in the Bandelier Tuff magma except the melt, and solubility of H_2O and HF in the melt decreases with decreasing pressure. Its explosive eruption indicates that the magma reached a sufficiently shallow level to become vapor saturated. Hence, it is likely that volatiles diffused into the wall rock and became incorporated in biotite, which was stable in the wall rock because of the lower temperature and more mafic bulk composition there.

Fluorine content of biotite in most of the GT-2 core is substantially lower (Figs. 2-10 and -11), but approaches fluorine content of biotite in the xenoliths in some highly fractured samples. It is possible that these fractures have carried volatiles from the nearby magmatic source and were later sealed.

The proximity of an F^- -enriched zone to GT-2, as indicated in the xenoliths, may explain the high F^- content observed in fluids circulated through GT-2.

In summary, the findings indicate that Precambrian xenoliths in the Bandelier Tuff were derived, during eruption of the tuff, from a contact metamorphic zone surrounding the magma body, and from the ring fracture zone above, surrounding the roof of the magma chamber. The xenoliths include samples similar to the GT-2 core, as well as more mafic compositions and more deformed textures. Deformation in the contact metamorphic zone involves shearing at submagmatic temperatures. The most important form of chemical alteration is formation of fluorine-rich biotite by diffusion of H_2O , HF , and perhaps potassium from the magma. Gabbro is a much more abundant rock in the vicinity of the magma body than at the surface. Of these features, the gabbroic rocks are least likely to

Fig. 2-10.

Partitioning of fluorine between amphibole and biotite (above), and Mg/Mg+Fe vs F/F+OH for biotite (below), from electron microprobe analyses. Solid lines are contours of constant $\log fH_2O/fHF$ for aqueous fluids in equilibrium with biotite at $T = 500^\circ C$ (Ref. 18).

Fig. 2-11.

Comparison of frequency distribution of F/F+OH for various sample sets. (Symbols are the same as in Fig. 2-10.) Note increase in F/F+OH with increasing alteration (most altered at top) for biotite and amphibole.

be limited to the immediate vicinity of the magma body, and hence may be encountered by deeper drilling at Fenton Hill.

Evolution of the Valles Caldera magma chamber. An understanding of the development and evolution of the magma chamber that produced the Valles Caldera is a necessary prerequisite to an assessment of the total geothermal system of the Jemez Mountains. In an effort to acquire this information, a petrologic-geochemical-strontium isotopic investigation of the igneous rocks of the Jemez Mountains was initiated in late FY77. This investigation, partially funded by the Division of Basic Energy Sciences, is being performed in cooperation with D. G. Brookins of the University of New Mexico and S. Baldrige of the California Institute of Technology.

The strontium isotopic data, in particular, will establish the amount of crustal melting involved in Jemez volcanism. These data can then be used to provide estimates of the volume of rock affected by the igneous activity.

To date, eight igneous rock units from the Jemez Mountains have been sampled and whole-rock chemical analyses have been completed on four of them. Strontium isotopic analysis is in progress at the University of New Mexico. This work will continue during FY78; completion is anticipated at the end of the fiscal year.

Bandelier Tuff project. A research project to study the Bandelier Tuff was initiated February 1, 1977. The project is funded as part of a LASL Health Division program. The purpose of the work is twofold:

(1) To determine the detailed stratigraphy of the Bandelier Tuff on the Pajarito Plateau and identify primary and secondary features of the tuff that control hydrologic transport directions.

(2) To determine the background geochemistry of the Bandelier Tuff and identify mobile cations in alteration zones within the tuff.

The Bandelier Tuff, with a total volume of 150 km^3 , consists of two sequences of air-fall and ash-flow deposits. This study concentrated mainly on the upper unit, erupted from the Valles Caldera. Results show that 12 flow units, which erupted over a relatively short time, make up the upper unit. Determination of the eruptive sequence is critical to an understanding of the nature of magma within the large chamber that provides the heat for geothermal reservoirs within the Jemez Mountains. The stratigraphic study provides a solid base on which to continue petrologic studies of the erupted rhyolitic tephra. Also needed for an understanding of the magma chamber is the composition and petrologic history. Work was started, during this study, on the chemical and mineralogic variation and variation of vesicularity and pumice shapes to determine eruption temperatures and viscosities. This is our "window" on which we may assess the initial temperature and physical properties of the cooling magma chamber.

2.3.2.5. Chemical Composition of Natural Waters of the Jemez Mountains.

The chemical composition of natural waters has been widely used as an exploratory tool for hydrothermal geothermal reservoirs¹⁹ because the abundances of certain dissolved cations reflect the temperature of the rock with which the water was last in equilibrium. Probably the most widely used of these geothermometers depends upon the known relationship between temperature and the amount of dissolved silica.²⁰ A second

geothermometer is based on the relative proportions of K^+ , Na^+ , and Ca^{+2} in the natural fluids.²¹ However, neither geothermometer has yet been used in exploring for or assessing HDR resources.

During FY77 a study to evaluate the applicability of the above methods to the exploration for hot dry rock was conducted. The information acquired should contribute to a better understanding of the heat source and heat-transfer mechanisms that have produced both HDR and hydrothermal reservoirs.

Fifty samples of water were collected from springs and streams within the Jemez Mountains. These samples were analyzed at the University of New Mexico for SiO_2 , Cl^- , F^- , SO_4^{-2} , Li^+ , Na^+ , K^+ , Ca^{+2} , and Mg^{+2} . In addition, data were obtained²² for 70 other samples from wells, test holes, and springs, which included abundances of SiO_2 , Ca^{+2} , Mg^{+2} , Na^+ , CO_3^{-2} , HCO_3^- , SO_4^{-2} , Cl^- , and F^- .

Where possible, both chemical geothermometers have been applied; absence of K^+ and Na^+ abundances in the data of Purtymun et al.,²² however, preclude use of the Na-K-Ca geothermometer for these data. Calculated reservoir temperatures taken with the Na-K-Ca geothermometer range from 120°-331°C. With the SiO_2 geothermometer, temperatures range from 26°-138°C. Because of the limited number of Na-K-Ca temperatures, the scatter in values, and the unreasonably high values for some samples, emphasis was placed on the SiO_2 temperatures.

When plotted on a base map of the Jemez Mountains, the SiO_2 temperature produced what is believed to be a reasonable pattern, that is, a general radial decrease from the center of the Caldera. This is particularly obvious where spring locations are controlled by radial faults extending out from the Caldera. For example, along the northeast fault system passing through Soda Dam, SiO_2 temperatures decrease from 113°-81°C.

2.3.3. Mono/Long Valley KGRA

LASL was asked to prepare a Request for Proposal (RFP) soliciting assessment and resource base characterization of the Mono/Long Valley KGRA, as a result of its selection as the prime candidate site by HDRAP. About 6 man-months were spent in compiling geological, geophysical, geochemical, legal, institutional, and environmental information on this area; in developing a technical plan for the assessment; and in preparing a review of the legal, institutional, and environmental barriers to development. The resulting document was submitted to ERDA-DGE in December, 1976. To date, however, no RFP has been issued.

The technical assessment plan proposed by LASL was based largely on published and unpublished data from the USGS. The objective of this plan was to suggest a rational assessment program for evaluating the total geothermal system of this KGRA.

Because of the complex geology of this region and differing amounts of previous work in specific locales, the KGRA was subdivided into five areas and a detailed technical assessment plan was prepared for each. Those five areas were: the resurgent dome, the western moat, the area between Mono Lake and Long Valley caldera, the area southwest and south of Long Valley caldera and within the KGRA, and the eastern moat. Criteria for subdivision into five areas are presented in Table 2-I. An additional plan for regional geophysics encompassing all five areas was developed. The proposed technical assessment effort concluded with a recommended synthesis of data from all five areas and development of a model of that total geothermal system.

As an example, this report will examine the technical plan (as outlined in Fig. 2-12) for area C, because of its high potential as an HDR site. As is shown in Table 2-I, this area lies within the Basin and Range Province east of the Hartley Springs fault and between Mono Lake to the north and the ring faults of the Long Valley caldera to the south.

Some of the USGS investigations in Long Valley that have provided data for this area are: Hill,²³ Kane et al.,²⁴ and Lachenbruch et al.^{25,26} Geologic investigations have been made in the Mono Craters area, but extensive geophysical and hydrologic investigations remain to be done.

The area is underlain by Mesozoic granitic rocks which are covered by Pliocene and Quaternary volcanic rocks and Quaternary alluvium and lake deposits. The predominant structures are the regional-- $\sim$ N25°W-trending--normal faults, some $\sim$ N70°W faults, and a set of $\sim$ N20°E faults.

Within this area, volcanic centers exist at Mono Craters and Glass Mountain. The rocks from Glass Mountain are the earliest from the Long Valley magma chamber (1.92 - 0.90 My);²⁷ the rhyolitic rocks of the Mono Crater have been dated from 12 000 - 13 000 y. The Mono Crater's magma chamber has produced frequent eruptions within this period, may be actively rising, and is capable of providing material for further eruptions.²⁷ The depth to the chamber is inferred from geochemical calculations to be 6 - 22 km.

The waters of the hot springs in the eastern sector of the area may be heated in passing around or through heat sources associated with the Mono Craters,

TABLE 2-1

BASIS FOR IDENTIFICATION OF FIVE AREAS FOR MONO/LONG VALLEY GEOTHERMAL ASSESSMENT

Area	Geology	Previous Work	Geothermal Potential
A. Dome	Resurgent dome in west caldera portion of caldera with about 1000 m of structural relief and 500 m of surface expression. Surface and near surface rocks are post-caldera tuffs, flows, and lake sediments. Bishop Tuff inferred to be at 1 km, basement at 2 km, possible magma at > 7 km. Strongly faulted, hot.	Extensive geologic mapping, geophysics, and some heat-flow holes.	Good prospect for hydrothermal. Poor prospect for hot dry rock because of likely presence of hydrothermal system above basement and pervasive fracturing in basement.
B. Western Moat	Caldera between west rim and dome. Depth to basement is 1 to 4 km. Extensive post-caldera vulcanism.	Thorough geologic mapping but little geophysics. Drilling at Casa Diablo Hot Springs and one heat-flow hole has been drilled.	Good prospect for hydrothermal - thick, wet fill capped by volcanics; geophysics and young volcanism indicate magmatic heat source, complicated by infusion of cold water from Sierra. Basement too deep for HDR.
C. North of Long Valley Caldera and East of Hartley Springs Fault	Basin and Range Province with Sierra basement. Mostly mantled by Bishop Tuff; contains the young (< 10 ⁵ yr) Mono Craters chain. Faulting related to Basin and Range and incipient Mono Craters ring fracture. Probably magma at depth.	No detailed geology or geophysics. Three heat-flow holes.	Good HDR prospect since basement is shallow and magma is present. Problems: magmatic activity may be too recent; extensive faulting may be concealed by surficial ash deposits. Poor hydrothermal prospect.
D. Southeast, south, and southwest of Caldera Ring Fault	Sierra block adjacent to caldera. Mostly granite and granodiorite with meta volcanic and meta sedimentary roof pendants. Recent vulcanism (< 10 ⁵ yr) at Mammoth Mt. and Devil's Post Pile.	Thorough geologic mapping, some geophysics including one heat-flow hole (3.75 HFU).	Good prospect for HDR in vicinity of Mammoth Mt. and Devil's Post Pile. Problems: access and environment. No prospect for hydrothermal system.
E. Eastern Moat	Region between resurgent dome and east rim of caldera. Depth to basement 1 to 4 km. Upper half of caldera fill is porous lake sediments and ash, lower half is densely welded, fractured Bishop Tuff. No young volcanic activity.	Thorough geologic mapping and geophysics. Some exploratory drilling.	Possible hydrothermal prospect. Hot, self-sealing system thought to exist within tuff. Farther from magma than other areas, but farther from cold Sierra water as well. Prospects for non-electric utilization. Drilling results not encouraging. Basement may be too deep for HDR.

Fig. 2-12.
Flow chart of technical plan for the area north of Long Valley Caldera and east of the Hartley Springs fault.

Key to Fig. 2-12.

Status - Review of all pertinent data in literature.

Geologic Mapping - Where not accomplished, map lithology and structure on a scale of 1:24 000 from aerial photographs and field, paying particular attention to hydrothermal alteration.

Reinterpret Gravity and Aeromagnetic Data - Review existing coverage emphasizing this area and correlating with mapping. An attempt should be made to delineate depth and size of magma chamber.

Magnetotelluric and/or DC Resistivity - A complete survey of the area using both these techniques is needed to locate both deep and shallow electrical conductors. This work is part of the regional geophysics survey recommended earlier.

Hydrology - The logs of the three heat-flowholes in this area should be examined for aquifer data, and a well inventory should be made for the area.

Commence Seismic Noise Survey - This investigation is necessary to define regions of hydrothermal activity.

Seismic Refraction Survey - This work, also part of the regional geophysical survey, is designed to delineate any magma chamber(s) associated with the Mono Craters.

Decision 1 - After analysis of data obtained by the above methods, a site for heat-flow holes can be selected.

Heat-Flow Holes - These holes should be drilled to a depth sufficient to provide reliable heat-flow data. Samples should be taken for thermal conductivity, porosity, and permeability measurements, and aquifer parameters should be determined. These data are fed into the hydrology data bank.

Decision 2 - All data obtained from the above investigations are used to select a site for a deep, slim hole.

Seismic Reflection and Detailed Structural Geology - The purpose of these investigations is to define faults and fractures, within a surface area of a 3-km radius around the drill site, which might intersect the hole.

Model - Before drilling, all data should be assembled into a model to predict the results of the slim hole.

Slim Hole - During drilling, a complete drilling record should be maintained and a complete lithologic log made. Continuous coring should be done or cuttings should be collected at 2-m intervals and cores taken as often as economically feasible.

Hydrology Testing - Simultaneously with drilling, tests should be made in situ for permeability and rates of flow in each aquifer.

Geophysical Logging and Core Examination - Spectral gamma logging is the most useful for defining lithology and 3-D sonic for locating fractures, but a complete suite of geophysical logs, including temperature should be run. These logs must be correlated with core and cuttings. Attention to alteration minerals is stressed, and permeability measurements should be made.

Refine Model - The previous model can now be revised in accordance with the new data from the slim hole.

Decision 3 - This decision is for more drilling to define the resource or more investigations before further drilling. In the second case, a recommendation for additional work should be made and the model refined before redrilling another slim hole. Because of the large area involved, more than one slim hole will probably be required to characterize the resource base.

much as the waters of the hot springs in the caldera seem to be related to heat sources in the western part of the caldera.

Three heat-flow sites discussed by Lachenbruch et al.²⁶ are included in this area: Aeolian Buttes (AB), 2.18 HFU; Johnny Meadow (JM), 0.41 HFU; and Sagehen Meadow (SM), 0.72 HFU. All are in the Basin and Range physiographic province. The data from the JM and SM sites show anomalously low heat flow, perhaps caused by hydrologic effects, compared to typical Basin and Range values.

The recent age of the Mono Crater's rocks, the associated hot springs, and the proximity to the magma chamber may indicate thermal anomalies in the vicinity worthy of geothermal exploration.

From the standpoint of political, legal, institutional, and environmental issues, we believe that Mono/Long Valley is one of the most difficult areas in the US for geothermal energy exploration, evolution, and development. Examples of the issues, any one of which could constrain the proposed activities, are:

1. Lake Crowley Watershed Protection. Lake Crowley is a principal water supply for the City of Los Angeles. The Bureau of Land Management (BLM) has caused lands to be withdrawn surrounding the lake for the protection of this watershed.

2. Fish Hatchery. The hatchery, located on Hot Creek and operated by the California Department of Fish and Game, is unique within the US, and as such will be protected to the extent of the Department's political power.

3. Hot Creek Fishing. This stream fishing area, under the jurisdiction of the California Fish and Game Department, is noted throughout the state and is heavily used.

4. Endangered and Rare Flora and Fauna. Several species of flora and fauna found in the area are on the federal endangered species list and additional flora and fauna have been added to the state's list. Also, the sage grouse in this area are considered as habitat sensitive and are being protected by the California Department of Fish and Game.

5. Aesthetics. The entire area from Mammoth Mountain to Lake Crowley is an extremely active recreational area, particularly for the residents of Los Angeles. Activities which can be considered as having an aesthetic impact may become controversial.

6. Restricted Areas. The area of interest is bordered by or contains wilderness areas, national monuments, and national forests.

2.3.4. Geophysics and Logging at Coso Geothermal Area

During June 1977, the US Navy asked a staff member (P. R. Kintzinger) for assistance with the proposed logging of a geothermal well to be drilled in the Coso Geothermal Area. Contact is being made with various agencies that have conducted geophysical surveys in the Coso Hot Springs area to determine current status of geophysical projects. This project accords with DGE's request for LASL to provide an HDR liaison person to the Coso program.

2.3.5. Conway Granite

As a result of the Near-Normal Geothermal Gradient Workshop held in March 1975, Glenn Stewart of the University of New Hampshire was funded by ERDA-DGE to drill a 900-m hole into the Conway Granite, New Hampshire. This hole was continuously cored and, upon completion, geophysical logs were run by Scott Keys, USGS.

Twenty-five zones, 0.6-m-long, were selected that apparently characterized the various lithologies penetrated. These samples were shipped to LASL for cutting and distribution to researchers. LASL is performing petrographic and whole-rock major- and trace-element analyses on splits of these samples.

Chemical analyses of the samples have been completed and the petrographic analysis is in progress. Samples of the granite were variable with respect to uranium concentrations, ranging up to about 33 ppm. Lamprophyric dikes intersected by the drill hole contained about 3 ppm uranium. Petrographic analysis indicates that several of the samples plot in the syenogranite field on the I.U.G.S. Q-A-P^{*} composition diagram. Rarer granitic compositions include monzogranite and mafic granodiorite. The lamprophyric dikes are rich in hornblende and clinopyroxene.

Analytical work on the Conway samples will be completed during FY78.

2.3.6. Data Compilation and Modeling

Throughout FY77, basic geological, geochemical, and geophysical data were compiled on all known and potential natural hydrothermal and HDR geothermal systems. Because of proprietary interests, little information was available for privately held reservoirs, and emphasis has had to be placed on assessments and investigations performed by the USGS and the national laboratories.

* International Union for Geological Science, quartz/alkali-feldspar/plagioclase.

At this time, insufficient data are available to permit quantitative modeling of HDR geothermal systems. We anticipated that in FY78, as Federal geothermal leasing proceeds, a freer exchange of information among the Federal agencies, industry, and the academic community will develop.

REFERENCES

1. "Hot Dry Rock Geothermal Energy: Status of Exploration and Assessment: Report No. 1 of the Hot Dry Rock Assessment Panel," Energy Resource and Development Administration report ERDA-77-74 (June 1977).
2. F. G. West and T. J. Shankland, "Exploration Methods for Hot Dry Rock: Report of the Panel Held June 22, 1976," Los Alamos Scientific Laboratory report LA-6659-MS (March 1977).
3. D. F. White and D. L. Williams, Eds., "Assessment of Geothermal Resources of the United States-1975," Geological Survey Circular 726 (1975).
4. Carlos Aiken, "Analysis of the Gravity Anomalies of Arizona," University of Arizona doctoral dissertation (1976).
5. M. Reiter, C. L. Edwards, H. Hartman, and C. Weidman, "Terrestrial Heat Flow Along the Rio Grande Rift, New Mexico and Southern Colorado," Bull. GSA 86, No. 6, 811-818 (1975).
6. E. R. Decker and S. B. Smithson, "Heat Flow and Gravity Interpretation across the Rio Grande Rift in Southern New Mexico and Western Texas," J. Geophys. Res. 80, 2542-2552 (1975).
7. "Definition Report: Geothermal Energy Research, Development and Demonstration Program," Energy Research and Development Administration, Division of Geothermal Energy report ERDA-86 (October 1975).
8. Carlos L. V. Aiken, A. W. Laughlin, and Francis G. West, "Residual Bouguer Gravity Anomaly Map of Northern New Mexico," Los Alamos Scientific Laboratory map LA-6737-MAP (March 1977).
9. R. M. Potter, "Heat Flow of the Jemez Plateau," Trans. AGU 54, 1214 (1973).
10. M. Reiter, C. Weidman, C. L. Edwards, and H. Hartman, "Subsurface Temperature Data in Jemez Mountains, New Mexico," New Mexico Bureau of Mines and Mineral Resources Circular 151 (1976).
11. G. H. Woods, Jr. and S. A. Northrup, "Geology of the Nacimiento Mountains, San Pedro Mountains and Adjacent Plateaus in Part of Sandoval and Rio Arriba Counties, New Mexico," USGS Oil and Gas Inv. Prelim. Map 57 (1946).
12. R. L. Smith, R. A. Bailey, and C. S. Ross, "Geologic Map of the Jemez Mountains, New Mexico," US Geological Survey, Miscellaneous Geologic Investigations Map I-571 (1970).

13. J. N. Albright, "Temperature Measurements in the Precambrian Section of Geothermal Test Hole No. 2," Los Alamos Scientific Laboratory report LA-6022-MS (July 1975).
14. F. Birch, R. F. Roy, and E. R. Decker, "Heat Flow and Thermal History in New York and New England," in Studies of Appalachian Geology: Northern and Maritime, W. White and E-an Zen, Eds. (Interscience, New York, 1968).
15. R. F. Roy, D. D. Blackwell, and F. Birch, "Heat Generation by Plutonic Rocks and Continental Heat Flow Provinces," Earth Planet. Sci. Lett. 5, 1-12 (1968).
16. G. R. Jiracek, C. Smith, and G. A. Dorn, "Deep Geothermal Exploration in New Mexico Using Electrical Resistivity," Proc. 2nd UN Symp. Development and Use of Geothermal Resources 2, 1095-1102 (1976).
17. P. R. Kintzinger, C. B. Reynolds, F. G. West, and G. Suhr, "Seismic Reflection Surveys near LASL Geothermal Sites," Los Alamos Scientific Laboratory report to be published.
18. J. L. Munoz and S. R. Ludington, "Fluoride-Hydroxyl Exchange in Biotite," Am. J. Sci. 274, 396-413 (1976).
19. A. H. Truesdell and R. O. Fournier, "Calculation of Deep Temperatures in Geothermal Systems from the Chemistry of Boiling Spring Waters of Mixed Origin," Proc. 2nd UN Symp. Development and Use of Geothermal Resources 1, 837-844 (1976).
20. R. O. Fournier and J. J. Rowe, "Estimation of Underground Temperatures from the Silica Content of Water from Hot Springs and Wet-Steam Wells," Am. J. Sci. 264, 685-697 (1966).
21. R. O. Fournier and A. H. Truesdell, "An Empirical Na-K-Ca Geothermometer for Natural Waters," Geochim. et Cosmochim. Acta 37, 1255-1275 (1973).
22. W. D. Purtymun, W. H. Adams, A. K. Stoker, and F. G. West, "Water Quality in the Vicinity of Fenton Hill Site, 1975," Los Alamos Scientific Laboratory report LA-6511-MS (September 1976).
23. D. P. Hill, "Structure of Long Valley Caldera, California, from a Seismic Refraction Experiment," J. Geophys. Res. 81, 745-753 (1976).
24. M. F. Kane, D. R. Mabey, and R. L. Brace, "A Gravity and Magnetic Investigation of Long Valley Caldera, Mono County, California," J. Geophys. Res. 81, 754-762 (1976).
25. A. H. Lachenbruch, M. L. Sorey, R. E. Lewis, and J. H. Sass, "The Near-Surface Hydrothermal Regime of Long Valley Caldera," J. Geophys. Res. 81, 765-768 (1976).
26. A. H. Lachenbruch, J. H. Sass, R. J. Munroe, and T. J. Moses, Jr., "Geothermal Setting and Simple Heat Conduction Models for Long Valley Caldera," J. Geophys. Res. 81, 769-784 (1976).

27. R. A. Bailey, G. B. Dalrymple, and M. A. Lanphere, "Volcanism, Structure, and Geochronology of Long Valley Caldera, Mono County, California," J. Geophys. Res. 81, 725-744 (1976).

3. INSTRUMENTATION AND EQUIPMENT DEVELOPMENT (J. R. Archuleta; B. R. Dennis, Task Mgr.; C. F. Fink; B. E. Todd)

The creation and subsequent study of hot dry rock geothermal reservoirs requires highly sophisticated tools and instruments that can function for relatively long periods of time in the hostile downhole environment. Some of this equipment already exists because of similar needs in the oil and gas industry. However, many of the relevant devices extant were marginal with respect to temperature-time exposure capability and required some development to render them adequate in a 200 - 275°C service range. In other cases, applicable commercial equipment does not exist and complete development is required.

When possible, we contracted with the appropriate commercial suppliers to perform the necessary upgrading or initial development work. In many instances, however, this could not be done and we were forced to either conduct the development in-house or postpone it.

The following sections discuss instruments and other equipment developed largely in this fiscal year.

3.1. High-Temperature Borehole Fluid Sampler

Chemical analyses of discrete fluid samples, taken at various depths in a geothermal borehole, are often useful in the investigation of geothermal reservoir properties. Borehole-fluid sampling tools are available commercially, and several were tested by the Hot Dry Rock Geothermal Energy Development Project. However, these tools did not operate satisfactorily in the Project's high-temperature (~200°C) boreholes. No commercial firms that were contacted would agree to provide an upgraded tool within LASL's budget and schedule constraints. Therefore, LASL undertook the development of a new fluid sampling tool.

Before development began, the following requirements were established:

1. The tool must be able to collect a sample by using only one electrical conductor of the cable plus the armor return.
2. The tool must be able to collect two samples at two different depths in the borehole (or two samples at one depth) by using three conductors of the cable.
3. The tool must be able to operate downhole at 200°C and 41 MPa (6000 psi) for 12-h durations.
4. The design must be capable of being upgraded, by suitable changes in components, to operate at 275°C and 68.9 MPa (10 000 psi). (This requirement is to allow for subsequent operation in deeper and hotter boreholes.)

5. The fluid sample is to be retained by a double seal, preferably metal-to-metal.

6. Surface readout is to include motor current and valve position status.

7. Diameter of the tool is not to exceed 92 mm (3-5/8 in.).

8. Sample container material must be stainless steel; volume is to be about 0.25 liters.

The fluid sampling tool, shown in Fig. 3-1, uses a dc permanent magnet motor and a planetary gearing system to rotate a shaft that can open or close a hand valve. The hand valve is mounted on the upper end-cap of the container and is normally closed, sealing the container. Check valves within the container allow inlet flow, but no reverse flow, thereby providing a seal for the sample. Surface readouts during a sampling run provide the operator with the motor current, motor running time, and shaft revolutions. Shaft revolutions are monitored by a microswitch, which senses lobes on a cam attached to the motor output shaft. The switch is activated every quarter revolution. The upper and lower clutch, in conjunction with the microswitch, augment operator control over the valve-opening sequence. The upper clutch allows the upper hand valve to be opened one revolution, whereas the lower clutch provides a two-revolution interval between opening the first valve and the second valve. The high-pressure bulkhead prevents water from damaging the cable head if the shaft seal fails.

Characteristics of the motor and gearing system are as follows:

1. Maximum motor voltage, 115 Vdc

2. Maximum current, 0.40 A

3. Speed reduction, 947:1

4. Output shaft rotation, 8 rpm (no load)

5. Normal rated torque, 21.5 N·m (190 in.-lb).

The valves are opened sequentially. The top valve opens first to obtain the first sample. In the sampling sequence, the first valve opens immediately with clockwise shaft rotation (viewed from the downhole end of the tool). After one clockwise shaft revolution, the upper clutch engages the container for the upper water sampler, and the torque is transmitted to the lower clutch. Two revolutions of the lower clutch, a total of four shaft revolutions, open the lower valve one revolution, obtaining the second sample. The hand valves are then closed by four counterclockwise shaft revolutions. Counterclockwise rotation is obtained by reversing the polarity of the motor voltage.

Fig. 3-1.
Fluid sampler.

All components (such as pressure vessels, seals, check valves, valves, bearings, motor, and switches, have been tested in a geothermal fluid-filled hole at 200°C and 34.5 MPa (5000 psi). The pressure vessels and sample containers were designed to operate in a 275°C, 68.9-MPa (10 000-psi) environment. The vessel pressure rating is conservative; it is not a true collapse pressure but the pressure that generates yield stresses on the outer-diameter wall.

Tha Bal-Seals used in the seal housing have been laboratory tested at 225-275°C and 41 MPa (6000 psi) for up to 13 days without failure. This type seal will be used in the sample containers upgraded to 275°C.

The dc permanent magnet motor has been modified to operate at 200°C. Brush spring failures due to hydrogen embrittlement occurred after at most 5-min total operating time in the unmodified motor. A replacement spring, made of stainless steel (17-7 PH, CH950), was designed that lowered the stress level but developed the same brush-to-armature pressure. To upgrade this tool to 275°C will require a controlled environment enclosure for the motor, which exploits the latent heat of fusion as a heat sink.¹

The fluid sampler has been used to obtain fluid samples from EE-1 at depths of 2865, 2895, and 2960 m (9400, 9500, and 9700 ft) with a seven-conductor instrumentation cable. Typical motor current and shaft revolutions shown in Fig. 3-2 are from a sampling sequence at 2960 m (9700 ft), where the borehole temperature is 204°C.

3.2. High-Temperature Downhole Fluid Injector

One technique used in establishing some of the characteristics of the HDR geothermal reservoir at Fenton Hill involved injection of sodium-fluorescein dye, as a tracer, into a fluid-filled borehole. Such dye-tracer flow tests characterize the reservoir system by using residence-time distribution studies. Again, a suitable unit was not available commercially and time and funding constraints led to LASL development of the tool.

The fluid injector² tool (called a "pillpusher" in the trade jargon) developed at LASL is shown in Fig. 3-3. It will deliver and eject a metered volume of a desired fluid, such as a dye or acid, into the borehole at a prescribed location. The material to be injected into the borehole is contained within a cylinder located at the bottom of the tool. The lower end of this cylindrical reservoir is sealed by a piston, which also acts as a wiper during injection. The upper end-cap contains the discharge ports and the flapper-type check valves, which allow flow out of the container during ejection but prevent

Fig. 3-2.
Typical motor current and shaft revolutions from downhole operation.

loss of the fluid during insertion of the tool. Pressure equalization of the reservoir allows use of a thin-wall cylinder for the container. The latching system holds the reservoir cylinder and the piston and rod assembly together until ejection. The release mechanism, which unlatches the container, is actuated by a motor-driven mechanical actuator. The cylinder drops over the rod and piston, discharging fluid through the orifices at the cylinder's upper end-cap. Vertical velocity is controlled by the wiper O-ring drag and by metering the fluid flow through the discharge orifice. The cylinder's motion is arrested by the rod and piston, thereby loading the cable and giving a positive indication of cylinder release. Three sizes of fluid injector — 0.0076, 0.011, and 0.038 m³ (2, 3-1/8, and 10 gal) — are designed to use a common release mechanism.

Technical Data Summary

Length: 3.2 m (126 in.)
Weight: 63.5 kg (140 lb)

Fig. 3-3.
Downhole fluid injector.

Temperature rating: 200°C

Pressure rating: 68.9 MPa (10 000 psi)

Injector capacity: 0.0076, 0.012 and 0.038 m³ (2, 3-1/8, and 10 gal)

Maximum diameter: 92, 102, and 152 mm (3-5/8, 4, and 6 in.)

Power requirements: 125 Vdc at 300 mA maximum

Cable requirements: one electrical conductor and sheath return

Motor: 15-W (1/50-hp) dc permanent-magnet-type

The pressure rating is conservative; it is not a true collapse pressure but the pressure that generates yield stresses on the internal-diameter wall of the tube. The pressure vessel is made of two pieces: one is an adapter (sub) to the cable head, and the other houses the motor and mechanical actuator.

The high-temperature dc motor develops 21 N·m (186 in.-lb) torque through a planetary gear reduction system. The torque is transmitted through a multi-jawed coupling to the mechanical actuator, which converts it to thrust. The mechanical actuator comprises a ball nut and a 19-mm diam, 12.7-mm lead screw. The actuator is rigidly supported (fixed) by a pair of spaced bearings at one end and simply supported at the seal area. The column buckling load is 66.7 kN (15 000 lb); the maximum operational load developed by the actuator is 9.3 kN (2100 lb). The ball bearing screw and nut are lubricated with Krytox 240 AC to provide satisfactory service at 200°C.

The actuator shaft is redundantly sealed at its exit from the motor compartment and is hydraulically balanced by sealing of the lower end of the piston at the balance cylinder. The actuator shaft serves two functions. It unlatches the locking mechanism and provides a 76-mm (3-in.) unseating displacement of the reservoir cylinder. During the unlatching sequence, the locking disk on the actuator shaft is displaced downward with outward actuator travel, allowing the reservoir cam to force the four steel balls off the locking ring. If the weight of the reservoir cylinder is not sufficient to cam the steel balls, additional actuator travel will apply a force on the reservoir's upper end-cap through the four 6.4-mm (1/4-in.) rods, driving down the reservoir cam, and dislodging the four locking balls. The downward reservoir movement will unseat the lower piston O-ring, allowing the reservoir cylinder to travel downhole. The balls are confined within the tool by the retaining shield.

The fluid injector has been used in a geothermal-fluid-filled wellbore at up to 200°C and 34.5 MPa (5000 psi). Dye was injected into hole EE-1 in several tool development tests and as part of residence-time distribution studies. As a result of the tool development tests, check valves were added at the prototype's discharge ports and incorporated into the final design to prevent dilution of the dye during tool insertion.

Structural strength has been verified by tests. The fluid injector was assembled without fluid in its reservoir, installed in a fixture, and the outer cylinder released. This severe condition, not typical of normal operation, develops maximum loads in the rod and piston assembly. Posttest examination indicated no permanent deformation in the loaded components.

3.3. High-Temperature Cable-Head Assembly

Instruments used in reservoir mapping often remain downhole for periods of 12 h at 200°C and 35-41 MPa (5000-6000 psi). Communication between the downhole

instrument and the recording facility is by a high-temperature multiconductor instrumentation cable terminated at the cable head. The cable must maintain mechanical and electrical integrity of the conductors for the duration of the test. Indeed, the development of high-temperature wellbore instruments (that is, those capable of functioning at 200-275°C) is constrained by the quality of the electrical connection between the subsurface electronics and the surface recording equipment.³

The design implemented at LASL⁴ is rated for continuous service up to 250°C. The primary function of the cable head is to provide a cable-to-tool electro-mechanical coupling device, which protects the cable's electrical conductors from the downhole high-pressure and high-temperature water environment. Other functions of a cable head include:

1. Establish a transition area from the downhole fluid high-pressure environment to the dry low-pressure environment in the sonde;
2. Provide a protected area for splicing the cable conductor ends to the high-pressure bulkhead;
3. Allow separation of the sonde and the cable in the event a sonde becomes jammed in the wellbore;
4. Provide a positive gripping area (fishing-bell) for overshot fishing tools in the event of tool separation;
5. Protect the cable from right-angle bending as sondes are being raised from the assembly table to the vertical position over the wellhead.

Four distinct cable heads, incorporating the same basic design, have been fabricated at LASL: (1) a 70-mm (2.75-in.)-diam cable head, the first design which has been in service for 1-1/2 yr; (2) a second cable-head configuration for initial evaluation of a new cable containing 12-twisted-pair conductors and a coaxial conductor (Fig. 3-4); (3) a third-generation 45-mm (1.75-in.)-diam cable head, designed to allow entry through a wellhead restriction and directional orientation through drill collars; and (4) a 53-mm (2-1/8-in.)-diam cable head is a standardized head employed in both a 11.9-mm (0.468-in.)-diam 7-conductor cable and with a 16.6-mm (0.656-in.)-diam 12-twisted-pair conductor cable.

A well-logging service company's typical cable head is moisture protected by simply encasing the splice area with grease. Cable-head failure occurs when

Fig. 3-4.
High-temperature cable-head assembly.

the grease breaks down or moisture collects at the high-pressure feedthrough block. The severe environment of geothermal boreholes necessitates frequent reheading.

The LASL cable-head design has but a single water entry path to the conductor splicing cavity, which is sealed with silicone rubber. Water migrating to the splicing cavity must enter at the top of the cable head, flow past the cable packoff and splice cavity, and radially through the silicone rubber to the conductor splice. The connector at the pressure terminal is protected further by a Viton boot cover. Thermal expansion of the silicone rubber increases the sealing pressure, thus aiding its function as a water barrier.

The cable head and sonde automatically separate when the cable tension exceeds 17.8 kN (4000 lb) plus $1.61 \times 10^{-4} \text{ m}^2$ (0.25 in.^2) times the ambient fluid pressure. The release load can be accurately determined as a result of the simple shear fuse design. The separation joint is located below the splice cavity to protect the cable conductor after separation. The cable is retained in the cable head by use of a cone and socket arrangement.

Flange-type O-ring design is used whenever possible to provide reliable sealing at critical joints. Metallic O-rings have been tested successfully and will provide a satisfactory method of upgrading the cable head to 275°C.

Multipiece design is used in the splice cavity and cable packoff area for ease in disassembly and reheading. Most components are manufactured from high-strength (4340) steel, heat treated to $1.24 \times 10^3 - 1.38 \times 10^3$ MPa (180 000 - 200 000 psi) tensile strength, allowing service to 103 MPa (15 000 psi).

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

3.4. Thermopile Probe

To improve borehole temperature measurements at increased logging rates, LASL developed a borehole thermopile temperature probe.⁵ The thermopile was constructed by wiring seven chromel-alumel thermocouples in series. Each ungrounded thermocouple was sheathed with 304 stainless steel tubing filled with magnesium oxide insulation. The 1.59-mm (0.0624-in.)-diam sheath had a wall thickness of 0.254 mm (0.01 in.). The cold junctions are immersed in an ice-filled Dewar housed in a sealed pressure shell (Fig. 3-5).

An additional thermocouple was set in the Dewar to measure the ice-bath temperature. The reference for this second thermocouple is provided by a self-compensating electrical bridge reference-junction (Consolidate Ohmic Model JR114APOC) that is also submerged in the ice bath. The reference junction was tested in an oven to ensure 0°C-compensation up to temperatures exceeding 80°C. This allows measurements to be made in the borehole after the ice has melted. The dewar, filled with crushed ice, will maintain an internal temperature of 0°C for 6 h when the downhole sonde is subjected to a borehole temperature of 200°C.

The time constant for the thermopile was measured for comparison with a thermistor probe. For a borehole logging rate of 7.62 m/min (25 ft/min) the temperature lag was 0.002°C with a time constant of 0.310 s. A comparison of response for the thermopile and a thermistor probe is presented in Table 3-I. The thermocouple characteristics are well known and, when calibrated, the accuracy is greater than 0.1%. The thermopile presents a low source impedance to the surface readout equipment. Figure 3-6 compares the temperature readout of the thermopile at logging rates of 9.2 and 43 m/min (30 and 140 ft/min). The temperature anomaly recorded during the thermopile test in hole EE-1 was caused

Fig. 3-5.
Borehole thermopile temperature probe.

TABLE 3-I
TEMPERATURE RESPONSE, THERMISTOR VS THERMOPILE

Logging Rate		Thermistor		Thermopile	
<u>m/min</u>	<u>ft/min</u>	<u>$\Delta\tau$</u>	<u>ΔT</u>	<u>$\Delta\tau$</u>	<u>ΔT</u>
7.62	25	7.63	0.058	0.310	0.002
24.38	80	7.33	0.179	0.165	0.0034
30.49	100	7.25	0.184	0.140	0.0036

$\Delta\tau$ = time constant of probe in seconds.

ΔT = temperature lag (true-indicated) °C.

by deterioration of the cement bond between the wellbore and casing over a relatively small interval at the bottom of the casing. The fluid in the borehole was circulating behind the casing in this region, thus producing the temperature variations. This anomaly was used as a bench mark to test the response of temperature-measuring devices at several logging rates.

3.5. High-Temperature Pressure Transducer

A high-temperature pressure transducer was used to survey the hydrostatic pressure in EE-1 as an evaluation of the potential utility of such a pressure transducer. Key specifications for this particular transducer were:

Compensated temperature range:	22-313°C (77 - 600°F)
Sensitivity:	39.96 mV
Zero shift:	0.001% FR*/C°
Sensitivity shift:	0.003% FR/C°
Combined nonlinearity & hysteresis:	0.02% FR
Full range:	34.45 MPa (5000 psi)
Input resistance:	459 Ω
Output resistance:	348 Ω

Data recorded during a wellbore survey (Fig. 3-7) have not been corrected for temperature and density. The transducer performed within specifications.

*FR = full range

Fig. 3-6.
Thermopile temperature response.

Fig. 3-7.
Pressure data, EE-1.

We calibrated the pressure transducer in the laboratory from zero to full range and returned to zero to determine the effects of temperature on the linearity, hysteresis, sensitivity, and zero shift. The calibration was repeated at 25, 100, 150, and 200°C; results are shown in Fig. 3-8. Maximum combined hysteresis and nonlinearity at 200°C was 0.247% FR, zero shift measured 0.001% FR/C°, and sensitivity shift was 0.006% FR/C°.

3.6. Controlled-Environment Enclosure

The controlled-environment enclosure was designed to LASL specifications to house and protect instruments from the hostile downhole environment of the geothermal wellbore. The enclosure was fabricated and tested by Mechanics Research Inc. under contract to LASL. Specifications required: (1) that it survive a 275°C external temperature for a minimum of 12 h during which 15 W of heat are dissipated from a source in the cavity; (2) that the internal temperature shall not exceed 85°C during this period; and (3) that the entire unit shall be sufficiently rugged to withstand, without debilitating damage, a prescribed shock test. The cavity to house the instrument(s) is 71 mm (2.8 in.) in diameter and 0.66 m (26 in.) long (Fig. 3-9). Twenty-eight kilograms (61 lb) of Cerrobend are used as a heat sink. The primary heat-transfer barrier is a superinsulated Dewar. The Dewar has a large opening at the upper end to permit loading of the instrument package and heat-sink containers. This opening, after assembly of the inner parts, is closed with a MIN-K plug. The lower end of the Dewar has a small port, permitting passage of an interconnect cable to an adjoining vessel, if required. The Dewar package is housed in a LASL-designed and -fabricated

Fig. 3-8.
Pressure transducer calibration.

Fig. 3-9.
Controlled-environment enclosure.

pressure vessel made of AISI 4340, heat treated to 1000 - 1200 MPa (145 000 - 175 000 psi), and designed to withstand 69 MPa (10 000 psi) external pressure. The entire vessel is 2.36 m (92-3/4 in.) long and weighs about 91 kg (200 lb).

The enclosure has been successfully laboratory tested in three 12-h thermal tests, each of which demonstrated that the instrument compartment temperature remains below 85°C for 12 h. The external temperature averaged 275°C for 12 h while the instrument compartment heaters maintained 15 W from the end of the 1st hour to the 11th hour.

The Dewar and internal components in the pressure vessel also successfully passed the vertical and horizontal drop tests. These tests simulate hitting the bottom of the borehole. The horizontal drop test simulates the nose cone of the tool hitting an obstruction on the sidewall of the borehole while descending at 60 m/min (200 ft/min).

3.7. Modular Workover Towers

To facilitate workover operations, we constructed modular towers over the wellbores at Fenton Hill. The towers were designed in sections 3.66 m square by 2.44 m high (12 ft square by 8 ft high). The sections are structurally similar (Fig. 3-10). The walls are constructed of 50-mm (2-in.) -thick fireproof, weather-resistant paneling. Up to five modules can be stacked over the wellhead, thereby providing a 12-m (40-ft) tower. The sliding doors of each module are oriented toward a well-logging rig and are open while equipment is being lowered, giving the operator full view of the sheaves, logging cable, and wellhead. Electrical wiring is provided from module to module by quick disconnect terminal boxes. A 318-kg (700-lb) winch unit has been installed in the top section to allow hoisting sections of large downhole instrumentation packages for assembly over the wellhead. The wellbore plumbing is enclosed in the heated tower to permit winter operation. Figure 3-11 shows a four-module 9.8-m (32-ft) tower.

Certain wellbore instrumentation (such as pressure, temperature, and flow-rate transducers) is protected from the weather by the tower and can be permanently installed. Floodlights installed on the top module facilitate night operation, as is frequently required in flow or ranging experiments.

3.8. High-Temperature Acoustic Calibration Facility

Using a LASL-developed downhole triaxial geophone package, we can record acoustic signals from fracturing events at high speed on magnetic tape. The

Fig. 3-10.
Structural configuration of modular section.

Fig. 3-11.
Modular workover tower.

records are filtered to remove the low-frequency signals where background is high. The signals are then digitized, displayed, and catalogued. Significant individual events are identified and particle motion at the geophone is synthesized for each. Analysis of arrival times and particle motion yields a vector that locates the source of the event relative to the geophone package. An assembly of these vectors defines the growing fracture surface in space and time.⁶

In an effort to develop an improved method of determining the relative positions of two deep boreholes as a function of depth, acoustic-ranging tests were conducted. An acoustic signal is generated in one borehole and is detected by an oriented three-axis geophone array set at a known depth in the other borehole. The sequence of generated signals (from a detonator fired at depth) is repeated at various measured depths. Distance is calculated from the

measured travel time of the P-wave from the signal generated in the first borehole (EE-1) and the previously measured sonic velocity at that depth. The distance is confirmed by the difference between P- and S-wave arrival times.

The acoustic techniques of microseismic fracture-mapping and ranging have been expanded to include shear-shadowing. The shear-shadowing technique requires multiple detonator firing (source generation) in the EE-1 borehole detected by the geophone package strategically placed in GT-2 at a fixed source/sensor positioning geometry. The experiment calls for repeated measurements at various positions and under various pumping pressures for detection of fracture inflation.

The response of the geophone array at elevated temperatures is critical in determining the accuracy and resolution so important to the success of all the acoustic techniques. A high-temperature acoustic test and calibration facility has been designed and fabricated.

The system will record the operational spectrum of a geophone or accelerometer package designed for assembly in the downhole sonde. The test system provides a means for exciting the acoustic transducer, mounted in the downhole sonde-carrying cradle, with a vibrational input from 5 Hz to 9 kHz in a temperature environment of 275°C (527°F). The test system will input along each axis of the three geophones, which are located orthogonally in the geophone package. Vibrational input can also be provided 10° off normal in the vertical plane for each of the three positions.

The system uses a Ling Model 411 shaker with a force rating of 25 kg (55 lb) to cover the specified frequency range. An Altec 9440A power amplifier provides the coupled drive to the shake table. This amplifier can deliver 800 W into an 8-Ω load in a monaural unbalanced mode. A special coupling fixture and support frame housed in a BMA Model L0-2 oven modified to extend over the temperature range of 35 - 275°C (Fig. 3-12) has been designed to transmit the shaker input over the designed frequency range to the acoustic cradle. The coupling fixture has an isolation spring to eliminate low-frequency oven background noise.

The shake table, coupling fixture, and oven are set on a large concrete isolation block mounted on a steel plate (Fig. 3-13). The isolation block is suspended from a bridge support structure by elastic cables. A winch unit in each of the bridge structures provides a leveling adjustment of the isolation

Fig. 3-12.
Geophone coupling fixture in oven.

Fig. 3-13.
High-temperature acoustic
calibration facility.

block. The bridge support decouples the isolation block from building, traffic, and background noise.

This system will allow for the calibration of acoustic transducers at elevated temperatures and facilitate the measurement of transducer degradation caused by extended exposure to the borehole environment.

3.9. Instrument Sonde Test Stand

Downhole instrument sondes have been used in the 200°C borehole environment. For operation at temperatures up to 275°C and pressures exceeding 410 bars (6000 psi), materials and components, including seals, motors, connectors, feed-throughs, potting compounds, and other electrical/mechanical equipment, must be designed and tested to meet these more stringent conditions. The maximum test conditions in the boreholes at Fenton Hill are limited to 200°C and 280 bars (4000 psi). In addition, testing sondes in the boreholes requires the use of the armored instrumentation cable, which subtracts from the limited life of such a cable in the hostile environment. Also, access to the boreholes at Fenton Hill will be limited because of scheduled flow through the energy extraction system for extended periods in FY78.

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

The design criteria for the test facility included a test chamber that will accept borehole sondes up to 152 mm (6 in.) diam and 6.1 m (20 ft) long. The chamber will be temperature-controlled up to 275°C and the fluid (water) pressure controlled up to 41.4 MPa (6000 psi). The chamber will reach the maximum operating temperature of 275°C in less than 2 h, starting from ambient. It must also be capable of cooling down to a temperature below 90°C from 275°C in less than 2 h.

A block diagram of the test stand is shown in Fig. 3-14. A 0.91-m (3-ft)-diam hole has been drilled to a depth of 10.7 m (35 ft). The hole was cased with a 10.36-m (34-ft) length of 0.61-m (2-ft) corrugated metal pipe (CMP) cemented in place. A metalbestos chimney, 9.14 m (30 ft) long with a 406-mm (16-in.) i.d. and 25.4-mm (1-in.) wall thickness, will house 18 electric heaters mounted as shown in Fig. 3-15. The chimney extends 0.61 m (2 ft) above a 1.11-m² (12-ft²) surface pad where a cool-down blower is mounted. The downhole instrument sondes will be lowered in the pressure test chamber made of 194-mm (7-5/8-in.) o.d. V-grade steel casing with 15-mm (0.595-in.) wall thickness. The high-pressure casing is 9.76 m (32 ft) long with a cap on the bottom and a header for a cable passthrough pressure seal at the surface. Figure 3-16 shows the chimney and heater assembly.

Final checkout of this test stand should be completed before the end of the 1977 calendar year.

3.10. Wellbore Survey Tools

A contract was negotiated with Eastman Whipstock of Houston, Texas, in August 1976 to provide a gyroscopic survey for downhole temperatures of 200°C. Testing was completed in January 1977. A similar contract was negotiated with Sperry-Sun of Houston. This testing was also completed in January 1977.

The basic design of both tools was about the same in that each used a vacuum heat shield and a Cerrobend metal heat sink to protect the gyro and batteries. The Eastman package was 127 mm (5 in.) in o.d. and featured a surface

Fig. 3-14.
Instrument sonde test stand.

Fig. 3-15.
Cross section of vessel with heaters and heat shield.

Fig. 3-16.
Chimney and heater assembly.

readout of internal temperature and operating voltage. The Sperry-Sun tool was 152 mm (6 in.) o.d., and was completely self-contained.

3.10.1. Eastman Whipstock Survey

On January 28, 1977, the survey team, consisting of an electrical engineer and a logger, arrived from Houston. Logging began in EE-1, but the first two runs ended in failure because of leaky O-ring seals. The seals were coated with Krytox 240 grease and the electrical connectors encapsulated in RTV sealant. Successful runs were then made in both holes with a maximum internal tool temperature of 45°C (113°F). Both holes were logged at 30.5-m (100-ft) intervals going down and 152-m (500-ft) intervals coming out. The corrected distance between the two holes at 2900-m (9500-ft) depth was determined to be 14 m (46 ft).

3.10.2. Sperry-Sun Survey

On February 14, 1977, two crews of three men each arrived with the Sperry-Sun tool. They ran two surveys in each hole, mostly at 7.6-m (25-ft) stations, and experienced no problems with the tool. The maximum internal temperature was less than 82°C (180°F). The two surveys in GT-2 produced almost identical results; the two surveys in EE-1 gave bottom-hole locations about 6.1 m (20 ft) apart.

3.10.3. Recommendations

1. Although the high-temperature survey tools worked well, the time between completion of the logging operation and receipt of the plot of the hole trajectory was too long — 16 days for Eastman Whipstock and nearly a month for Sperry-Sun. Even a few days is too long a waiting period, especially if a \$5000/day drilling rig is over the hole waiting for survey results before continuing to drill. A digital readout device for gyroscopic survey tools, which would give instantaneous values of drill angle and direction, is commercially available. If coupled to an X-Y plotter, the hole trajectory could be plotted immediately. Procurement of such a device should be pursued vigorously to eliminate the waiting time.

2. The accuracy of the survey depends upon a magnetic survey reading taken at the surface. An error of only 1° in this initial reading can cause a bottom-hole error of 1.8 m (6 ft) in a hole with a trajectory like that of EE-1. Reference points, which are not determined magnetically, should be located on the ground surface within sighting distance of the wellbores. The points will

facilitate determination of initial bearing angles for the logging crews. (This work has been done at Fenton Hill.)

3.10.4. Results

The plots of the logs for the surveys are shown on Figs. 3-17 and -18. The distance of 13.3 m (43.5 ft) between the two boreholes at 2900-m (9500-ft) depth agrees quite well with measurements made by other methods. Both tools performed adequately under the conditions for which they were designed.

3.11. Postworkover Survey

On August 29 and 30, 1977, Sperry-Sun surveyed the newly drilled portion of GT-2 and resurveyed EE-1 using hot-hole gyroscopic multishot equipment. During the previous EE-1 surveys conducted in February, the gyroscope used during the first two runs differed by 8 min from the one used in the following two runs.

Fig. 3-17.
Eastman Whipstock survey.

Fig. 3-18.
Sperry-Sun survey.

This resulted in a bottom-hole separation of about 6 m (20 ft) between the two surveys and required a resurvey.

Surveying was done at 30-m (100-ft) stations throughout the hole, except for 7.6-m (25-ft) stations in the dog legs from 2130 to 2255 m (7000 to 7400 ft) and from 2930 to 2990 m (9600 to 9800 ft). After reaching a depth of 2990 m (9800 ft), the tools were withdrawn from the hole with readings being taken every 305 m (1000 ft) as a check. Actual "in-hole" time was 5.5 h. A heat tab on the outside of the heat shield registered a temperature between 188 and 193°C.

Hole GT-2B was surveyed from 2130 to 2700 m (7000 to 8850 ft) as follows:

2130 to 2440 m (7000 to 8000 ft)	30.5-m (100-ft) stations
2440 to 2590 m (8000 to 8500 ft)	7.6-m (25-ft) stations
2590 to 2700 m (8500 to 8850 ft)	30.5-m (100-ft) stations

The 7.6-m (25-ft) stations were in intervals of sharp hole deviation where GT-2B was "kicked off" from the old hole. The bottom station was at 2700 m (8850 ft). The tool was withdrawn from the hole with check stations being taken at 152-m (500-ft) intervals up to 2130 m (7000 ft), and no readings were taken above this depth. Because all three previous surveys (two by Sperry-Sun and one by Eastman Whipstock) were so close, one was selected to tie into, thus saving the expense and time of resurveying the shallow portion of GT-2. Run 6 of Sperry-Sun was chosen because it appeared to be the most accurate and also because at 2130 m (7000 ft) it actually coincides with the previous Eastman survey run in January.

The actual "in-hole" time in GT-2 was 3.5 h. The temperature registered outside the heat shield was again 188 - 193°C. Inside, the temperature was less than 104°C.

From the most recent survey of EE-1, the distance between the original GT-2 and EE-1 at sea-level datum of -148 m (-486 ft) is 14.25 m (46.75 ft) on a bearing of N24°E. This compares with the 12.2 m (40 ft) derived at this depth from sonic-ranging experiments.

This distance at this same datum from GT-2 to the February 1977 Sperry-Sun runs 1 and 2 measures 16.3 m (53.3 ft) and to runs 3 and 4 is 17.5 m (57.5 ft). To the Eastman Whipstock survey, run in January 1977, the distance is 15.6 m (51.1 ft).

The straight line distance through the fracture from 2758 m (9050 ft) in EE-1 to 2664 m (8740 ft) in GT-2B is 94.5 m (310 ft).

Although the gyrosurveys do not exactly coincide, the distance between the boreholes at the bottom appear to be within 1.5 m (5 ft) of the distances derived from the sonic-ranging experiments.

REFERENCES

1. J. R. Archuleta, C. F. Fink, and J. Kurtenbach, "Equipment Development Report: Borehole-Fluid Sampling Tool," Los Alamos Scientific Laboratory report LA-7152-MS (February 1978).
2. J. R. Archuleta, C. F. Fink, and J. Kurtenbach, "Equipment Development Report: Fluid Injector Tool," Los Alamos Scientific Laboratory report LA-7151-MS (February 1978).
3. Bert R. Dennis and Billy E. Todd, "Transducer Technology for Deep Borehole Geothermal Environments," Proc. 8th Transducer Workshop, Wright Patterson, Dayton, Ohio, April 22-24, 1975, pp. 17-55.
4. J. R. Archuleta and B. E. Todd, "Equipment Development Report: High-Temperature Cable-Head Assembly," Los Alamos Scientific Laboratory report to be published.
5. Bert R. Dennis, Evon L. Stephani, and Billy E. Todd, "A Thermopile Probe to Measure Temperature Anomalies in Geothermal Boreholes," Proc. 9th Transducer Workshop, Ft. Walton Beach, Florida, April 26-28, 1977, pp. 330-352.
6. B. R. Dennis, J. H. Hill, E. L. Stephani, and B. E. Todd, "Development of High-Temperature Acoustic Instrumentation for Characterization of Hydraulic Fractures in Dry Hot Rock," 22nd International Instrumentation Symposium, San Diego, California, May 25-27, 1976, pp. 97-108.

4. DRILLING AND FRACTURING (B. R. Dennis, Task Mgr.; D. J. Miles; R. A. Pettitt; R. E. Williams)

The major activity in this category during FY77 was the series of workover and redrilling operations conducted in the GT-2 wellbore, with the objective of producing a low-impedance flow path from GT-2 to the fracture at the bottom of EE-1. In the course of these workover operations, some attempts were made to extend the existing fracture system.

Also discussed herein are some of the special tools and techniques employed, and unusual problems encountered, in translating conventional drilling technology to the hot granitic environment.

4.1. Fenton Hill Workover Redrilling Program

Before redrilling of GT-2 began in April 1977, the geothermal system at Fenton Hill was comprised of holes EE-1 and GT-2 drilled about 3050 and 2930 m (10 000 and 9600 ft), respectively, and connected through a high-impedance connection near the bottom of both holes. Hole EE-1 was cased to 2930 m (9600 ft). Hole GT-2 was cased to 773 m (2535 ft); below that depth a string of steel tubing [11.4 and 14 cm (4-1/2 and 5-1/2 in.)] extended to a 19.4-cm (7-5/8-in.) liner cemented into the hole with the top at 2735 m (8972 ft) and the lower end at 2930 m (9600 ft). The tubing was connected to the liner by means of a polished bore receptacle.

The plan of action for the redrilling program was to remove the tubing from GT-2, set a cement plug in the hole at appropriate depth, sidetrack the hole at about 2500-m (8200-ft) depth, and then directionally drill into the fracture extending from EE-1. Cores were to be taken to determine the characteristics and orientation of fractures encountered.

The first phase of this drilling program, removal of the old tubing string in GT-2, was accomplished smoothly. A pulling rig was rented from DA&S Oil Well Servicing, Inc. of Hobbs, New Mexico. With this equipment the tubing was removed in mid-December 1976 without incident (Fig. 4-1). At the end of March 1977, the Noble Drilling Corporation started mobilizing their N-115 rig on the Fenton Hill site (Fig. 4-2). The rig was a National 110 drilling rig with a depth capacity of 6100 m (20 000 ft).

During the redrilling effort, LASL had under contract the Minerals Management Division of Scientific Software Corporation to work with the HDR staff in planning

Fig. 4-1.

Pulling rig on location to remove tubing and PBR mandrel from GT-2.

Fig. 4-2.

Noble Company's drilling rig over GT-2.

and executing the redrilling program. C. Heibucker (Scientific Software Corp.) acted as drilling supervisor for the entire redrilling operation. John Luchetta (Scientific Software Corp.) participated as drilling engineer, particularly on cementing and well completion. Roy Lemons (self-employed) participated as drilling engineer and consultant; his knowledge and experience were very valuable to the redrilling operation.

The first attempt to sidetrack out of GT-2 began on April 7, 1977. A cement plug was set in the hole at the appropriate depth, faced off at 2519 m (8263 ft), and the kickoff attempted at the top of the plug. The downhole assembly consisted of a Dyna-Drill motor to provide power to the bit, a bent sub above the Dyna-Drill to produce the side thrust, and a single-shot orientation tool to determine bit orientation. A carbide button hard-rock bit was used. This attempt to get out of the hole was not successful.

On April 10, another cement plug was set in the hole and a second attempt was made to kick out. Diamond sidetrack bits, followed by diamond forward-cutting bits, followed by a button bit were used on the Dyna-Drill. This attempt did not succeed.

On April 23, a third attempt was started. The GT-2 wellbore was underreamed from 25-cm (9-7/8-in.) diameter to 41 cm (16 in.) for about 3 m (10 ft) so that the ledge so formed in the hole would facilitate the sidetrack operation. A cement plug was set in the hole and faced off down to the underreamed section. On April 25, a diamond bit (20-cm diam) was run on the Dyna-Drill; its performance indicated that the kick out was begun. This was followed by a 24.5-cm (9-5/8-in.) diamond bit and then with a 24.5-cm button bit. At this stage it became clear that the hole had been successfully sidetracked. It is not certain, however, whether the kick out began at the underreamed ledge or nearby in an enlarged section of the original hole.

Drilling of the new hole (GT-2A) continued closely along the intended course for several days. During the drilling in GT-2A, the target fracture was kept pressurized by pumping into EE-1. On May 5, at a depth of 2635 m (8645 ft), a pressure response was observed in GT-2A, indicating that successful contact with the target fracture had been achieved. The point of contact was directly above the point where the target fracture intersected EE-1. Figure 4-3 is a projection on a vertical plane of the course followed by the original hole GT-2, the re-drilled GT-2A, and the target fracture. (It also shows the hole GT-2B to be referred to below.) Drilling continued and a depth of 2799 m (9184 ft) was reached on May 9. During the next few days, several flow experiments were carried out to measure the impedance through the connection. These experiments showed that the impedance was unacceptably high, and on May 17 a decision was made to cement off GT-2A and to redrill along a lower trajectory in an attempt to achieve a more satisfactory connection.

On May 18 a cement plug was set in the hole at 2572 m (8437 ft), and the effort to sidetrack off this plug was begun on May 19. The hook-up used was a 20-cm (7-7/8-in.) carbide button bit on the Dyna Drill and a bent sub. This was followed by two runs with 24.5-cm (9-5/8-in.) button bits. By May 23 it was clear that kick out had succeeded (probably at about 2530 m, where the logs had indicated the presence of a ledge) by orienting so as to get out on the low side of the wellbore. Drilling continued during the next few days. Some difficulty

was encountered at 2647 m (8686 ft) in steering the hole along the desired trajectory based only on the single-shot survey. The Scientific Drilling Control directional guidance tool was brought on site and proved to be only partially useful. On May 28, a strong pressure signal was observed in GT-2B, indicating that fracture intersection had been achieved at 2673 m (8769 ft). A core was taken and then a series of flow experiments was carried out to determine the impedance. By June 3, it appeared that the impedance was not as low as had been desired, but was acceptable (< 10 bar-s/liter). A core run was made on June 19 at 2715 m (8907 ft) using a Smith Tool Stratopax coring bit. An excellent core was recovered.

The trajectory of hole GT-2B is shown in Fig. 4-3.

Directional drilling, casing, coring, cementing, and setting of open-hole packers for flow tests were of considerable importance in this drilling operation and are discussed in detail later in this section.

The completion of the hole was performed in the following manner: (1) a cement plug was set above the intersection between GT-2B and the fracture, and this plug was faced off to a depth where firm cement was found; (2) a 19.4-cm (7-5/8-in.)-o.d. casing was set from the plug to the surface and supported in a special casing-head assembly at the surface; (3) the casing was cemented from the plug up 457 m (1500 ft) and the drilling rig was released; (4) the same pulling rig that removed the old tubing from this hole returned to drill out the residual cement in the casing, drill through the cement plug, and continue to the bottom of the hole; (5) hydraulic jacks were positioned at the wellhead and were used to stretch the casing (this is necessary so that the casing string will not increase in length and extend above its present position at the top of the hole when it becomes heated during energy extraction); (6) the casing was set down on load cells, included in the design of the special casing head, and a Christmas tree was added on top of the assembly to provide a logging port and valves for pumping connections.

4.2. Drill Bits

A total of 36 bits were used in the redrilling program. Ten diamond bits were used in the sidetracking operation (Fig. 4-4). Several unsuccessful attempts were made to obtain cores with five diamond coring bits. A Smith Tool Stratopax button-type coring bit was successful in cutting a 1.2-m (4-ft) core at a depth of 2713 m (8902 ft) in the GT-2B hole. The remaining 20 bits used in the redrilling operations were hard-rock button or toothed bits.

Fig. 4-3.
EE-1/GT-2 downhole connection.

Fig. 4-4.
New sidetracking diamond bit.

Most of the drilling time was spent in sidetracking the hole and in directional drilling. The Dyna-Drill mud motor was used in these operations. The diamond bits used gave poor performance in cutting the granitic formation and lasted for only a few feet of drilling.

The button bits performed well, but little meaningful wear-life information can be extracted from the data. During the drilling of the lower part of the GT-2A hole, however, one bit, a 9JA Smith 24.5-cm (9-5/8-in.) bit, was run to failure. It drilled 137 m (448 ft) of hole in 52 h. The rotary speed for this drilling was 40 rpm, and the weight on the bit was 22.5 tons (50 000 lb). All the standard coring bits were furnished by Christensen Diamond Products; the tricone bits were by Smith and Security.

4.3. Directional Drilling

In the workover program, directional drilling was used to deviate the hole from its existing path and to guide the hole to the proper contact with the fracture from EE-1.

The requirements for the directional drilling equipment were as follows:

- to produce a side thrust on the bit at the bottom of the hole
- to operate in high-temperature ($\sim 180^{\circ}\text{C}$) zones
- to regulate the directional orientation of the drill bit
- to be as economical as possible.

To meet these needs it was decided to use a Dyna-Drill downhole mud motor to provide the required power to the drill bit, a bent sub above the Dyna-Drill to produce the side thrust, and a single-shot orientation tool to determine bit orientation and hole deviation. The Dyna-Drill is temperature-limited by the fact that it utilizes elastomers in certain critical components, thus it is not ideally suited for use at Fenton Hill downhole temperatures. Time on bottom without rotation was minimized where possible in order to extend life.

Roy Lemons was the Dyna-Drill supervisor.

A summary of Dyna-Drill runs is presented in Tables 4-I and 4-II. It is fair to state that, though a number of unsatisfactory runs were encountered, the Dyna-Drills did perform well enough that two holes were kicked out and drilled closely along the desired trajectories. As can be seen from Table 4-I, the Dyna-Drill with a bent housing was run in the hole three times. This limited experience does not warrant any conclusions as to its performance.

Steering of the hole during the directional drilling operation relied almost entirely on single-shot surveys. These were economical and effective. However, during the drilling of GT-2B, at a depth of 2647 m (8686 ft) and a deviation of $5^{\circ}15'$, it proved impossible to control the orientation of the bit with only the single-shot orientation equipment. The Scientific Drilling Control directional guidance tool was then brought in and used with LASL's wire line. Using the directional guidance tool, we determined that the bit could not be maintained in the desired orientation because of the extreme curvature of the hole. At this time the hole was drilled ahead for 9 m (30 ft) and reamed by conventional drilling before continuing with the directional work.

4.4. High-Temperature Packers

In August 1976, a sole-source purchase request was issued to Lynes United Services for the fabrication of six open-hole high-temperature packer elements and two mandrel assemblies. The fabrication and testing of the packers was completed at the Lynes facility in Houston in November, and the packers were subsequently sent to Hobbs, New Mexico, for storage until scheduled for use at Fenton Hill.

TABLE 4-I

DYNA-DRILL OPERATIONS - HOLE GT-2A

Dyna-Drill Number	Bent Sub (°)	Date of Run	Depth [m (ft)]	Operating Time (h)		Bit	Remarks
				In Hole	On Bottom		
76327 ^a	2	4/9/77	2518.6 (8263)	16	4	Sm ^b 24.5 cm (9-5/8 in.) 9JA button	Dyna-Drill (DD) did not operate; tool plugged with fill, stator overheated and damaged; sent to Midland, Texas, for repair.
76197	2	4/9/77	2518.6-2543.0 (8263-8343)	21	10	Sm 24.5 cm (9-5/8 in.) 9JA button	DD operated satisfactorily; partial disintegration of rubber marine bearing seal, sent for repair. Unable to sidetrack, recementing required.
65672 1-1/2° bent housing	1-1/2	4/12/77	2488.1 (8163)	10	1	Sec ^c 25.1 cm (9-7/8 in.) H7SGJ tooth	Drill collars plugged with cement cuttings. DD did not operate.
Same	1-1/2	4/13/77	2488.1-2494.2 (8163-8183)	13	9	Sec 25.1 cm (9-7/8 in.) H7SGJ tooth	DD operated satisfactorily.
Same	1-1/2	4/14-15/77	2494.2-2498.8 (8183-8198)	17	8	Ch ^d 25.1 cm (9-7/8 in.) MD-411ST dia. ^e	DD operated satisfactorily; partial disintegration of rubber marine bearing seal, sent for repair.
76291	1-1/2	4/16/77	2505.5 (8220)	10	1	Ch 24.5 cm (9-5/8 in.) MD-43 dia.	DD did not operate, wireline broke, pulled tool.
Same	2	4/17/77	2505.5-2508.2 (8220-8229)	19	11	Ch 24.5 cm (9-5/8 in.) MD-43ST dia.	DD operated satisfactorily.
Same	2	4/18/77	2508.2-2509.4 (8229-8233)	16	8	Ch 24.5 cm (9-5/8 in.) MD-43ST dia.	Rubber marine bearing seal deteriorated, sent for repair.
76327	2	4/19/77	2509.4-2513.4 (8233-8246)	15	7	Ch 24.5 cm (9-5/8 in.) MD-41ST dia.	Rubber marine bearing seal deteriorated, sent for repair.
76197	2	4/20-21/77	2515.2-2518.3 (8252-8262)	16	9	Ch 24.5 cm (9-5/8 in.) MD-331 dia.	DD operated satisfactorily; sent for overhaul. Unable to sidetrack after conventional drilling run to 2523.7 m (8280 ft). Underreaming and recementing required.
65661	2	4/25-26/77	2471.9-2476.8 (8110-8126)	20	9	Ch 20 cm (7-7/8 in.) MD-43GST dia.	DD operated satisfactorily. DD assembly contained fiberglass marine bearing seal.
Same	2	4/26/77	2476.8-2481.1 (8126-8140)	19	10	Ch 20 cm (7-7/8 in.) MD-43GST dia.	DD operated satisfactorily.
Same	2	4/27/77	2476.8-2480.8 (8126-8139)	15	4	Sm 24.5 cm (9-5/8 in.) 9JA button	DD operated satisfactorily; reamed hole.
76327	2	4/29/77	2480.8-2481.1 (8139-8140)	11	3	Ch 24.5 cm (9-5/8 in.) MD-43GST dia.	DD operated satisfactorily; bit did not cut, loose rock in bottom of hole.
Same	2	4/29/77	2481.1-2481.4 (8140-8141)	19	2	Sm 24.5 cm (9-5/8 in.) 9JA button	DD operated satisfactorily; clean-up run. DD assembly kept at site.
76291	2	4/29/77	2481.4-2482.3 (8141-8144)	14	5	Ch 24.5 cm (9-5/8 in.) MD-43GST dia.	DD operated satisfactorily; bit quit cutting.
Same	2	4/30/77 5/1/77	2482.3-2503.9 (8144-8215)	19	11	Sm 24.5 cm (9-5/8 in.) 9JA button	DD operated satisfactorily; no apparent damage to DD assembly. Hole GT-2A considered sidetracked at 2482.3 m (8144 ft).

^aDyna-Drill numbers, 76XXX denotes 19.7-cm diam (7-3/4 in.). 65XXX denotes 16.5-cm diam (6-1/2 in.).

^bSm - Smith Tool Company.

^cSec - Security/Dresser Industries.

^dCh - Christensen Diamond Products Company.

^edia. - diamond bit.

TABLE 4-II

DYNA-DRILL OPERATIONS - HOLE GT-2B

Dyna-Drill Number	Bent Sub (°)	Date of Run	Depth [m (ft)]	Operating Time (h)		Bit	Remarks
				In Hole	On Bottom		
65648 ^a	2	5/19/77	2510.9-2518.0 (8238-8261)	22	14	Sm ^b 20 cm (7-7/8 in.) 9JS button	DD operated satisfactorily; unable to sidetrack.
Same	2	5/20/77	2510.9-2520.4 (8238-8269)	21	13	Sm 24.5 cm (9-5/8 in.) 9JA button	Reamed hole and continued drilling; unable to sidetrack, could not locate shoulder of 20-cm (7-7/8-in.) hole.
Same	2	5/21/77	2520.4-2534.1 (8269-8314)	23	14	Sm 24.5 cm (9-5/8 in.) 9JA button	DD operated satisfactorily; hole GT-2B considered sidetracked at 2520.7 m (8270 ft.)
65670	2	5/24-25/77	2610.6-2647.5 (8565-8686)	24	17	Sm 24.5 cm (9-5/8 in.) 9JA button	DD operated satisfactorily but difficult to hold direction. Ordered Scientific Drilling Control "EYE" to site.
65686	2	5/26/77	2647.5 (8686)	8	1	Sm 24.5 cm (9-5/8 in.) 9JA button	SDC "EYE" did not work, pulled DD tool without operating.
Same	2	5/27/77	2647.5 (8686)	27	19	Sm 24.5 cm (9-5/8 in.) 9JA button	Could not orient DD assembly correctly because of extreme curvature of hole. Pulled DD tool without operating.
65670	2	5/28/77	2656.6-2672.8 (8716-8769)	16	6	Sm 24.5 cm (9-5/8 in.) 9JA button	Drilled 9 m (30 ft) of straight hole with conventional assembly, then continued with DD assembly and SDC "EYE". Fracture intersected at 2672.8 m (8769 ft), tool pulled.
65661	2	5/30/77	2675.5 (8778)	9	1	Sm 24.5 cm (9-5/8 in.) 9JA button	DD tool would not turn on bottom, operated OK upon withdrawal. May have been plugged with cuttings, but washed out on way out of hole.
65670	2	5/30-31/77	2675.5 (8778)	8	1	Sm 24.5 cm (9-5/8 in.) 9JA button	DD tool would not turn on bottom; possibly plugged. Terminated directional drilling.

^aDyna-Drill numbers, 76XXX denotes 19.7-cm diam (7-3/4 in.). 65XXX denotes 16.5-cm diam (6-1/2 in.).

^bSm - Smith Tool Company.

Two packers were tested at Houston in separate runs. The test chamber consisted of a 41-cm (16-in.)-i.d. pipe with a 25-cm (10-in.)-i.d. pipe mounted concentrically within it. The annulus was filled with heated oil; the inside pipe was filled with water and was allowed to stabilize to the oil temperature. The test chamber was preheated to 204°C; the packers were inserted in the inner pipe and soaked for 4 h before inflation. They were then pressurized to 16 MPa (2300 psi) and left for 15 h. Upon deflation they were retrieved easily from the test chamber and were still flexible, showing only a small amount of permanent set near the ends of the rubbers.

Two complete tools were made. Each tool was about 2.6 m (8-1/2 ft) long, with a 91-cm (36-in.)-long inflatable rubber section, 22 cm (8-5/8 in.) over a braided steel-wire backing. Four additional rubber elements were fabricated but not tested.

On May 11, after the fracture zone in EE-1 had been intersected at 2636 m (8645 ft) by the GT-2A bore, the first high-temperature packer was used in an attempt to improve the connection between the holes. The packer was set at 2522 m (8275 ft) in GT-2A, and pumping began at a rate of 636 liters/min (4 bbl/min) at 10.7 MPa (1550 psi). A short time later a water flow up the annulus occurred, and pumping was discontinued. The packer was pulled; the rubber element had been completely stripped off.

The next day, a second packer was set at 2513 m (8245 ft) in GT-2A, and the hole was pressurized to 11 MPa (1600 psi) at a flow rate of 150 liters/min (1 bbl/min). In about 20 min, flow again occurred up the annulus. A check of the load on the packer indicated that it was apparently still holding. Pumping was increased to 874 liters/min (5-1/2 bbl/min), the pressure rose to 12.6 MPa (1830 psi), while the annulus flow increased to 284 liters/min (75 gpm). After 159 000 liters (1000 bbl) had been injected, pumping was terminated and the hole shut in. The packer was pulled; all of the rubber element was again missing.

On May 27, a second intersection of the EE-1 fracture zone was accomplished with bore GT-2B at a depth of 2672 m (8769 ft). A packer assembly was set at 2655 m (8706 ft) on June 1 before a flow test to determine the amount of impedance between the two holes. Pumping began at a rate of 159 liters/min (1 bbl/min) and was increased to 795 liters/min (5 bbl/min) with a pressure of 12.6 MPa (1830 psi). The packer held very well, with only a small leak developing after several hours of pumping. When this packer was pulled, the rubber sheath remained in the hole,

TABLE 4-III
PACKER OPERATIONS

Date	Depth [m (ft)]	Hours In Hole	Hours Inflated At Setting Depth
May 11, 1977	2522 (8275)	31	20
May 12, 1977	2513 (8245)	25	16
June 1, 1977	2654 (8706)	17	8

Fig. 4-5.

Lynes high-temperature open-hole packer, after being pulled from setting depth of 2655 m (8706 ft) ($\sim 180^{\circ}\text{C}$) in GT-2B.

as shown in Fig. 4-5. Remains of the rubber elements continued to be circulated out of the hole on the last day of drilling, July 8.

The packers were all set with a retrievable Otis standing valve on a wire line. The setting pressure was 10.3 MPa (1500 psi).

The Lynes high-temperature packers performed satisfactorily at the elevated downhole temperature ($\sim 180^{\circ}\text{C}$). We now believe that leakage into the annulus probably occurred through fractures in the rock around the packer. Packer operations are summarized in Table 4-III.

4.5. Casing

The redrilled hole GT-2B was cased from the surface to a depth of 2613 m (8572 ft). The casing string was 20 cm (7-7/8 in.), part S-95 and part N-80, as available. Sections of the stronger S-95 were placed at the bottom of the string, where the compressive stress would be greater, and at the top, where the tensile stress would be highest. The casing was run in on June 23, 1977.

4.6. Cementing Operations

Cementing operations in the GT-2 redrilling program fell into the following categories: (1) cementing plugs for sidetracking, (2) cementing plug before setting casing, and (3) cementing of casing. All cementing work was performed by Halliburton Cementing Services of Farmington, New Mexico. The basic mix design, accepted as the standard high-stress, chemical- and heat-resistant mix throughout the oil industry, was used in all operations. This mix consisted of Class B cement, 40% silica flour, plus proprietary additives of retardants and friction reducers. Table 4-IV summarizes the cementing operations. All cement was placed through open-ended pipe except for the cementing of the casing.

4.7. Logging

All commercial diagnostic logging operations were done by Dresser-Atlas. The logs run in GT-2 from February 7, 1977 (Fig. 4-6) checked on current conditions and contributed to the lithology studies. The EE-1 logs during that period were run to determine the condition of the bonding of the cement behind the 19.4-cm (7-5/8-in.) casing. The gamma-ray log was run as a background for comparison with the radioiodine log, which was run to trace the fluid path as it channeled through the cement behind the pipe. This tracer log agreed for the most part with the results obtained by the cement-bond logs.

The suite of logs run in GT-2B from June 12 to 14, 1977 investigated hole conditions and lithology in the new portion of the hole (Fig. 4-7).

TABLE 4-IV
SUMMARY OF CEMENTING OPERATIONS

Date	Volume (sacks)	Remarks
April 6, 1977	125	Plug for sidetracking, pipe at 2580 m (8465 ft). Cement required excess setting time.
April 10, 1977	125	Plug for sidetracking, pipe at 2530 m (8300 ft). Less water and retarder used in mix.
April 23, 1977	150	Plug for sidetracking after underreaming hole to 41-cm (16-in.)-diam, pipe at 2451 m (8040 ft). Hole successfully sidetracked at 2482 m (8144 ft).
May 18, 1977	110	Plug before setting casing, pipe at 2571 m (8437 ft) in GT-2A. Hole successfully sidetracked at 2521 m (8270 ft).
June 20, 1977	50	Plug prior to setting casing, pipe at 2637 m (8650 ft). Plug moved up the hole about 152 m (500 ft); no solid cement encountered. Cement probably dispersed by flow from EE-1.
June 21, 1977	50	Same operation as previous day, but with EE-1 shut-in and unpressurized. Top of hard plug at 2595 m (8515 ft), drilled out to 2613 m (8572 ft).
June 23, 1977	360	19.4-cm (7-5/8-in.)-diam casing set at 2613 m (8572 ft). Maximum fill-up calculated to be 730 m (2395 ft) for a 25-cm (10-in.)-diam hole. Cement plug bumped on bottom with a pressure of 6.9 MPa (1000 psi); pressure built to 12.1 MPa (1750 psi), was held for 5 min, then released. Drilling of cement shoe completed on July 7, 1977.

Fig. 4-6.
Dresser Atlas Petroleum Logging
Services, February 7-11, 1977.

Fig. 4-7.
Dresser Atlas Petroleum Logging
Services, June 12-14, 1977.

The acoustic cement-bond log in GT-2B, run July 11, 1977, measured quality of the bonding behind the recently run 19.4-cm (7-5/8-in.) casing. The same log performed in EE-1 was a measure of the change, and possible deterioration, of the bonding, which had taken place since the previous running of this log on February 9, 1977.

REFERENCE

1. Roland A. Pettitt, "Testing, Planning, and Redrilling of Geothermal Test Hole GT-2, Phases 4 and 5," Los Alamos Scientific Laboratory report to be published.

5. RESERVOIR ENGINEERING (R. B. Duffield, Project Mgr.; J. W. Tester, Task Mgr.)

A major objective of the Hot Dry Rock Geothermal Project has been to construct and operate at the Fenton Hill site a heat-extraction loop capable of delivering to the surface several thermal megawatts of heat. The first realization of this objective was achieved in the last weeks of FY77 by the successful 96-h operation of the Fenton Hill circulation loop. Continued sustained operation is a primary objective for the next fiscal year.

Success in the completion and operation of the heat-extraction loop has been achieved, in part, through the many achievements in the area of Reservoir Engineering. The term "reservoir engineering" as used here includes those activities directed at understanding the creation, characterization, and performance of a hot dry rock reservoir. It includes the areas of hydraulic fracturing to create a reservoir; the development of means to map the fractures and boreholes which comprise the reservoir; the development of techniques to modify the reservoir; the development of modeling techniques to describe the hydraulic, chemical, and heat-extraction characteristics and performance of the reservoir; and the analysis of performance data obtained during experimental testing and operation of the reservoir. It also includes, in addition to these technical tasks, study of the economic aspects of HDR systems.

The objectives of the Reservoir Engineering efforts during most of the year were twofold: (1) Using the Fenton Hill boreholes and reservoir as a downhole laboratory, develop new techniques, and extend the capability of available techniques, across the range of topics included in Sec. 5. (2) Select those techniques capable of execution at Fenton Hill to elucidate the geometry and orientation of the wellbores and fracture system connected to EE-1, so that redrilling from GT-2 could produce the desired low-impedance EE-1/GT-2 connection for use in the heat-transfer loop. Project management assured that applicable techniques were identified and applied to the Fenton Hill Program in a timely fashion. Significant events and important decisions of the year related to developing the redrilling strategy and to operating the Fenton Hill reservoir are summarized below.

In November 1976, a sodium carbonate leaching experiment was carried out at Fenton Hill as an attempt to reduce the high flow impedance through the

downhole system. Although a considerable amount of quartz was dissolved, the impedance was not reduced and a decision was made to redrill out of GT-2 in a new direction to intercept the fracture which had been produced at the bottom of EE-1. While steps were being taken to bring a drilling contractor on site to begin drilling in April 1977, work continued to develop precise wellbore surveying techniques for directional drilling and to define the geometry of the fracture system.

Beginning in November of 1976, a renewed intensive effort was directed toward the use of acoustic-ranging methods to measure the distance between two boreholes and to determine the orientation of one borehole with respect to the other. An improved detonator holder and an improved geophone package were developed. In January, an experiment using these improved instruments was carried out. Twelve detonators were fired in GT-2 at a depth of 2915 m (-264 m sea level) with the geophone package at the same depth in EE-1. Analysis indicated that the bearing of GT-2 from EE-1 at 2915 m was 281° (i.e., WNW) and the separation distance was about 9 m (30 ft).

A magnetic directional experiment was carried out in December 1976, and attempted again with an electromagnet in January 1977. The results of the experiments confirmed that GT-2 was west-northwest of EE-1.

During January and February 1977, new gyro surveys of EE-1 and GT-2 from the surface to total depth were performed by Eastman Whipstock and by Sperry-Sun. Each of these surveys was carried out with survey tools that incorporated much-improved heat shielding developed by the companies, in response to the Project's needs. The hole configurations given by these surveys were available by early March and were in reasonable agreement with the LASL measurements.

There were three important results from these surveying and ranging measurements. (1) The bottom of GT-2 was west of EE-1. (2) The general configuration of each hole was determined with considerable certainty. (3) The uncertainties in the distance (± 1.5 m) between the holes at depth, and the orientation of GT-2 with respect to EE-1, were determined accurately enough to plan the redrilling strategy. This work emphasized the importance of being able to determine distance and orientation by downhole measurement for engineering HDR systems. Gyro surveys at the present state of development are not sufficiently accurate to establish relative borehole-to-borehole distances by themselves, but when complemented with acoustic ranging, the required accuracy is obtained.

During this period, a strong effort was made to develop techniques for determining the vertical extent of an inflated fluid-filled fracture by attenuation of the compressional and shear phases from acoustic sources. Successful experiments were carried out in March. Detonators were fired in EE-1 and detectors were located at predetermined depths in GT-2. Shots were made at several depths from 2415 to 2728 m (7923 to 8950 ft). Attenuation of the received signals was observed at a depth of 2630 m (8625 ft) but not as high as 2560 m (8400 ft). This result was most important in establishing the target for redrilling. An induced potential (IP) experiment executed in March was in general agreement with this attenuation experiment. Taken collectively, these experiments provided the basis for the redrilling program and dictated the path along which GT-2A was drilled. The fact that the intersections with the pressurized fracture system were found at predicted positions in GT-2A and GT-2B gave support to the validity of the techniques employed.

In addition, the study of the nature and significance of the passive microseismic signals received in a borehole while inflating a nearby fracture continued during 1976. Analysis of the signals enabled the locus of the source of the signals to be mapped with some confidence. However, the mechanism that produces the signals is not understood, nor is there an explanation for the fact that the signals are not always detectable when a fracture is being inflated. In planning the redrilling operation, only fracture orientation was inferred from passive microseismic experiments, whereas acoustic attenuation and IP were used to define vertical extent. Nonetheless, it is believed that microseismic signals generated in fractures during inflation are of great potential use in mapping fractures, and work in this area will continue.

During this period, K. Aki (MIT) was retained as a consultant by LASL to work with the HDR Project. Together with a graduate student, Michael Fehler, Aki attempted to formulate quantitatively the attenuation, reflection, and scattering of acoustic waves in their interaction with rock, in particular with rock containing discontinuities such as fluid-filled fractures. The results of his work are presented in Sec. 5.1. It is believed that continued effort along the lines initiated by Aki and Fehler will provide a sounder basis for understanding acoustic mapping methods in basement rock.

Section 5.1, Fracture and Borehole Mapping Technique Development, is treated in order under the subheadings: Borehole Ranging, Microseismic Methods, Shear-Shadowing and Acoustic Reflection Methods, Induced Potential Measurements,

Iodine Logs, Temperature Logs, Geophysical Logs, and Advanced Methods. Work in other areas of reservoir engineering appears in subsequent sections, 5.2 - 5.5. Laboratory work covering core analysis, rock thermal conductivity and permeability, rock-water interactions (solution chemistry and rock alterations), and chemical stimulation methods are discussed in Sec. 5.2. Field work concerning pressure-transient and impedance testing, fluid permeation losses, hydraulic fracturing, residence time-distribution analysis, and chemical leaching with sodium carbonate is presented in Sec. 5.3. A geometric model for the present GT-2/EE-1 system is described in Sec. 5.4; the permeability-porosity modeling work appears in Sec. 5.5. In addition Sec. 5.5 includes reservoir and wellbore heat-transmission effects and wellbore-to-fracture impedance modeling. The important economic factors relating to HDR commercialization and the present status of our cost optimization models for electric, nonelectric, and cogeneration applications are discussed in Sec. 5.6. In all cases the subsections present specific topics not necessarily consistent with the actual event chronology. Therefore, the reader is referred to Appendix B for a listing of the time sequence of experiments.

5.1. Fracture and Borehole Mapping Technique Development (R. L. Aamodt, K. Aki, J. N. Albright, M. C. Fehler, W. S. Keys, P. R. Kintzinger, J. Landt, H. D. Murphy, R. M. Potter, R. W. Spence, F. G. West)

5.1.1. Borehole Ranging

The EE-1 and GT-2 wellbores are 76.8 m (252 ft) apart at their wellheads, with EE-1 N14°E from GT-2. Wellbore surveys were made before FY77 in each hole, by gyrocompass to a depth of 762 m (2500 ft) and by magnetic compass and tiltmeter from this depth to the bottom. Cumulative errors in these surveys resulted in an uncertainty in the wellbore position of about 6 m (20 ft) in the horizontal plane near 2925-m (9600-ft) depth at the bottom of GT-2. In late 1976, the EE-1 wellbore was diverted toward the GT-2 wellbore in an attempt to intersect a fracture created from the GT-2 wellbore. Because of the uncertainty in the relative wellbore positions, an attempt was made to perform seismic ranging experiments to establish the distance and direction between the wellbores at several depths. In these experiments, detonators were fired in the GT-2 wellbore near the 2925-m depth, and the resulting acoustic signals passed through the rock and were detected by three orthogonally oriented geophones in an instrument package locked into the wall of the EE-1 wellbore at the same depth. By observing the relative signal amplitudes in the two horizontal geophones, with

their orientation known, we hoped to determine the direction of the signal source. If the travel time and velocity of the seismic signal were known, the distance between the wellbores at the firing depth could be established.

These first attempts at detonator ranging were only partially successful. Orientation of the geophone package was successfully achieved only once, and in that experiment the direction of the incoming signal was incorrectly chosen, probably because of lack of understanding of the effects of the detonator source orientation on the seismic signal. The distance between the wellbores was measured as 7.9 m (26 ft) (later experiments refined this to 9 ± 0.7 m (30 ± 2 ft)). Partially as a result of the error in direction, no intersection of the GT-2 fracture was accomplished. A high-impedance connection was achieved between the EE-1 wellbore and the GT-2 fracture. Communication was improved by creating a fracture from the EE-1 wellbore, and the next year was spent in development of experimental procedures and instrumentation to improve our understanding of the two-fracture system.

The importance of improving the seismic ranging experiment was apparent, and considerable effort was spent on this problem. The high-temperature performance of the geophones was improved by cooperation with the manufacturer. A new instrument package was constructed to work within the confines of the 11.4-cm (4-1/2-in.)-diam pipe in the GT-2 hole. The reliability of directional information obtained with this package was poor, for reasons not completely understood but probably related to the flexibility of the slim package--when clamped in the wellbore the section containing the geophones was not always properly clamped against the rock. However, the time of arrival of the seismic signal was correct. For accurate ranging, the firing time of the detonator must also be known, and some effort was spent in developing a reliable signal pulse at firing time. After this was done, experiments were begun to define the relative positions of the EE-1 and GT-2 wellbores more accurately, preparatory to redrilling.

5.1.1.1. Seismic Ranging Measurements. Until a new geophone instrument package was developed that would give reliable direction measurements, the ranging experiments had to depend on distance measurements alone. Table 5-I lists the experiments conducted at various depths in the two wellbores, converted to sea-level (SL) elevations, and the observed travel times. The detonators sometimes fired a few tenths of a millisecond after the trigger signal, so when there was a variation in transit time, the shortest time was chosen.

TABLE 5-1
MEASURED TRANSIT TIMES BETWEEN WELLBORES
IN MILLISECONDS

Sea-Level Depth (m)	Depth (ft)	Expt. 140	Expt. 143	Expt. 145	Expt. 146	Best Value
549	1800		16.03			16.03
457	1500		14.20			14.20
366	1200		12.03			12.03
274	900		9.55			9.55
183	600		7.57			7.57
91	300		6.18		6.07	6.07
55	180		5.91		5.39	5.39
18	60		5.42		4.83	4.83
-18	-60		4.32		4.24	4.24
-55	-180		3.91		3.88	3.88
-91	-300	3.82		3.29, 3.30	3.40	3.29
-198	-650	2.39		1.83		1.83
-264	-865	1.65, 1.53				1.53

In November 1976 a computer algorithm was developed that reduced acoustic-ranging data for comparison with standard, wellbore magnetic survey data for the purpose of determining the probable positions of EE-1 relative to GT-2. In the construction of the algorithm it was assumed (and later verified) that the magnetic survey of each wellbore was internally accurate--that relative wellbore depths, as well as the relative inclination and drift of each wellbore at any depth, had been accurately measured. Using the algorithm, we studied the following parameters:

- V - the propagation velocity of compressional acoustic waves between GT-2 and EE-1 at the depths at which ranging data were acquired
- σ - the standard deviation of the best fit of magnetic survey to ranging data
- $\Delta\theta$ - the relative error in magnetic survey data of the angle in horizontal projection between the GT-2 and EE-1 wellbore trajectories
- ΔZ - the relative error in measurement of depth between the GT-2 and EE-1 magnetic surveys.

The most likely coordinates of EE-1 relative to GT-2, corresponding to the best fit of magnetic survey data to ranging data, were calculated for a range of reasonable propagation velocities. The coordinates of EE-1 relative to GT-2 at -18 m (-60 ft) SL for $\Delta\theta = \Delta Z = 0$ are shown in Fig. 5-1. Depending on the value assumed for velocity, various locations are possible for EE-1.

Figure 5-2 gives the standard deviation for the best fits shown in Fig. 5-1. East and west target fits show sharp minima of comparable value at velocities of 5.85 and 6.34 m/ms (19.2 and 20.8 ft/ms), respectively. For velocities less than 6.1 m/ms (20 ft/ms), easterly positions, identified as the east target, were likely. For velocities greater than 6.1 m/ms, westerly positions, identified as the west target, were likely. Minima associated with best fits obtained for reasonable values of $\Delta\theta$ and ΔZ did not differ within measurement error from those in Fig. 5-2. Hence, the assumption that the magnetic surveys are internally accurate is valid. Table 5-II gives the differences between wellbore distances derived from magnetic survey data (calculated distance) and from ranging data (measured distance) for the most likely east and west targets.

Although this analysis served to define two likely positions for EE-1 which can be distinguished on the basis of velocity, the actual velocity was

Fig. 5-1.

Coordinates of the best fit of magnetic survey to ranging data.

Fig. 5-2.

Standard deviation of best fits vs velocity.

TABLE 5-II
CALCULATED-MINUS-MEASURED DISTANCE

Depth (m)	West Target ^a (m)	East Target ^b (m)
548.6	+1.3	0.3
457.2	-1.4	-0.6
365.8	+0.5	+1.2
274.3	-0.3	+0.1
182.9	-0.8	-1.2
91.5	-0.2	-0.8
54.9	-0.1	-0.4
18.3	-0.5	-0.5
-18.3	-0.5	-0.2
-54.9	+0.8	1.2
-91.5	+0.6	1.2
-198.1	-1.0	0.2
-263.7	+0.7	0.1
Standard Deviation	0.8	0.8

^aVelocity = 6340 m/s.

^bVelocity = 5850 m/s.

not separable from the data. Consequently only an independent measurement of relative wellbore position could resolve the ambiguity.

5.1.1.2. Magnetic Ranging Experiment. Because the acoustic ranging data could be fitted by two equally probable wellbore configurations, one with EE-1 west of GT-2 and one with EE-1 east of GT-2, both at a distance of about 9 m (30 ft) at the -264-m (-865-ft) SL depth, two experiments were devised to resolve the ambiguity. In the first of these, a 7.62-m (25-ft) -long permanent magnet was constructed from 100 bar magnets, each 15 by 2.5 by 1.2 cm (6 by 1 by 1/2 in.), placed in pairs, inside a nonmagnetic tube. The magnet was lowered into the EE-1 hole below the casing, which ended at a SL depth of -264 m (-865 ft). A standard wellbore survey tool, containing a heat-shielded compass and camera, was lowered in GT-2 below its casing, which ended at -268 m (-878 ft). Figure 5-3 shows the geometry of the experiment, and Fig. 5-4 the calculated and

observed compass deflections with the magnet placed at various depths. The calculations shown are for the configurations with GT-2 west of the EE-1 in the region of measurement. The agreement between calculations and measurements was excellent, and because the alternative wellbore configuration would reverse all the observed deflections, it could definitely be ruled out.

5.1.1.3. Acoustic Ranging with Direction. To get unambiguous direction measurements with the detonator source, the explosion had to be symmetrical in the wellbore, so that a compressive sound wave would be transmitted in all directions. A detonator holder that would assure this requirement was constructed and tested during the early ranging measurements. A new geophone instrument package, 15 cm (6 in.) in diameter, was then constructed which ensured that the geophones were pressed firmly against the wellbore wall. An experiment designed to test the directional capability of the new package, and if successful, to confirm the results of the magnetic survey, was conducted in January 1977. Twelve detonators were fired at the -264-m (-865-ft) SL depth in GT-2, with the geophone package at the same depth in EE-1. The geophone package was raised and resealed between each firing so that various package orientations could be tested. The experiment was successful; the standard deviation of a single measurement was 8.6° . The mean bearing of GT-2 from EE-1 was 281° , a direction in agreement with the results obtained with the magnet, and had a standard deviation of 2.6° . As desired, numerous different package orientations were obtained (Fig. 5-5). Figure 5-6 shows the observed signal directions. Figure 5-7 shows the relative wellbore positions finally chosen, based on the Eastman gyro survey discussed below for GT-2 (where all the surveys were in good agreement) and the single-shot magnetic survey for EE-1 (where results for this survey fell between that of the Eastman and Sperry-Sun gyro surveys discussed below). The estimated error in the relative positions near -264-m (-865-ft) depth, ± 1.5 m (± 5 ft), was very adequate for the redrilling program.

5.1.1.4. Gyrocompass Wellbore Surveys. Contracts were negotiated with Eastman Whipstock and Sperry-Sun for gyrocompass surveys in EE-1 and GT-2. They developed high-temperature tools, which became available in early 1977. The EE-1 and GT-2 wellbores were logged by Eastman in late January and by Sperry-Sun in mid-February. The results of these surveys in EE-1 and GT-2 at a depth of 2800 m (9186 ft) are also shown in Fig. 5-7. The standard deviation of the gyro-determined EE-1 positions from the sonic ranging position was 6.6 m (22 ft). The GT-2 gyrocompass positions agreed to within a radius of slightly over 1 m

Fig. 5-3.
Geometry of compass deflection experiment.

Fig. 5-4.
Calculated and observed compass deflections vs depth.

Fig. 5-5.
Azimuth of the geophone package locking arm for each detonator shot.

(3 ft). The difference in accuracy may arise from the fact that the direction of drift of EE-1 changes several times, whereas that of GT-2 is essentially constant. The gyrocompass surveys confirmed the results of the early ranging experiments, placing the bottom of EE-1 unambiguously to the east of GT-2.

5.1.1.5. Surveys During Redrilling. With the relative positions of the wellbores now well established, magnetic compass surveys were taken at regular intervals during the redrilling of paths A and B in GT-2. Details of the paths are shown in Fig. 5-7, and the final wellbore configuration (GT-2/GT-2B) is shown in Fig. 5-8. The mismatch between surveys in EE-1 in Fig. 5-8 is the result of tying the gyro surveys into the wellhead locations, but choosing the EE-1 magnetic survey location to agree with the acoustic ranging experiments, and is a measure of the relative accuracy of the surveys.

5.1.2. Microseismic Methods

5.1.2.1. Microseismic Mapping. The present method for acquiring and analyzing microseismic data has been previously reported.^{1,2} Briefly stated, early work in this area showed that (1) microseismic events could be induced through reservoir pressurization, (2) signals arising from these events and detected at a single triaxial geophone station provided sufficient information so that the foci of the events could be mapped, and (3) such maps commonly would exhibit linear trends of seismicity, which could reasonably be associated with hydraulically activated fractures. Efforts were initiated to acquire additional microseismic data, to further map the GT-2/EE-1 system prior to redrilling activities, and to better understand the source of microseismic events.

Attempts to acquire additional microseismic data were made in June 1975 (Experiment 129) and March 1976 (Experiment 159). The former involved a total of 12 hours over a period of 4 days of water injection into EE-1 and simultaneous monitoring for microseismic events while the geophone package was positioned sequentially at four different depths in GT-2. Throughout the experiment, signals of the nature shown in Fig. 5-9 were observed; however, because of low signal-to-noise ratios resulting from anomalous performance of some system elements, and of differences in frequency response between geophones, only a limited amount of useful mapping information was obtained.

The performance of the geophone system on the fourth day, during which the package was positioned at 2852 m (9360 ft), enabled us to map 11 events. The

Fig. 5-9.
Typical record of microseismic event
occurring in Experiment 129.

Fig. 5-10.
Activity induced through EE-1 pressuri-
zation (June 1976).

activity detected, now referred to as the EE-1 seismic zone, is shown in Fig. 5-10. A linear northwest-striking locus of activity is defined, which lies outside the region between the wells and represents the most distant feature of this kind mapped.

A further effort to collect microseismic data occurred in association with the acoustic attenuation measurements made in Experiment 159. Eight hours of data were obtained over 2 days during which a total of $\sim 300 \text{ m}^3$ ($79 \times 10^3 \text{ gal}$) of water was injected into EE-1 and the geophone package was positioned at either 2743 or 2591 m. Remarkably, no microseismic events of magnitudes comparable to those previously observed were detected.

When considered from the perspective of earlier efforts, these two experiments provide evidence of an "aseismic" trend in the activity of the GT-2/EE-1 fracture system. Figure 5-11 gives histograms of the activity monitored under comparable conditions in terms of injection rate ($\sim 800 \text{ liters/min} \approx 210 \text{ gpm}$) and geophone location, over the period October 1975-June 1976. Clearly the seismicity of the system has decreased. The decrease appears correlative with the decrease in maximum pressure attainable at the 800-liters/min injection rate. The latter is known to be due principally to the enlargement of the conductive

Fig. 5-11.
Histograms indicating the "aseismic" trend in the GT-2/EE-1 system.

Fig. 5-12.
Relationship of seismically active zones to known or inferred fractures.

fracture system that occurred during intervening flow experiments. (See Ref. 2, Fig. 5-10, p. 71.) These data combined with earlier mapping results are shown in Fig. 5-12, which summarizes the information relevant to the orientation of fractures in the GT-2/EE-1 system. Since the creation of the system, two seismic zones, presumably associated with hydraulically opened fractures, have been identified. Because the activity of these zones was measured with single-station seismometry, each zone may in fact be located at a position centrosymmetric to the geophone station at which the measurement was made; that is, to GT-2 for the GT-2 seismic zone and EE-1 for the EE-1 zone. Of the two possible locations, the one closest to the pressurized well was selected for plotting. Because microseismic measurements have been made infrequently during the growth of the system, these zones may be only a part of a larger, more complex seismically active system. Other fractures are known to have taken substantial amounts of water. The probable relationship of these fractures to the seismic zones is also indicated in Fig. 5-12. The orientation of the fractures in the body of the system corresponds to that indicated at the wellbore, either by seismviewer photographs or by analysis of the width of temperature anomalies, with the assumption that the fractures are vertical. Before the 1977 drilling activities the active elements of the GT-2/EE-1 system appeared to be several northwesterly striking fractures. Since then, no evidence contrary to this picture has arisen.

5.1.2.2. *Microseismic Source Mechanism.* The data available for investigation of microseismic-event focal mechanisms are limited to those contained in records obtained by using only a single triaxial geophone station. The data are further restricted by nonuniqueness in focal-point determinations. These determinations are based in part on measurements of the azimuthal approach of microseismic signals to the geophone station. Because the focal mechanism for individual events is not known a priori, two locations in opposite directions from the station are equally possible focal points. In early mapping work, a direction could often be chosen for individual events so that, collectively, event foci uniquely defined a planar zone of seismicity; that is, a planar solution was found. In these particular instances, however, a centrosymmetric ambiguity remained. Although the strike of a zone could be determined, the question of whether or not the zone lies, for example, to the northwest or southwest could not be answered without knowledge of the dominant focal mechanism(s). Ultimately, the aseismic trend and widespread dispersion of activity will make planar solutions less certain or nonunique. In the future the problem can be eliminated through the combined use of one or more stations in each of the wellbores.

Professor K. Aki (MIT), using the existing data, tentatively arrived at two possible models that may aid in explaining the seismicity of the EE-1/GT-2 system. The following is a summary of his work.

Seismograms of the microseismic events usually show large amplitude of S waves relative to P waves (see, for example, Fig. 5-9). In some cases P waves show extremely small amplitudes, suggesting the existence of nodal direction for their radiation. Because there is no nodal direction for P waves for a tensile crack, the above evidence strongly supports the assumption that these events are related to shear cracks. The idea that the events may be tension cracks, due to extension of the edge of the main crack as it is pressurized, is untenable. As described by Aki et al.,³ a tensile crack driven by excess fluid pressure is dynamically stable because the vacuum left behind the moving crack tip will act as a cohesive force under an ambient pressure. Although a jerky extension is possible if the strength distribution is heterogeneous, the seismic motion caused by such an extension will have predominant periods determined by the linear dimension of the crack. The observed spectra of microseismic events, on the other hand, suggest that their source dimension is much smaller than the linear dimension of the main crack.

Assuming that the microseismic events are shear cracks, one can interpret the senses of first motions of P and S waves in terms of the geometry of fault planes and slip directions. Consider two simple cases: a strike slip on a vertical fault plane and a dip slip on a fault plane with a 45° dip angle. The directional dependence of amplitudes of P waves and SH waves for the strike-slip case can be written as

$$\begin{aligned} P &= \sin \sigma \sin 2\phi \\ SH &= \sin \sigma \cos 2\phi \end{aligned}$$

and those for the dip-slip case as

$$\begin{aligned} P &= \sin^2 \sigma \sin^2 \phi - \cos^2 \sigma \\ SH &= \sin \sigma \sin 2\phi \end{aligned} ,$$

where σ is the angle between the vertical and the direction from its source to the receiver, and ϕ is the azimuthal angle measured from the fault strike.

Figure 5-13 shows the senses of first motions of P and S waves observed on a horizontal plane for the above two cases. The sense of slip is marked in Fig. 5-13a for the strike-slip case. The sense of slip for the dip-slip case is taken as normal, that is, the overhanging side of the fault moved downward. The radiation pattern for the dip-slip case depends on σ and ϕ . The tension axis in this case corresponds to the axis of minimum compressional principal stress (S_3), if the fault plane is formed at an angle 45° from the principal stress axis.

The pattern of P and S first motions in relation to the tension axis is quite similar for the strike-slip and dip-slip cases. This suggests that the tension axis may be reliably estimated from single-station data on the P and S first motions, even if enough data to determine a complete fault-plane solution are not available.

This method was applied to the records obtained by geophones placed in EE-1 while the EE-1/GT-2 system was pressurized through GT-2. Analysis showed that it is possible to make the foci lie along a line by an appropriate choice of the two possible alternative locations.² The azimuth of the line is determined as N27°W at geophone depth 2828 m (9277 ft), N40°W at 2965 m (9727 ft), and N63°W at 3026 m (9927 ft). The geophone depth 2828 m (9277 ft) was reoccupied later during the same experiment, and again the line of locations was determined to lie in the direction N27°W.

Fig. 5-13.
Sense of first P- and S-wave motions for
(a) strike-slip and (b) dip-slip
faulting.

Fig. 5-14.
Alternative determinations for micro-
seismic foci.

The events detected during the initial occupancy at 2828 m (9277 ft) were relocated by use of the particle motion of the first cycle of P waves read directly from the unfiltered record. Figure 5-14 shows two alternative locations for each event in a polar diagram in which the radial distance is the S-P time measured in milliseconds, and the azimuth is the direction of P-wave particle motion. For each event, the two alternative locations are plotted. These events are all clustered in two zones, each having a length of about 40 m (except one event which showed a complex record). These clustered events all showed southward onset of P waves and westward onset of S waves. The beginning of S waves is very sharp and the sense of the first motion is unambiguously defined. For this combination of the senses of P and S waves, the tension axes are found to be as shown in Fig. 5-14. The direction of tension axis differs by 90° between two alternative locations. If the events are in fact located to the north

of EE-1, the tension axis is northeast. If the events are located to the south of EE-1, the tension axis is northwest.

The records obtained at other depth levels and at 2828 m (9277 ft) later in the experiment are more complicated, and the patterns of P and S first motions indicate that more than one focal mechanism may be involved.

From the seismic data and their interpretation given above, coherent physical models of the fracture of the Fenton Hill site may be constructed. Two assumptions are made: (1) that the main crack formed by hydraulic fracturing is normal to the minimum compressional principal stress S_3 and (2) that the microseismic events are shear cracks induced by the increase of pore pressure and decrease of effective stress in the manner suggested by Lockner and Byerlee.⁴ With these basic assumptions, two models (Models 1 and 2) are possible. Because the locus of seismic activity strikes northwest,² only Model 1 is tenable.

Model 1, the least principal stress S_3 is oriented northeast. In this case, the main crack plane will be oriented northwest. Microseismic events will be dip-slip normal faulting with the dip direction to the northeast if S_1 (maximum compressional principal stress) is vertical. The events will arise from strike-slip movements on a vertical fault if S_1 is horizontal. Because the contact between gneiss and granodiorite dips northeast, it is natural to associate this contact and possible parallel discontinuities with the fault plane of microseismic events. In this case, the events arise from dip-slip normal faulting resulting from vertical S_1 . A schematic view of this model is shown in Fig. 5-15.

Model 2, the least principal stress S_3 is oriented northwest. In this case, the main crack plane will be oriented northeast. If the microseismic events are dip-slip, their slip plane would not agree with the plane of discontinuities. So, it is more natural to consider the microseismic events as strike-slip on vertical plane. In this case, S_1 is horizontal in the northeast direction. A schematic view of this model is shown in Fig. 5-16. Hill⁵ proposes a similar model to explain the source mechanism of earthquake swarms occurring in a volcanic area.

Fault-plane solutions of earthquakes to the south⁶ and north⁷ of the Fenton Hill area show the tension axis northwest (about N70°W), in agreement with Model 2. On the other hand, the gravitational effect of caldera topography may locally result in a northeast direction for S_3 at the Fenton Hill site, supporting Model 1.

Fig. 5-15.
Model 1, dip-slip normal faulting.

Fig. 5-16.
Model 2, strike-slip faulting.

5.1.3. Shear-Shadowing and Acoustic Reflection Methods

During the period March 10-22, 1976, a series of acoustic measurements (Experiment 159) were made for the purpose of delineating the vertical extent of water-bearing fractures created in the GT-2/EE-1 system. The presence or absence of fractures between wells was inferred on the basis of the scattering, attenuation, and refraction of acoustic signals intersecting the fractures under conditions in which they were pressurized.⁸ Observations made during the successful sidetracking of GT-2 into the GT-2A and GT-2B trajectories have

confirmed these inferences. Given the availability of two wells, the capability of detecting a fracture system between wells now appears to exist. A review of the experiment follows.

A triaxial geophone package was used to detect signals arising from the firing of detonators housed in a dumbbell-shaped tool. The ends of the tool served both to centralize the detonators in the wellbore and to partially deflect acoustic energy out of the wellbore. A single vertical geophone placed in the tool above the detonators enabled precise firing time to be established. The detonator signals were rich in frequency components up to 5 kHz, and therefore were particularly useful in the study. A detailed description of the geophone package has been previously given;² that for the detonator tool is given in Sec. 3.

The source and receiver positions occupied during the succession of measurements are given in Table 5-III. The four shot lines were inclined 45° to the horizontal. Experience had shown that at this inclination, signals from detonations would contain a significant shear-wave component. The upper two shot lines traverse rock dominantly granitic gneiss in lithology; the lower two, granodioritic rocks. The procedure followed on each of four successive days was:

1. With the GT-2/EE-1 system at hydrostatic pressure (unpressurized), the triaxial geophone system was locked in position in GT-2.
2. The detonator package was positioned in EE-1; three detonators were fired in succession at an interval of about 10 min.
3. The detonator package was reloaded and returned to the former position.
4. EE-1 was pressurized to 10.7 MPa (1550 psi), 1.4 MPa (200 psi) in excess of the pressure at which fractures in the GT-2/EE-1 system are known to be held open and extended.
5. Three detonators were then fired, thereby completing the measurements along a specific shot line.

A total of six signals traversed a particular shot line; three propagated through an unpressurized system, and three through a pressurized system. Of the 24 planned detonator firings, 23 were fired successfully. The station depth and coupling of the geophone package remained unchanged for all measurements along a particular shot line. As evidenced by analysis of signals traversing the 2415-m (7923-ft) shot line (discussed below), pressurization of the EE-1

TABLE 5-III

SEISMIC DATA FROM EXPERIMENT 159

EE-1 Depth Detonator (m)	GT-2 Depth Geophone (m)	Distance Along Shot Line (m)	System Pressured	P-Wave Arrival Time (ms)	S-Wave Arrival Time (ms)	P-Wave Velocity (m/ms)	S-Wave Velocity (m/ms)	$\frac{V_p}{V_s}$	Poisson's Ratio	Young's Modulus (MPa)
2415	2463	68.1		11.71	19.24	5.82	3.54	1.64	0.206	7.86×10^4
"	"	"		11.95	19.49	5.70	3.50	1.63	0.199	7.64×10^4
"	"	"		12.26	19.99	5.56	3.41	1.63	0.199	8.00×10^4
"	"	"		MISFIRE						
"	"	"	x	11.57	19.02	5.89	3.58	1.64	0.206	8.05×10^4
"	"	"	x	11.50	19.06	5.92	3.57	1.66	0.214	8.04×10^4
2560	2591	45.4		7.53	12.53	6.03	3.62	1.67	0.217	8.30×10^4
"	"	"		8.12	13.20	5.59	3.44	1.63	0.196	7.36×10^4
"	"	"		7.72	12.85	5.88	3.54	1.66	0.218	7.93×10^4
"	"	"	x	7.49	12.62	6.06	3.60	1.68	0.228	8.28×10^4
"	"	"	x	8.36	13.36	5.43	3.39	1.60	0.178	7.04×10^4
"	"	"	x	8.68	13.81	5.23	3.29	1.59	0.173	6.61×10^4
2644	2667	34.0		5.81	9.81	5.85	3.46	1.69	0.230	7.66×10^4
"	"	"		5.89	9.89	5.77	3.43	1.68	0.225	7.50×10^4
"	"	"		5.89	9.99	5.77	3.40	1.68	0.234	7.42×10^4
"	"	"	x	6.37	10.87	5.34	3.13	1.71	0.238	6.31×10^4
"	"	"	x	6.17	10.92	5.51	3.11	1.77	0.265	6.36×10^4
"	"	"	x	6.21	10.77	5.47	3.16	1.73	0.251	6.50×10^4
2728	2743	23.1		4.40	7.25	5.25	3.19	1.65	0.208	6.39×10^4
"	"	"		4.62	7.52	5.00	3.07	1.63	0.197	5.87×10^4
"	"	"		4.61	7.66	5.01	3.01	1.66	0.216	5.73×10^4
"	"	"	x	4.24	7.29	5.45	3.17	1.72	0.244	6.50×10^4
"	"	"	x	4.30	7.43	5.37	3.11	1.73	0.248	6.23×10^4
"	"	"	x	4.62	7.68	5.00	3.01	1.66	0.216	5.73×10^4

wellbore did not change the characteristics of the source appreciably. Along that shot line no effects attributable to pressurized fractures were observed.

5.1.3.1. Results. Representative examples of the signals that traversed the GT-2/EE-1 fracture system during times at which it was either at hydrostatic or elevated pressures are given in Figs. 5-17 and -18. Compressional and shear waves are clear on most records, particularly so for records obtained on the hydrostatic system. Table 5-III gives propagation velocities measured for compressional and shear waves, V_p , V_s , and also various calculated elastic parameters. The latter was calculated with a bulk rock density of 2.6 g/cm^3 . Both V_p and V_s decrease uniformly from values of 5.8 and 3.5 m/ms (19.0 and 11.5 ft/ms) at the uppermost shot line to 5.2 and 3.1 m/ms (17.1 and 10.2 ft/ms) at the lowermost shot line. No change in propagation velocity resulting from pressurization of the system can be noted within measurement precision. However, analysis of the azimuthal approach of the direct signal to the geophone package indicated that a velocity change upon system pressurization did occur along the 2644-m (8675-ft) line. Hodograms of the compressional-wave arrival show that signals traversing the pressurized system along this line deviated from those of the hydrostatic system by $3.6 \pm 1.4^\circ$. The direct arrival necessarily was refracted on oblique incidence and passage of the signal through a bound volume in which propagation velocities were changed by system pressurization. Comparable determinations could not be made with signals from other shot lines because lower signal-to-noise ratios prohibited measurements of acceptable precision.

In many respects the interpretation of the early portion (0-25 ms) of records obtained from the upper two shot lines and that from the lower two are similar. Figures 5-17 and -18 give three-component geophone records taken from a shot line of each pair--the lines initiated by the detonator positions 2415 m (7923 ft) and 2644 m (8675 ft), respectively. The low-frequency signal seen on the vertical records arose from oscillations caused by water flowing past the geophone package during system pressurization. Records for the 2644-m (8675-ft) line clearly show that the pressurization of the GT-2/EE-1 fracture system significantly modified signal waveforms. Waveforms appear to be changed in the time interval between compressional and shear arrivals, as well as in the remaining portion of the coda. Either the shear-wave arrival was lost, or the sense of the consequent first motion reversed. The variation in waveform of signals from the 2415-m line is small in comparison. The difference between

Fig. 5-17.
Triaxial geophone records from the (a) 2644-m
and (b) 2415-m shot lines.

Fig. 5-18.
Triaxial geophone records from the (a) 2644-m
and (b) 2415-m shot lines--full coda.

records can be largely attributed to nonreproducible characteristics of the detonator source pulse, and may be used as a measure of it.

The sum of the signal power measured by each triaxial component and averaged for 200- μ s intervals for all signals is given in Figs. 5-19 and -20. The arrival of compressional and shear waves is clearly evident. A third arrival occurs at 12 ms in records from the 2644-m line. After the second or third arrival signal power decays exponentially in each case except that for signals traversing the pressurized system along the 2644-m line. These signals show no appreciable decay during the first 25 ms of the coda. In fact, low-frequency components appear to have been amplified. This effect is difficult to explain by a single planar crack filled with fluid. For example, if plane waves are incident on a crack of infinite extension, the transmitted waves will always be attenuated. If the crack is finite, waves diffracted around the crack edge will interface with resulting amplification as well as attenuation. For a single-crack model with a few-hundred-meter radius, these waves will arrive much later than observed. The possibility of excitation of an interface wave guided by the fluid-filled crack is examined later in this section.

The power spectra of all signals recorded in the vertical geophone set from each shot line are shown in Figs. 5-21 and -22. Maxima in the power spectrum occur at frequencies near 600 and 2800 Hz, respectively. Signals traversing the pressurized system along the 2644-m line show an attenuation of frequency components above 1000 Hz. The loss of the 2800-Hz component implies that attenuating structures were created along this shot line, which may have a width or characteristic spacing as small as 2 m.

5.1.3.2. Reflection and Scattering. Professor K. Aki (MIT), in an examination of records from the 2415-m line, has found that although no significant changes were effected on the direct P or S waves by system pressurization, large, relatively long-period waves arriving after the passage of direct waves were produced. Figures 5-18 a and b show the entire coda of signals recorded before and during pressurization for shot lines at 2644 and 2415 m, respectively. For example, as shown clearly in Fig. 5-18b, a prominent arrival shows up about 40 ms after the direct P arrival along the 2415-m line when the system is pressurized. Professor Aki has interpreted these new arrivals as waves reflected or scattered from the inflated fractures.

To isolate the arrivals, we applied a low-pass filter to each signal from the 2415-m line to improve the signal-to-noise ratio, and the signal traversing

Fig. 5-19.
Signal power vs time, 2644-m shot line.

Fig. 5-20.
Signal power vs time, 2415-m shot line.

Fig. 5-21.
Z-component power spectrum, 2644-m shot line.

the hydrostatic system was subtracted from that traversing the pressurized system. By taking the difference, direct waves and waves scattered from heterogeneities other than the fracture were eliminated. Figure 5-23 shows band-pass-filtered, horizontal-component seismograms obtained from the 2415-m line when the system was pressurized. The filter frequency range is between 0.25 and 0.5 kHz. Also shown are differential seismograms obtained by subtracting the seismograms for the hydrostatic case (filtered by the same filter) from the ones for the pressurized case. On subtraction, the direct P and S waves disappear. Except for the first wavelet appearing at about 30 ms, the waves arriving at the time interval from 40 to 130 ms in the differential seismogram are nearly identical to the seismogram for the pressurized system. The wavelet at about 30 ms may be due to a small difference in source location between the hydrostatic and pressurized cases. If the seismic source were near a strong heterogeneity in the medium, a small change in source location would cause a large change in the seismogram. The main energy of the waves, which arrives during the time interval from 40 to 130 ms and was not present in the uninflated case, is impossible to attribute to a small change in source location. Because the direct P waves have small amplitude, those waves are probably S-to-S reflection or scattering with some contribution from S-to-P reflection or scattering from newly formed heterogeneities by pressurization of the fracture system. If they are waves caused by the S-to-S scattering, the arrivals at 40 ms imply the existence of a scatterer at a maximum depth of about 2500 m (8200 ft). In applying a similar analysis to the long-period arrivals appearing in records from the remaining shot lines, a spread of the observed arrival times (90 ms) corresponds to a depth range of the scatterer of about 150 m (500 ft) if the S-to-S scattering mechanism applies. The particle motion by the filtered differential seismogram during the passage of the scattered wave tended to be oriented linearly in the southeast-to-northwest direction after 60 ms. The particle motion was found also to be oriented in the north-northwest direction for portions around 50 ms. A similar analysis was repeated for the filter passband between 0.5 and 1 kHz. In this frequency band, a strong arrival stands out at around 50 ms, and very little difference is manifest for later portions of the seismogram between the inflated and deflated cases.

At least three interpretations of the indirect arrival identified in records obtained from the 2415-m line are possible. The arrival may be an S wave (1) scattered from the top of a fracture, (2) reflected from a vertical

Fig. 5-22.
Z-component power spectrum, 2415-m shot line.

Fig. 5-23.
X- and y-filtered components from the 2415-m shot line.

fracture located outside the region between wells, or (3) reflected from an inclined fracture. Each interpretation is compatible with the observation that, along the 2415-m shot line, the direct arriving P and S waves do not show evidence of having intercepted a pressurized fracture. The second interpretation is a special case of the third. Not taken into account is the probability that the observed records may be the result of interactions with more than one fracture. Insufficient data exist to establish which of these interpretations, or additional ones, is most probable. The following is a brief, semiquantitative discussion of the pertinent aspects of interpretations 1 and 3.

5.1.3.3. Scattering from a Vertical Crack. A complete solution of the scattering problem for a finite crack may be obtained by a finite-difference calculation but would be very time consuming. Consider only the simplest case in which the direction of propagation of incident waves is parallel to the crack plane. If the particle motion of incident S waves is decomposed into components parallel and perpendicular to the crack plane, the parallel component will have no interaction with the crack because the shear stress along the crack plane is zero for this particular incident wave. (See also Sec. 5.1.3.5, "Plane waves and elastic media"). On the other hand, the finite shear stress exists along the crack plane for perpendicularly polarized S waves. The vanishing of this stress over the crack surface, then, becomes the source of scattered waves. The scattered waves will be polarized in the direction normal to the crack plane. The predominantly northwest particle motion observed in differential seismograms after 60 ms thus suggests that the crack orientation is northeast. The strong arrival in the frequency band 0.5 - 1 kHz at about 50 ms corresponds to the crack orientation in the east-northeast direction.

For a rough order-of-magnitude estimate of the scattered-wave amplitude, the formula for S waves generated by a slip on a fault plane can be used. By placing the slip $\Delta U(\zeta, t)$ as a function of location ζ on the fault plane and time t , the amplitude of S waves may be estimated as

$$V_s \approx \frac{1}{4\pi\beta r} \int_{\Sigma} \Delta \dot{U}(\zeta, t - \frac{r}{\beta}) d\Sigma ,$$

where the dot on ΔU represents the time derivative. For such an order-of-magnitude estimate, one can assume that the slip on the crack resulting from

incident plane waves $V_0 \exp [i\omega(t - \frac{x}{\beta})]$ may be roughly equal to V_0 . By placing the length of the crack in the direction parallel to the incident wave front ℓ , the effective source area (in which a constructive interference occurs) for scattered waves may be roughly estimated as $\frac{\lambda}{4}\ell$, where λ is the wavelength. Then, the approximate result is

$$\frac{V_s}{V_0} \approx \frac{1}{8} \frac{\ell}{r} .$$

If the crack length ℓ and the distance r are comparable, as in our case, this formula shows that the scattered waves may be an order of magnitude less in amplitude than the incident waves. Because observation at the 2415-m shot line shows scattered waves with amplitudes comparable to the direct waves, either the radiation of direct S waves in the direction to the scatterer V is much stronger than along the 2415-m shot line or the fracture system consists of multiple cracks instead of a single crack.

5.1.3.4. Reflection from an Inclined Crack. To find the polarization of plane S waves reflected from a crack, consider separately the component parallel to the crack plane and the component obliquely intersecting it. If the reflector is a horizontal plane, the reflections are SH and SV waves. The following unit vectors are needed to describe the problem.

- $\hat{n}$: normal to the crack plane defined outward on the side of crack where the reflection takes place.
- $\hat{S}$: directed to the seismic source from the point of reflection.
- $\hat{r}$: directed to the receiver from the point of reflection.
- $\hat{h}$: intersection of incident wave front and crack plane. This is the direction of S-wave component parallel to the crack plane.
- $\hat{V}$: perpendicular to $\hat{h}$ in the plane of wave front. This component of S-wave motion intersects the crack plane obliquely.
- $\hat{V}_0$: direction of particle motion of incident S waves.
- $\hat{V}_1$: direction of particle motion of reflected waves when the $\hat{V}$ -component S waves are incident.

For a problem with known reflector, source, receiver locations, and incident-wave polarization, $\hat{n}$, $\hat{S}$, $\hat{r}$, and $\hat{V}_0$ are known. Then, the following equations determine the rest of the unit vectors.

$$\left. \begin{aligned} \tilde{h} \cdot \tilde{v} &= 0 \\ \tilde{h} \cdot \tilde{S} &= 0 \\ \tilde{h} \cdot \tilde{h} &= 1 \end{aligned} \right\} \quad (5-1)$$

$$\left. \begin{aligned} \tilde{v} \cdot \tilde{h} &= 0 \\ \tilde{v} \cdot \tilde{S} &= 0 \\ \tilde{v} \cdot \tilde{v} &= 1 \end{aligned} \right\} \quad (5-2)$$

$$\left. \begin{aligned} \tilde{v}_1 \cdot \tilde{h} &= 0 \\ \tilde{v}_1 \cdot \tilde{r} &= 0 \\ \tilde{v}_1 \cdot \tilde{v}_1 &= 1 \end{aligned} \right\} \quad (5-3)$$

When the incident waves consist only of SV waves (that is, $\tilde{v}_0$ is parallel to the vertical plane containing $\tilde{S}$), $\tilde{v}_0$ (v_{0x} , v_{0y} , v_{0z}) and $\tilde{S}$ (S_x , S_y , S_z) are related by

$$\tilde{v}_0 \cdot \tilde{S} = 0$$

and

$$v_{0x}S_y - v_{0y}S_x = 0 \quad (5-4)$$

The incident waves with unit amplitude may be expressed as

$$\text{Incident waves} \equiv [I \parallel] \tilde{h} + [I \perp] \tilde{v}_1, \quad (5-5)$$

where

$$\left. \begin{aligned} [I \parallel] &= \tilde{v}_0 \cdot \tilde{h} \\ [I \perp] &= \tilde{v}_0 \cdot \tilde{v}_1 \end{aligned} \right\} \quad (5-6)$$

We shall express the reflected waves as

$$\text{Reflected waves} \equiv [R \parallel] \tilde{h} + [R \perp] \tilde{v}_1, \quad (5-7)$$

where $[R \parallel]$ can be obtained from $[I \parallel]$ by solving the problem of SH-wave reflection, and $[R \perp]$ can be obtained from $[I \perp]$ by solving the problem of SV-wave

reflection. The sign of $[R \perp]$ must be compatible with the definition of $\underline{V}$ and $\underline{V}_1$. Equation (5-7) gives the polarization of reflected S waves.

As an example, let us consider the contact between gneiss and granodiorite as the reflector. The dip direction and dip angle of the contact plane are N42°E and 63° (from horizontal plane), respectively. For the 2415-m line, unit vectors defined earlier have the following values. With x-axis in the east, y-axis in the north, and z-axis upwards,

$$\begin{aligned}\underline{v} &\equiv (v_x, v_y, v_z) = (0.70, 0.55, 0.45) \\ \underline{s} &= (0.56, 0.62, 0.55) \\ \underline{h} &= (0.128, -0.720, 0.682) \\ \underline{v}_0 &= (-0.368, -0.408, 0.835) \\ \underline{v} &= (-0.819, 0.312, 0.483) \\ \underline{r} &= (0.820, 0.464, 0.337) \\ \underline{v}_1 &= (-0.559, 0.516, 0.649) .\end{aligned}$$

For an incident SV wave with unit amplitude,

$$[I \parallel] = \underline{v}_0 \cdot \underline{h} = 0.816$$

and

$$[I \perp] = \underline{v}_0 \cdot \underline{v} = 0.832 .$$

If the contact plane is inflated by nonviscous liquid and reflects SH waves completely,

$$[R \parallel] = [I \parallel] .$$

If we further assume that SV waves are completely transmitted without reflection, that is, $[R \perp] = 0$, then the reflected S waves will be polarized in the direction of $\underline{h}$. This direction, as well as that for scattered signals, is shown in Fig. 5-24. As mentioned, the predominant direction of particle motion (0.25 - 0.5 kHz) around the arrival time 50 ms is oriented north slightly west. Both the arrival time and polarization direction agree well with predictions, if we assume that $[R \perp]$ is negligible.

5.1.3.5. *Interaction of Seismic Waves with a Water-Filled*

Fracture. As mentioned earlier, signals traversing the pressurized system along the 2644-m (8675-ft) line not only show attenuation of high-frequency components (Figs. 5-21 and -22), but also indicate that low-frequency components (~ 600 Hz) in phase with comparable signals traversing the hydrostatic system are amplified. The latter effect is seen clearly in x-component records (Fig. 5-17) as a low-frequency arrival 12 ms after the P-wave onset. We tentatively concluded that this arrival may be due to waves trapped between two or more fractures acting as reflectors in both the pressurized and unpressurized case, but that their reflective properties change somewhat upon pressurization. We made the following calculations of the interaction of acoustic waves with a fluid-filled fracture to elucidate the proposed mechanism.

In this work we assumed that a fluid layer exists that extends to infinity in the xy plane and is of finite thickness d measured parallel to the z-axis. As a first step toward solving the general problem of interaction of a given finite waveform with a fluid layer, the case of plane time-harmonic waves incident on a fluid layer is studied. Because superposition of plane (and inhomogeneous) waves can yield any waveform, in principle, the case of any wave train incident on the fluid can be solved.

We assume that the fluid layer is infinite in extent to simplify calculations. The effects of edges of the fluid layer will not be important as long as source and receiver are located at least a few wavelengths from these edges and the total length of the crack is at least a few times the wavelength. When the wavelength approaches the size of the crack, the effects of diffraction around the crack tips must be considered.

Figure 5-25 shows an example of the problem to be solved. In this case a plane P wave of amplitude P_{inc} is incident on the fluid at the solid at angle γ from the plane of the fluid. At each fluid-solid contact, reflected and transmitted waves are generated. A reflected P wave of amplitude P_{ref} travels away from the fluid at angle γ . A reflected S wave of amplitude S_{ref} travels away from the fluid at an angle θ given by Snell's law. Because the fluid has finite viscosity, there will be P and S waves in the fluid. They can be expressed as upgoing (traveling in -z-direction) and downgoing (traveling in +z-direction) waves. P and S waves leave the fluid traveling in a -z-direction and are labeled P_{trans} and S_{trans} , respectively. Physical properties of the

Fig. 5-24.

Observed and theoretical polarization for signal recorded at the 2415-m line.

Fig. 5-25.

Refracted and reflected waves from a P wave incident on a water-filled fracture.

solid are given by λ , μ , and ρ , where λ and μ are Lamé's parameters, μ is rigidity, and ρ is rock density. The fluid is described by η , the viscosity; κ , the bulk modulus; and ρ^f , the fluid density.

Plane waves in elastic media. Three types of plane waves will be discussed. A P wave is a longitudinal wave; that is, the direction of particle motion is parallel to the direction in which the wave travels. Shear or S waves are those in which the particle motion is perpendicular to the direction of travel. Because the perpendicular to the line of travel defines a plane, study of the interaction of waves with plane boundaries is made easier if S waves are further classified by the vector components of the associated particle motion. The directions of the vectors are chosen according to the direction of the boundary to be studied. An SH wave is one whose particle motion is parallel to the interface under study. SH stands for horizontally polarized shear. The name clearly applies if the boundary under study is horizontal, for example, the surface of the earth. An SV wave (vertically polarized shear) is one whose particle motion is perpendicular both to the SH particle motion and to the direction of wave propagation. Generally, a shear wave is a combination of SH and SV waves. The advantage of the classification of S waves when studying plane boundaries lies in the fact that an SH wave interacts with the boundary to produce only SH waves; no P or SV waves are generated because the SH-wave particle motion is in a direction unique to the P and SV waves so that no coupling of motion to these waves can occur. P and SV waves can couple, so that study of their interactions with boundaries is generally more complicated than if only SH waves are present.

The elastic wave equation for displacements in three dimensions can be broken into four second-order differential equations if displacements are defined in terms of potential functions.

$$\vec{U} = \nabla\phi + \nabla \times \vec{\psi} \quad , \quad (5-8)$$

where $\vec{U}$ is the displacement vector, ϕ is a scalar potential that describes P waves, and $\vec{\psi}$ is a vector potential that describes S waves. The equations that ϕ and ψ_i must satisfy are

$$\rho \partial^2 \phi / \partial t^2 = (\lambda + 2\mu) \nabla^2 \phi \quad , \quad (5-9)$$

$$\rho \partial^2 \psi_i / \partial t^2 = \mu \nabla^2 \psi_i \quad . \quad (5-10)$$

For the case of P or SV waves incident with the coordinate system shown in Fig. 5-25, displacements occur only in the x- and z-directions, so we can assume that $\psi_1 = \psi_3 = 0$. For the case of SH wave incident, there is motion only in the y-direction, so $\psi_2 = 0$.

To find plane-wave solutions to Eqs. (5-9) and (5-10) we assume a solution of the form

$$\phi, \psi_i = f(\omega t - \vec{k} \cdot \vec{x}) = A \exp \{ i \omega t - i k x \cos \delta - i k z \sin \delta \} \quad , \quad (5-11)$$

where A is the amplitude of the wave, k is the wave number equal to $2\pi/\text{wave-length}$, and δ is the angle the propagation vector makes with the x-axis. By assuming a solution of the form of Eq. (5-11) calculations are made in the frequency domain, that is, the Fourier transforms of Eqs. (5-9) and (5-10) have essentially been taken.

Plane waves in viscoelastic media. To obtain the appropriate equations that must be satisfied in viscoelastic media we replace λ by $\kappa + \frac{2}{3}\mu$ and μ by the operator $\eta \frac{\partial}{\partial t}$ in Eqs. (5-9) and (5-10) to obtain

$$\rho \partial^2 \phi / \partial t^2 = \kappa \nabla^2 \phi + \frac{4}{3} \eta \partial (\nabla^2 \phi) / \partial t \quad , \quad (5-12)$$

$$\rho \partial^2 \psi_2 / \partial t^2 = \eta \partial (\nabla^2 \psi_i) / \partial t \quad . \quad (5-13)$$

Waves in a viscoelastic media attenuate because of the finite value of viscosity. This attenuation should be incorporated into expressions for ϕ and ψ_i . The amplitude of the wave must decrease along the direction of travel of the wave. One further criterion must be met by ϕ and ψ_i to specify and satisfy boundary conditions at each interface: the wavelength in the x-direction must be the same for both P and S waves in fluid and solid. This requirement can be shown to yield Snell's law. This ensures that peaks and troughs of waves coincide at the interface so that boundary conditions do not need to be functions of x. To satisfy the above two conditions, we force the solutions Eqs. (5-12) and (5-13) into the form

$$\phi, \psi \sim A \exp\{i\omega t - ik_x X \pm igZ\} \quad , \quad (5-14)$$

where $k_x = k \cos \delta$

$$g = \ell + im \quad .$$

Substituting Eq. (5-14) into Eq. (5-12) for the scalar potential we obtain expressions for m and ℓ :

$$|md| = \sqrt{\frac{-b + \sqrt{b^2 - 4ae}}{2a}}$$

$$|\ell d| = \frac{4}{3} C_1 md + \sqrt{\frac{16}{9} C_1^2 m^2 d^2 - (k_x^2 d^2 - m^2 d^2) + C_2^2} \quad , \quad (5-15)$$

where d = fluid layer thickness

$$a = 64C_1^4/9 + 8C_1^2 + 9/4$$

$$b = -k_x^2 d^2 a + 9C_2^2/4 + 4C_2^2 C_1^2$$

$$e = -C_2^4 C_1^2$$

$$C_1 = \eta w/k$$

$$C_2^2 = \rho l_w^2 d^2/k$$

A similar procedure for the vector potential yields

$$|\ell d| = \sqrt{\frac{-k_x^2 d^2 + \sqrt{k_x^4 d^4 + \gamma^4 d^4}}{2}}$$

$$|md| = \sqrt{\frac{k_x^2 d^2 + \sqrt{k_x^4 d^4 + \gamma^4 d^4}}{2}} \quad , \quad (5-16)$$

where

$$\gamma = \sqrt{\frac{w\rho}{\eta}} \quad .$$

Boundary conditions and method of solution. The boundary conditions at each solid-fluid interface for the cases of incident P or SV waves are that the displacements in the x- and z-directions, the normal stress in the z-direction, and the shear stress in the x-direction acting along the plane of contact between fluid and solid, be continuous across the interface. These four boundary conditions at each interface yield a set of eight complex equations, which can be solved to find eight complex unknowns. These complex equations can be converted into 16 real equations with 16 real unknowns which can be easily solved by computer.

As a further check, two additional equations must be satisfied at each interface. These equations come from the requirement that kinetic energy flux through an area A of the interface be conserved. The amount of energy leaving each interface must be equal to the amount of energy arriving at the interface. The rate of transport of kinetic energy through an area A at the interface is

$$KE = \frac{1}{2} \rho \dot{\vec{U}} \cdot \dot{\vec{U}}^* A \sin \partial c, \quad (5-17)$$

where $\dot{\vec{U}}^*$ is the complex conjugate of the particle velocity and c is the velocity of propagation of the P (or S) wave. The two equations resulting from the requirement of balance of kinetic energy flux are used as a check on the values of the computed reflection and transmission coefficients. In all cases, the equations were satisfied to at least three decimal places.

For the case of incident SH waves, only two boundary conditions exist at each interface. These conditions are the requirements of continuity of displacement in the y-direction and continuity of shear stress across the interface. Solution for SH waves involves only four complex equations with four complex unknowns. This problem was solved analytically.

Because SV waves at normal incidence behave like SH waves, a further check of the solution for incident SV waves is available. A check of the results of transmission and reflection coefficients for SV waves at 89.9° with those for SH waves at 90° angle of incidence shows the results to be in agreement.

Input parameters used to generate the results to be presented were chosen to correspond with conditions in situ at Fenton Hill. These are

$$\begin{aligned}
\eta &= 0.0014 \text{ P} \\
\rho^1 &= 1.0 \text{ g/cm}^3 \\
\rho &= 2.69 \text{ g/cm}^3 \\
\alpha &= 6.0 \times 10^5 \text{ cm/s} \\
\beta &= 3.5 \times 10^5 \text{ cm/s} \\
\lambda &= 3.1 \times 10^{11} \text{ g/cm s}^2 \\
\mu &= 3.3 \times 10^{11} \text{ g/cm s}^2 \\
\kappa &= 1.19 \times 10^{10} \text{ g/cm s}^2
\end{aligned}$$

Incident SH waves. Solution for SH waves or normal incidence can be written in terms of two dimensionless parameters. The first parameter is related to attenuation of waves in the fluid.

$$\gamma d = d \sqrt{\omega \rho^1 / 2\eta} \quad .$$

The second parameter is the fluid-to-solid acoustic impedance ratio.

$$Q^1 = \sqrt{\eta \omega \rho^1 / 2\mu \rho} \quad .$$

When Q^1 is near one, coupling of waves between the fluid and solid is expected. In terms of these parameters the transmission coefficient, S_T/S_i , and reflection coefficient, S_R/S_i , are

$$\frac{S_T}{S_i} = 4 G Q^1 (1+i)$$

$$\frac{S_R}{S_i} = [1 - Q^{12}(1+i)^2] \left[e^{(\gamma+i\gamma)d} - e^{-(\gamma+i\gamma)d} \right] G \quad , \quad (5-18)$$

where

$$G = e^{i\omega \frac{d}{\beta}} \left\{ \left[Q^1(1+i) + 1 \right]^2 e^{(\gamma+i\gamma)d} - \left[Q^1(1+i) - 1 \right]^2 e^{-(\gamma+i\gamma)d} \right\} \quad .$$

Figure 5-26 shows values of $|S_T/S_i| = T$ and $|S_R/S_i| = R$ on a γd vs Q^1 plane. Regions where $R = 1$ and $T = 1$ are marked. The region labeled $E = 1$ is that part of the plane where $T \neq 1$ and $R \neq 1$ but where $T^2 + R^2 = 1$, which means that all energy incident on the fluid layer is either transmitted or reflected. The region $E < 1$ is that region where $T^2 + R^2 < 1$, which means that some energy is lost because of viscous dissipation in the fluid.

When Q^1 is near 1, and γd is small, there is perfect transmission of waves by the fluid layer. As γd increases, energy is lost in the fluid and the transmission coefficient decreases. If frequency is small, γd and Q^1 are small; if frequency is large, the two parameters are large. At both of these extremes in frequency SH waves are perfectly reflected. When viscosity is high, Q^1 is large and γd is small. When viscosity is low, Q^1 is small and γd large. At both of these extremes the SH waves are perfectly reflected.

The line $Q^1 = \gamma d$ represents a line that may be completely parameterized by frequency. At constant η_1 , ρ^1 , ρ , and μ , and variable frequency, the values

Fig. 5-26.
Reflection coefficients for perpendicularly incident P waves.

of Q^1 and γd fall along a line parallel to the line $Q^1 = \gamma d$. Points A and B shown in the figure represent values of Q^1 and γd that hold downhole at Fenton Hill for frequencies equal to 10^4 and 10^2 Hz, respectively, if fluid thickness is 0.1 mm. SH waves at normal incidence will be perfectly reflected by the crack in the frequency range $10^2 - 10^4$ Hz.

Solution for reflection and transmission coefficients for SH nonnormal waves at incidence is

$$\frac{S_T}{S_i} = 4\mu k \sin\theta \eta w (i\ell - m)H$$

$$\frac{S_R}{S_i} = \left[\mu^2 k^2 \sin^2\theta - \eta^2 w^2 (i\ell - m)^2 \right] \left[e^{(i\ell - m)d} - e^{-(i\ell - m)d} \right] H \quad (5-19)$$

$$H = e^{ik \sin\theta d} / \left[\eta w (i\ell - m) + \mu k \sin\theta \right]^2 e^{-(i\ell - m)d} - (\eta w (i\ell - m) - \mu k \sin\theta)^2 e^{-(i\ell - m)d} \quad (5-20)$$

These expressions can be reduced to a form identical to Eq. (5-18) for normal incidence, if $k = \text{wave number} \ll \gamma$. This assumption is valid for Fenton Hill because, for 1000 Hz, we have $k = 1.8 \times 10^{-2}/\text{cm}$ and $\gamma = 1500/\text{cm}$. By using this assumption, redefining Q^1 by $Q^1_\theta = Q^1/\sin\theta$, replacing $e^{i\frac{w d}{\beta}}$ by $e^{i\frac{w d}{\beta} \sin\theta}$, Eq. (5-19) becomes Eq. (5-18). Thus, the plot in Fig. 5-26 is also valid for SH waves at nonnormal incidence. For a frequency of 10^4 Hz we have $Q^1 = 7.0 \times 10^{-6}$ and $Q^1_{50} = 8.1 \times 10^{-5}$, which is very near point A in Fig. 5-26. This shows that at Fenton Hill SH waves at any angle of incidence between 5 and 90° to a fluid layer of thickness 0.1 mm will be perfectly reflected.

Incident P and SV waves. Figures 5-27 through 5-30 are plots of amplitudes of transmitted and reflected waves normalized by incident SV-wave amplitudes for a fluid layer of thickness 1 mm. Values are plotted as a function of angle of incidence for three different frequencies. Also plotted in Figs. 5-27 and -28 are reflection amplitudes for the case of SV waves in a solid incident on a single solid-fluid boundary. The single interface problem has no characteristic length, so the results are independent of frequency.

Fig. 5-27.

Reflected P-wave amplitude vs incident SV-wave angle.

Fig. 5-28.

Reflected SV-wave amplitude vs incident SV-wave angle.

Fig. 5-29.

Transmitted P-wave amplitude vs incident SV-wave angle.

Fig. 5-30.

Transmitted SV-wave amplitude vs incident SV-wave angle.

The results for SV waves incident on a fluid layer of thickness 0.1 mm are essentially the same and are not reproduced here.

For the case of incident SV waves, there is a "critical angle" below which P waves in the solid are inhomogeneous, that is, they attenuate with distance away from the fluid layer. This is similar to the critical-angle phenomenon in optics when light passes between two media where the speed of light is larger in the second medium than in the first. The difference is that in our case the speed of P waves in the solid is greater than the speed of S waves in the solid. Snell's law is (see Fig. 5-25)

$$\frac{\alpha}{\cos \gamma} = \frac{\beta}{\cos \phi} \quad . \quad (5-21)$$

For a given angle of incidence, θ , Snell's law can be satisfied for real γ only if

$$\cos \theta < \beta/\alpha \quad . \quad (5-22)$$

For Fenton Hill, Eq. (5-22) is satisfied if $\theta > 54.31^\circ$. For angles less than this, reflected and transmitted P waves travel parallel to the interface and attenuate away from the fluid.

Figures 5-31 through 5-34 show results for a P wave incident on a fluid layer of thickness 1 mm. As is the case for incident SV waves, the results for a thickness of 0.1 mm are nearly frequency independent. Figures 5-31 and -32 also show, respectively, reflected P and S waves for a P wave incident from a solid against a single fluid interface.

Application to amplification of low-frequency waves.

Waves transmitted through a fluid-filled fracture may have a larger amplitude than the incident wave and still have conservation of kinetic energy flux. To see this, refer to Eq. (5-17) and Snell's law. For incident SV waves, Snell's law states that reflected and transmitted P waves travel away from the fluid at a very small angle, γ , if θ is slightly greater than critical. Replacing δ in Eq. (5-17) by γ , we see that kinetic energy flux for reflected or transmitted P waves may be very small if γ is small, even though the displacements $\vec{U}$ are large. This means that the kinetic energy flux for a reflected or

Fig. 5-31.

Reflected P-wave amplitude vs incident P-wave angle.

Fig. 5-32.

Reflected SV-wave amplitude vs incident P-wave angle.

Fig. 5-33.

Transmitted P-wave amplitude vs incident P-wave angle.

Fig. 5-34.

Transmitted SV-wave amplitude vs incident P-wave angle.

transmitted P wave may be less than that of the incident SV wave, even though the P wave has larger amplitude than the SV wave.

Figure 5-35 shows plots of amplitude vs frequency for P waves transmitted through fluid layers of thickness 1 and 5 mm. When SV waves are incident at 54.32° , just greater than the critical angle to a fluid-filled fracture 1 mm thick, waves with frequency less than about 3600 Hz leave the fluid with higher amplitude than the incident SV wave, whereas those of higher frequency leave with lower amplitude. For thickness of 5 mm, waves of frequencies less than 790 Hz have increased amplitude, whereas the higher frequencies have less amplitude than the incident SV wave.

Figure 5-36 shows a possible mechanism to explain the amplification of low-frequency signals upon pressurization of the hydraulic fracture. Two fractures are necessary to trap a wave. An SV wave is trapped between two fractures. It is trapped in such a way that it strikes the fracture at nearly the critical angle. An SV wave incident at a near-critical angle is almost perfectly reflected, whereas at other angles between 25° and 65° there is little reflected SV wave. The wave impinging on the fluid at a near-critical angle produces a transmitted P wave, which is amplified relative to the incident SV wave.

Fig. 5-35.
Transmitted P-wave amplitude vs incident SV-wave frequency.

Fig. 5-36.
Two-fracture mechanism for amplification of incident SV waves.

5.1.4. Induced Potential Measurements

Before the redrilling work, an induced potential log was made in the GT-2/EE-1 system. A steel liner between 2735 and 2920 m (8973 and 9581 ft) in GT-2 and casing to the depth of 2926 m (9600 ft) in EE-1 provide basic limits to the results that were obtained. Figure 5-37 shows the results of the measurement and the conditions under which the log was made. A current electrode was positioned at 2941 m in EE-1, 15 m below the casing. Grounding was either to a distant salt pit or to the EE-1 casing. A 5-s/cycle source current was maintained at 1 A. Potential measurements were made as GT-2 was logged from 2255 to 2758 m (7400 to 9050 ft) and from 2758 to 2255 m for conditions in which the GT-2/EE-1 system was either at hydrostatic pressure or pressurized to 10.8 MPa (1560 psi).

Differences in grounding did not change the measured potential at a given depth when the EE-1 pressure was held constant. The measurements for the two grounding configurations have been averaged and are shown in Fig. 5-37. The effect of elevated fluid pressure on the experimental rock volume is most pronounced near the top of the GT-2 casing and decreases as depth decreases, until a return to far-field, unperturbed values is obtained. Assuming that the effect seen is a direct measure of water injected into a vertical fracture, we may reasonably infer, based on decreased resistivity, that the fracture extends to 2500 m (8200 ft) between the GT-2 and EE-1 wellbores.

5.1.5. Radioactive Iodine Logs

The use of radioactive tracers in determining the position of flow entrances both in open hole and behind casing has proved very successful in EE-1 and GT-2. After a natural gamma-ray background log has been run (measuring the radioactivity that accompanies uranium, thorium, and potassium), a capsule containing 10 - 20 mCi of I^{131} in solution is either mechanically or explosively broken at a prescribed depth. Pumping is then started, and the progress of the radioactive pulse is followed by logging through it with a Geiger-Müller detector.

5.1.5.1. Experiments. The first experiment using this technique (March 20, 1976) showed radioiodine entering the fracture below the casing in EE-1. The position of the fracture was well defined by residual amounts of the iodine that may be trapped in fine fissures at the fracture entrance (Fig. 5-38). Temperature measurements taken during various stages of pumping into EE-1 have shown that a substantial fraction of the flow might be flowing behind the casing

through a poorly cemented region and then exiting into the rock higher up. Qualitative substantiation for this theory was provided by a cement-bond log (Fig. 5-39a), which showed a poorer quality of bonding from ~2758 m (9050 ft) KB* to the bottom of the casing. Another tracer experiment (February 11, 1977) was run to better define this "countercurrent" flow and to determine the exit point (or points) of the flow. The tracer (10 mCi) was released at ~2865 m (9400 ft) KB. A flow of 128 liters/min (34 gpm) was then maintained for the next 67 min, after which the system was vented. The movement of the pulse past several points in the wellbore definitely established the movement of the pulse down to the bottom of the casing and then up behind the casing to an exit region of 10-m width [2758 - 2768 m (9050 - 9080 ft)] (Fig. 5-40). Measurement of integrated gamma activity at several stations indicated that substantially all of the iodine (>90%) was traveling to this exit point and that the original fracture below the casing was accepting only a minor portion of the flow. This observation, coupled with measurements of the velocity of the radioiodine peak behind the casing, indicated that there was essentially no cement in this region. This conclusion was strengthened by the results of another cement-bond log, which now showed no bonding of the casing from 2752 m (9028 ft) KB to the bottom of the casing (Fig. 5-39b). The movement of the radioiodine at higher elevations was less well defined. Apparently, the cement bonding was good enough to force most of the flow into the exit region mentioned above. However, some radioactivity was detected in the logs taken just before venting above the 2752-m (9028 ft) KB depth with several peaks at depths of 2713 m (8900 ft) and 2731 m (8960 ft), among others. The latter peak coincides with a region of poor cement bonding. These observations are consistent with the concept of localized nonvertical regions of higher permeability intersecting a vertical main flow path. The logs are then measuring iodine bleeding away from the main fracture and crossing the EE-1 wellbore at various levels. Upon venting, the radioiodine returned as a broadened pulse with an estimated 80% of the integrated input gamma activity. Figure 5-41 shows the radioiodine intensity at several depths during the vent. An estimate of the integral of each of the curves shows that some radioiodine is returning into the EE-1 borehole between

* All depths are log depths from drilling rig kelly bushing.

Fig. 5-37.
Induced potential logs of GT-2.

Fig. 5-38.
 I^{131} definition of the primary fracture entrance in EE-1 at 2758 m.

Fig. 5-39.
EE-1 cement-bond logs.

Fig. 5-40.
The relative position of I^{131} pulse and detector during February 11, 1977 measurements.

2774 and 2804 m (9100 and 9200 ft) KB in contradiction to the flow phase, which showed that essentially no tracer was entering the borehole wall below 2768 m (9080 ft).

5.1.5.2. GT-2 Experiments. A similar experiment in GT-2 showed the major flow entrance into the GT-2 fracture to be at a depth of 2790 m (9154 ft) with ~85% of the flow entering at this point.

5.1.6. Temperature Logs

5.1.5.1. Historical Review of EE-1 Shut-In Temperature Surveys.

An historical summary of selected temperature surveys, all replotted to the same scale, is presented in Fig. 5-42. Only the downhole region of interest, 2438 - 2987 m (8000 - 9800 ft), is shown. Depths are reported as true vertical depth measured from an elevation of 2652 m (8700 ft) SL, quite close to the actual elevation of the EE-1 wellhead.

The uppermost curve of Fig. 5-42 shows a temperature survey taken December 24, 1975, 2 months after initiating a fracture in EE-1. The anomaly designated as number 1, at 2920 m (9590 ft), corresponds to the bottom of the EE-1 casing, where the first fracture was initiated. The next survey was a postflow survey taken after Experiment 114. The EE-1 surface pressure during this experiment

Fig. 5-41.
Peak I^{131} pulse intensity vs time and depth.

Fig. 5-42.
EE-1 temperature surveys.

attained 100 bars (1450 psi), which was in excess of the pressure estimated to initiate new, or extend old fractures. The pumping rate, however, was fairly low, limited to about 2.7 liters/s (1 bbl/min). This survey gives the hint of new wellbore-to-reservoir connections, designated as numbers 5 and 6. We believe that the cement between the EE-1 casing and the rock formation had deteriorated because of the high temperature, thereby allowing water to permeate up the resultant annulus and then into the formation at the depths indicated at these new connections. On three different occasions cement-bond logs were run in EE-1, which do show a steady deterioration of the cement bond below 2750 m (9000 ft). Furthermore, a review of the four-arm caliper logs run in EE-1 show that these, and the connections discussed below, often correspond to the position of joints and weak spots in the rock.

On March 5, 1976 (Experiment 117), EE-1 was pressurized to 11.4 MPa (1650 psi) at rates as high as 14 liters/s (5 bbl/min). The results are evident in the survey conducted on January 26, 1977. We now clearly see connections 5 and 6, as well as 2 through 4. Connections 2, 4, and 6 seem to be the more important ones. On May 11, 1977 (Experiment 161), after drilling path GT-2A, but before drilling GT-2B, EE-1 was pressurized to 12.8 MPa (1850 psi) at 27 liters/s (10 bbl/min). The bottom survey shows the results, a new major connection at 2650 m (8700 ft), with additional smaller connections at 2525 and 2480 m (8290 and 8145 ft).

An analysis of temperature surveys taken while pumping into EE-1 (see Sec. 5.4.4.) indicates that at this time very little water flows into the first EE-1 fracture, connection 1. Apparently, it has sealed to some extent, and most of the injected water now flows up behind the casing to regions of lower earth stress.

5.1.6.2. Identification of GT-2B Flow Connections. Figure 5-43 presents the results of several temperature surveys run in the redrilled GT-2B path. Only the depths of interest are shown, and these are reported as true vertical depths measured from an elevation of 2650 m (8700 ft). The uppermost curve shows a shut-in background survey (no flow). It shows two strong anomalies (indicated as 1 and 2) at 2700 and 2670 m (8860 and 8755 ft) and a relatively weaker anomaly at 3, where the depth is 2620 m (8590 ft). Toward the direction of shallower depths, the sudden increases in temperature that occur at 1 and 2 were caused by prior pumping into EE-1 while GT-2B was vented. The flow of hot water into GT-2B at 1 and 2 had resulted in a local heating of the wellbore there.

To determine the relative amounts of water flowing into these connections, the well was surveyed at various times after the start of pumping into GT-2B. In sequence, the results of these surveys are also presented in Fig. 5-43. The cooling of the wellbore, as well as the convective flow-induced dispersion of the anomalies, is readily apparent. The ratio of the flow rates at two particular depths, denoted as depths 1 and 2, is given by Murphy:⁹

$$\frac{Q_2}{Q_1} = \frac{\Delta T_2 g_{e,1}}{\Delta T_1 g_{e,2}} \left\{ \frac{\sqrt{1 + \lambda_2^2} - \lambda_2}{\sqrt{1 + \lambda_1^2} - \lambda_1} \right\}, \quad (5-23)$$

where the effective average gradient is

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

$$\bar{g}(t) = \frac{1}{t} \int_0^t g(\tau) d\tau \quad (5-24)$$

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

The temperature results of Fig. 5-43 were analyzed according to Eq. (5-23) and the resulting flow rates, normalized to the surface injected rates, are shown in Fig. 5-44. A total of 22% of the pumped flow enters the formation at GT-2B connection 1, 78% at connection 2, and a negligible amount at 3.

5.1.7. Geophysical Logs

Geophysical logs not discussed elsewhere in this report were taken in GT-2/GT-2B by Dresser-Atlas on June 12-14, 1977. Table 5-IV identifies the logs and gives the depth interval over which each was run. Repeat sections are associated with every log except the variable density acoustic log, which is a modified graphical representation of waveform data used in calculations of specific acoustic travel times for the Acoustilog. Above 2484 m (8150 ft) each log repeats intervals formerly covered by the GT-2 logs taken on December 10,

TABLE 5-IV

LOGS RUN JUNE 12-14, 1977, IN GT-2/GT-2B

Log	Primary Interval (m)	Repeat (m)
Laterolog		
Spontaneous potential ^a	T.D. ^b - 778	T.D. - 1830
Gamma Ray		
4-arm caliper	T.D. - 1646	T.D. - 2438 2600 - 2450 792 - 746
Spectralog	T.D. - 2438	T.D. - 2652
Signature	T.D. - 2438	None
VDL	None	T.D. - 2438
Acoustilog	T.D. - 2378	2438 - 2378

^aThe SP log is unreliable above 2100 m (6900 ft).

^bT.D. = total depth.

1974. The following is an overview of significant aspects of the logs with regard to properties of the GT-2/EE-1 reservoir rocks.

5.1.7.1. Four-Arm Caliper Logs. Figure 5-45 shows primary and repeat caliper logs for the bottom 76 m of GT-2B. Caliper anomalies between 2639 and 2651 m (8658 and 8698 ft) were produced by reaming. The lower two anomalies are evident at depths at which pressurized fractures were intersected during drilling. These zones are the producers in the present system. Asymmetric caliper anomalies of a similar nature were also present in EE-1 after its completion. With continued operation of the GT-2/EE-1 loop, temperature (see Sec. 5.1.6) and, in some cases, cement-bond anomalies appeared at depths comparable to the caliper anomalies. Figure 5-46 shows the relationship between anomalies in EE-1. Clearly, the caliper anomalies indicate the presence of natural fractures with a characteristic spacing of 4 m, which could be, and in several cases were, activated hydraulically during tests of the GT-2/EE-1 system. Zone anomalies 2 through 4 are directly accessible by water flowing in the annulus behind the casing in which cement integrity has been lost (see Sec. 5.1.5.). The primary injection zone in EE-1 is at the depth corresponding to

Fig. 5-43.
GT-2B temperature surveys.

Fig. 5-44.
GT-2B flow fraction vs depth.

Fig. 45.
GT-2B caliper logs.

anomaly 4. Because the cement is intact between anomalies 6 through 9, the temperature and cement-bond anomalies may well be produced by flow in fractures intersecting EE-1.

5.1.7.2. Laterolog. Figure 5-47 shows the GT-2B, EE-1, and a previous Laterolog from the 2650- to 2710-m (8694- to 8892-ft) depth interval. Good replication is seen in the primary and repeat GT-2B logs. In the GT-2B logs several depth intervals show a constant resistivity of 8000 Ω -m. This value does not represent the true formation resistivity, but rather the upper limit measurable with the Dresser tool. Below this resistivity the rocks exhibit considerable character. None of the low-resistivity plateaus, broad maxima exceeding 8000 Ω -m, or asymmetric spikes seen in the EE-1 log appear in the GT-2 counterpart. This observation suggests that the EE-1 data, formerly considered to be significant, are fallacious. A direct indication of the fluid-filled fractures intersected during GT-2B drilling, which appear in the caliper logs, is not evident.

5.1.7.3. Spectralog and Acoustilog. The application of the Spectralog in the study of the basement rocks at Fenton Hill has already been presented.¹⁰ On completion of the GT-2B log, sufficient information became available so that we could determine the spatial orientation of the gneiss-granodiorite contact near the top of the EE-1/GT-2 fracture system. Figure 5-48 clearly shows the resolution with which the contact has been defined in GT-2, GT-2B, and EE-1. The contact strikes N27 $\pm$ 2°W, dipping northeasterly at 52° $\pm$ 10.

The Acoustilog shown in Fig. 5-49, along with an earlier log, represents the first successful Acoustilog taken at Fenton Hill below 2750 m. The accomplishment is attributed to use of a combination of low logging rate, $\sim$ 4 m/min (13 ft/min); reduced signal repetition rates (5 signal/s); noise gates; and logic for the rejection of extraneous signals. A second GT-2/GT-2B log from 2438 to 2377 m (8000 to 7800 ft) replicated details of the primary log to a resolution of 1 μ s/m, so that the validity of the log was confirmed. The log shows that below 2400 m (7875 ft) the reservoir rocks exhibit a uniform velocity of 5.85 m/s (19.2 ft/s), as measured at the GT-2B wellbore. This value of velocity corresponds closely to that measured by active acoustic ranging techniques (Sec. 5.1.1.).

5.1.7.4. Televiewer Logs. Beginning in 1975 the open-hole regions of the GT-2 borehole were scanned by means of the USGS high-temperature borehole televiewer, under the direction of Scott Keys. The borehole televiewer,

Fig. 5-46.

Four-arm caliper and cement-bond anomalies.

Fig. 5-47.
EE-1 and GT-2B Laterologs.

Fig. 5-48.

EE-1, GT-2, and GT-2B gamma-log definition of the gneiss-granodiorite contact.

Fig. 5-49.
GT-2 and EE-1 Acoustilogs.

developed by Zemanek et al.,¹¹ is a sonic scanning tool with a demonstrated capability of detecting and mapping natural as well as induced fractures that intersect the borehole wall.² Several examples of these features in GT-2 are shown in Fig. 5-50, in which typical fractures appear as sinusoidal intersections on the televiewer map of the borehole wall. Orientation of the scans is provided by a magnetometer, which starts the circumferential traces at magnetic north. A specific example is a fracture (Fig. 5-50a) entering the wellbore at a depth of 2634 m (8643 ft) and leaving at 2635 m (8646 ft). The dip and direction of dip of this fracture derived from the map are 71° and 287° (N73°W), respectively.

The televiewer shows numerous fractures in the original GT-2 wellbore, similar to those shown in Fig. 50a, throughout the depth range of the EE-1/GT-2B fracture system. Pressurization of these natural features may be providing the additional lateral flow paths that are required in one model of the system.

Figure 5-50b shows a complex fracture system in the EE-1 borehole below the casing. This system, as shown in other televiewer maps, extends over a length of ~33 m (110 ft) in the EE-1 wellbore. Analysis of these pictures gives a set of fractures dipping 80° with dip angles either northeast or southwest (Fig. 5-51). Orthogonal to this fracture set is a near-vertical fracture striking $N33^\circ E$. Tracer experiments show that pressurization causes fluid to enter the wellbore wall over this region.

Other portions of the televiewer scans have been analyzed for the location of other fractures. Figure 5-52 is a frequency plot of the directions of dip for all detectable fractures in GT-2 between 836 and 2704 m (2744 and 8871 ft).

5.1.8. Advanced Methods

Many techniques other than those thus far reviewed can possibly yield pertinent information regarding the size, height, and orientation of hydraulic fractures. Two such methods, both in a conceptual stage, have received special attention. These are techniques based on tiltmeter and magnetic induction measurements. The former is not constrained by casing and so can be particularly helpful in studying the height and orientation of fractures in EE-1 above 2926 m (9600 ft). The latter represents an extension of existing methods for detecting horizontal or nearly horizontal fractures to provide for optimum resolution of vertical fractures believed to be prevalent in the EE-1/GT-2 system.

5.1.8.1. Tiltmeter. Modern tiltmeters can resolve tilts of 10^{-8} rad at 1-Hz bandwidth, and have an inherent long-term stability of 5×10^{-7} rad per month. They are linear over the range of $\pm 6 \times 10^{-3}$ rad (0.34°), so the tiltmeter must be initially aligned within 0.3° of vertical. However, such tiltmeters must be operated within a temperature range of $-30^\circ C$ to $+50^\circ C$, and therefore require environmental protection downhole.

Large fractures at a depth of a few radii below the surface can theoretically be detected by the deflections they produce at the surface, but the calculated signal is only marginally above surface noise.

Downhole, at distances as far away from the fracture plane as 0.4 radius, Sneddon's calculations¹² show that the change in tilt, when a 100-m-radius fracture is inflated, is 50×10^{-8} rad for a fracture 0.1 mm wide, or 500×10^{-8} rad

Fig. 5-50.
Representative televiwer logs from GT-2 and EE-1.

Fig. 5-51.
Attitude of fractures mapped in the
2935- to 2949-m depth interval.

Fig. 5-52.
Histogram of fracture dip angles.

for one 1 mm wide. Over large regions the direction of tilt will be away from the fracture plane, so fracture orientation can probably be determined in a single wellbore near the fracture, conceivably from the wellbore from which the fracture was made. The location of the top and bottom of a fracture should also be determinable with accuracy of a few tenths of the tiltmeter-to-fracture distance.

The extreme sensitivity of the tiltmeter makes it susceptible to mechanical and thermal perturbations accompanying fluid flow in a wellbore. The magnitude of these effects can only be determined by experiment. Another disadvantage of the tiltmeter is the time required for a single measurement, as it will always be necessary to change the state of fracture inflation to obtain meaningful data. Strategies such as growing a fracture past an emplaced tiltmeter may improve the efficiency with which information is gathered.

The tiltmeter will, of course, also respond to swelling or shrinkage of rocks from changes in pore fluid pressure or temperature; therefore, it may be difficult to interpret the response if several mechanisms are combined.

A downhole tiltmeter may provide new information different from that obtainable by other techniques. Like other downhole tools it should be used as part of an ensemble of measurements to define downhole geometry.

5.1.8.2. Vertical Induction Log. The state of the art in induction logging tools permits determination of formation resistivity in the range from 0.1 to 1000 Ω -m. Present tools are limited to about 150°C. These devices are designed to operate in oil-based (nonconductive) drilling fluid, and look "into" the rock about 3 m. The instrument measures secondary magnetic fields driven by eddy currents in the formation. The received signals are very small (on the order of tens-of-nanovolts or -160 dBV). Extreme care must be given to the electronics, grounding, shielding, mechanical deformations, etc. Present induction logs work very well as a result of many years of refinement and experience. The tools are designed to detect horizontal fractures or changes in the properties of horizontally layered formations.

We considered using magnetic induction to detect vertical conductive fractures because (1) redundant measures of fracture orientation based on different physics is needed; (2) the magnetic induction technique can perform the required mapping task, providing information on the fracture orientation near the borehole; and (3) the magnetic induction technique has been highly refined by industry, and good use can be made of their experience.

Because this instrument has major differences from its industrial counterparts, and because of the initial specialized application, the Hot Dry Rock Geothermal Project has funded the initial development efforts.

Summarized here are the use, theory, and design considerations of a high-temperature vertical conductive fracture detector.

Instrument use. The instrument will measure the orientation of a vertical conductive fracture if the fracture thickness times the fracture conductivity is greater than 10^{-4} mho. The instrument is placed in the borehole at the location the fracture orientation is desired. The fracture orientation is essentially averaged over a volume roughly 1/2 m from the borehole wall in the vicinity of the coil sets in the instrument. The fluid in the borehole is the same fluid filling the fracture, and because the borehole fluid is much nearer to the coils than the fracture, this borehole fluid must be displaced for proper operation. The fracture orientation is mapped by rotating the coil set, either mechanically or synthetically by electronic processing. Because of the nature of the magnetic fields produced by a coil, the instrument performs best in a singly fractured system. The fine detail of multiple fractures cannot be measured. As conceived, the instrument will be self-contained with the thermal protection for the electronics and power supplied from the surface.

Theory of operation. The basis of operation of the instrument can be summarized by several equations from electromagnetic theory. Consider the two-coil instrument shown in Fig. 5-53. The quasistatic electric field surrounding a small current loop (the upper coil) is

$$E_{\phi} = -j \frac{2\pi \times 10^{-7} f I_T N_T S_T}{r^2} \sin\theta \text{ v/m} , \quad (5-25)$$

where $j = \sqrt{-1}$; the conventional r , ϕ , and θ spherical coordinate system is used; f is the frequency in hertz; I_T is the current; N_T is the number of turns; S_T is the area of the loop; and the medium is assumed to contain no magnetic material.

This electric field sets up currents in the surrounding conductive structures. This current distribution can be found from Ohm's law for cases where the geometry contains the symmetry of E_{ϕ} :

$$J = \sigma E \text{ A/m}^2, \quad (5-26)$$

where σ is the conductivity of the surrounding medium. (If the geometry does not contain this symmetry, a more elaborate boundary value solution is required.)

The magnetic field at the receiving coil can then be found with Ampere's law:

$$\vec{H}(\vec{r}) = \int_V \frac{J \, ds \, d\vec{l}' \times (\vec{r} - \vec{r}')}{|\vec{r} - \vec{r}'|^3}, \quad (5-27)$$

where r is taken at the location of the receiver coil and r' is taken at the location of the eddy currents, J .

Finally, the voltage induced in the receiving coil is found by

$$V_R = N_R \frac{d\Phi}{dt} \quad (5-28)$$

or

$$V_R = j N_R S_R 8\pi^2 \times 10^{-7} f \vec{H} \cdot \hat{n}_R. \quad (5-29)$$

Combining these equations for a homogeneous medium (that is, the rock in which the fracture is formed) yields

$$V_R = - \frac{(8\pi^2 \times 10^{-7} f)^2}{8\pi R} N_T S_T I_T N_R S_R \sigma \text{ volts}, \quad (5-30)$$

where R is the distance between the coils and σ is the conductivity of the rock.

A direct magnetic path exists between the two coils, giving rise to a "transformer" signal. This signal is

$$V_T = j \frac{8\pi^2 \times 10^{-7} f}{4\pi R^3} N_T S_T I_T N_R S_R \text{ volts}. \quad (5-31)$$

This signal can be 1000 to 10 000 times as large as the signal arising from the rock or the fracture, and, consequently, is eliminated by the addition of a third, "bucking," coil by choosing

$$\frac{N_T S_T}{R_T^3} = \frac{N_B S_B}{R_B^3} \quad (5-32)$$

and $I_T = I_B$, as shown in Figs. 5-54 and -55.

A detailed analysis shows that the borehole fluid must be displaced, which leaves a rectangular hole in the fracture. The three coils are located in this hole. For this geometry, the signal caused by the fracture is

$$V_F = (4\pi \times 10^{-7} \text{ f})^2 N_T S_T I_T N_R S_R \sigma t F \cos^2 \beta \text{ volts}, \quad (5-33)$$

where σ is the conductivity of the fluid filling the fracture, t is the thickness of the fracture, F is the function of the geometry of the problem (that is, coil locations), and β is the angle between the plane of the coils and the plane of the fracture. Typically, F is about 30 for the instrument now under design.

The $\cos^2 \beta$ term permits the fracture direction to be mapped. The coils are rotated, and a maximum signal indicates that the coils are lined up with the fracture.

Typical expected signal levels are:

Transformer, $V_T = 1.13 \text{ mV}$.

Rock, $V_R = 0.46 \text{ } \mu\text{V}$

Fracture, $V_F = 0.18 \text{ } \mu\text{V}$.

Instrument design. Several aspects of the design (see Fig. 5-55) have been mentioned earlier, such as the three-coil configuration and a means required to displace the borehole fluid. The electronics must be both very stable and sensitive. Generally, synchronous phase-sensitive detectors will do this job best. The local earth's magnetic field will be used as a local reference direction. A commercial fluxgate magnetometer will provide this information in a manner similar to the system used in the USGS televiewer. The measurements will be digitized and transmitted to the surface on the wire line. For mechanical simplicity and reliability, two complete coil sets will be used

Fig. 5-53.
Two-coil induction tool.

Fig. 5-54.
Elimination of transformer signal by
bucking coil.

Fig. 5-55.
Hardware requirements for vertical in-
duction logging tool.

and the coil rotation synthesized electronically, thus requiring no actual mechanical rotation. The measurement will sequence automatically upon application of power to the electronics. Borehole fluid will be displaced with an inflatable bladder. This bladder will be inflated with oil; the pumping system will be contained in the instrument. The electronics will be protected with a pressure housing and a dewar. The remainder of the instrument will be constructed to operate at downhole ambient temperature and pressure. The coil support section must be made of a high-temperature dielectric material.

This concept incorporates a wide variety of currently used techniques. No breakthroughs are required, but some development is necessary because no instrument has yet been constructed employing all of these concepts.

5.2. Laboratory Studies of Reservoir Properties (J. P. Balagna, L. A. Blatz, R. W. Charles, J. G. Dodson, C. J. Duffy, A. C. Eddy, C. O. Grigsby, C. E. Holley, Jr., A. W. Laughlin, J. M. Potter, W. L. Sibbitt, J. W. Tester, R. J. Vidale)

5.2.1. Core Studies

During the drilling of GT-2 and EE-1, 29 cores totaling about 36 m were collected from the Precambrian section. As previously reported,^{2,10,14,15} Precambrian lithologies were determined by modal analysis, geochemistry, and spectral gamma logging, as well as by macroscopic examination. Whole-rock major- and trace-element analyses have now been performed on 40 samples. Geochronologic studies¹⁶⁻¹⁹ have helped determine genetic relations and characterize the thermal history of the Precambrian rock units.

Briefly, the Precambrian section largely consists of an extremely variable 1700-My-old gneissic unit with some included schists or amphibolite, intruded by a major 1400-My-old biotite-granodiorite pluton and three monzogranite dikes, apparently contemporaneous with the pluton. The granitic gneisses, which comprise about 75% of the Precambrian section, are foliated and over a few centimeters distance range compositionally from syenogranitic to tonalitic, averaging monzogranitic. The biotite granodiorite is the reservoir rock; it is very homogeneous, characterized by high-modal biotite and sphene and high K_2O , TiO_2 , and P_2O_5 contents (see Table 5-V). Filled or healed fractures, containing primarily calcite or silica, are ubiquitous in the biotite-granodiorite reservoir rock.

Microprobe studies (MP) are underway of the major mineralogy, alteration products, and fracture fillings in the Precambrian rocks, particularly in the reservoir rock. Generally, the felsic minerals are analyzed by microprobe for six elements, sodium, aluminum, silicon, potassium, calcium, and iron; and the

TABLE 5-V
BIOTITE-GRANODIORITE RESERVOIR ROCK

Whole-Rock Chemistry ^a (Average of 6 samples)		Modal Analysis ^b (Average of 3 samples)	
Oxide	(%)	Mineral	(%)
SiO ₂	64.27	Alkali feldspar	19+6
TiO ₂	0.95	Plagioclase feldspar ^c	36+5
Al ₂ O ₃	14.48	Quartz	26+6
Fe ₂ O ₃	2.96	Biotite	12+3
FeO	2.92	Chlorite	0.5+
MgO	1.39	Opaque minerals	<1
CaO	3.11	Muscovite	0.5+
MnO	0.091	Myrmekite	≤ 1
SrO	0.044	Calcite	0.5+
Na ₂ O	3.32	Epidote	2+2
K ₂ O	4.23	Apatite	<1
H ₂ O(-)	0.07	Sphene	2+1
H ₂ O(+)	0.98	Zircon	Tr ^d
CO ₂	0.26	Amphibole	<0.5
P ₂ O ₅	0.57	Other	Tr

^aReference 14.

^bSee Table 5-VII for mineral chemical formulae.

^cComposition: An₃₃₊₃ or 30 - 36% Ca-end member.

^dTr ≤ 0.1%.

mafic minerals for ten, potassium, chromium, sodium, calcium, manganese, magnesium, titanium, iron, aluminum, and silicon.

Reconnaissance probe work on the feldspars in the biotite-granodiorite pluton reveals that the plagioclase is generally oligoclase, ranging in composition from An₂₄ to An₂₉, with rare andesine (An₃₂). The oligoclase sometimes has more sodic (even albitic) rims (An₄₋₁₈), or, rarely, rims of alkali feldspar (Or₅₉). There is some albitic plagioclase with cores ranging from An_{0.1} to An_{5.0} and rims, An_{0.2} to An_{5.0}. The albite exhibits minor zoning, or has rims

that may be more calcic or more sodic than the cores. Rarely, end-member albite ($An_{0.3}$) is rimmed by end-member orthoclase (Or_{97}). Alkali feldspar grains analyzed range from Or_{90} to Or_{99} ; some have oligoclase (An_{15}) rims.

Probe studies of mafic minerals, particularly biotite or chlorite and amphibole, have also been initiated (see Tables 5-VI and -VII). In the biotites, Fe_2O_3 and FeO , and TiO_2 tend to be low, and Al_2O_3 , MnO , MgO , and K_2O tend to be high. SiO_2 , and Fe_2O_3 and FeO values are generally lower at shallower depths, whereas MnO and MgO have slightly higher values at shallower depths. In the chlorites at the 2906-m (9527-ft) depth in GT-2, MnO and K_2O tend to be high and CaO is low.

TABLE 5-VI
CHEMICAL ANALYSES OF BIOTITE AND CHLORITE FROM
THE BIOTITE-GRANODIORITE RESERVOIR ROCK

Oxide	Biotite ^a (%)	Chlorite ^b (%)
SiO_2	32-38	25-30
TiO_2	1-2	<1
Al_2O_3	14-17	17-21
Total Fe as FeO	16-20	22-23
Cr_2O_3	0-1	<0.05
MnO	0.4-0.7	0.7-1.0
MgO	11-13	16-18
CaO	0-6	≤0.3
Na_2O	<0.1-0.2	<0.1
K_2O	8-10	<0.1-3.0

^aRange of 71 microprobe analyses of biotites from four samples from depths 2906, 2907, 2930.1, and 2930.4 m (9527, 9530, 9607, and 9608 ft) in GT-2.

^bRange of three analyses from depth 2906 m (9527 ft) in GT-2.

TABLE 5-VII

CHEMICAL FORMULAE, BIOTITE-GRANODIORITE MODAL ANALYSIS MINERALS

Alkali feldspar (orthoclase or microcline)	KAlSi_3O_8
Plagioclase feldspar	
Anorthite (An)	$\text{CaAl}_2\text{Si}_2\text{O}_8$
Albite (Ab)	$\text{NaAlSi}_3\text{O}_8$
Quartz	SiO_2
Biotite	$\sim\text{K}(\text{Fe},\text{Mg})_3(\text{OH})_2(\text{AlSi}_3\text{O}_{10})$ plus substitutions
Chlorite	$(\text{Mg},\text{Fe})_6\text{Si}_4\text{O}_{10}(\text{OH})_8$ plus substi- tutions
Muscovite	$\text{KA}l_2\text{Si}_3\text{AlO}_{10}(\text{OH})_2$
Myrmekite	An:Ab feldspar and SiO_2 (quartz)
Calcite	CaCO_3
Epidote	$\text{Ca}_2\text{Fe}^{+3}\text{Al}_2\text{Si}_3\text{O}_{12}(\text{OH})$
Sphene	CaTiSiO_5
Zircon	ZrSiO_4
Amphibole (Ferrohastingsite)	$\text{NaCa}_2\text{Fe}_4^{+2}\text{Fe}^{+3}\text{Si}_6\text{Al}_2\text{O}_{22}(\text{OH})_2$

5.2.2. Thermal Conductivity

The lifetime and heat extraction rate from a given-size HDR reservoir can be substantially controlled by the in situ rock thermal conductivity. Therefore, information concerning the dependence of thermal conductivity (λ) on moisture content and temperature is important for proper design and management of the reservoir. A combined effort of laboratory and field measurements^{20,21} was completed in FY77 and the results are summarized below.

For the laboratory studies, well-characterized GT-2 core specimens were used. Thermal conductivities, modal analyses, and densities were determined for all Precambrian core samples studied under wet and dry saturated conditions. A cut-bar thermal conductivity comparator was used for steady-state measurements parallel to the core axis, and a needle probe was used for transient measurements perpendicular to the core axis. Fused quartz and Pyroceram 9606 were used as reference standards for both types of measurements. Dry rock samples were measured from 0 - 250°C; wet, water-saturated rock samples were limited to a range

below room temperature. Thermal conductivities of water-saturated rocks were of the order of 1 - 4% higher than the dry rock, but at this time we are still uncertain about the degree of saturation achieved.

Figure 5-56 summarizes the conductivity values measured from 0 - 250°C on selected GT-2 samples described in Table 5-VIII. The sample designation corresponds to the depth (in feet) below the surface, as measured from the kelly bushing on the drilling rig.

Sample 9608, described as a foliated gneiss with foliations parallel to the axis of the core, was selected for conductivity determinations in both directions - parallel and perpendicular to the axis of core. The conductivity values and their temperature coefficients for orthogonal directions were nearly equal for a sample thickness of 3.75 cm. The conductivity parallel to the foliations increased as the sample thickness was decreased. For example, for a sample thickness of 0.8 cm the conductivity in the parallel direction was more than 20% greater than the conductivity in the perpendicular direction. Measurements made on foliated rocks can be very misleading until a sufficiently thick sample is used to provide a statistically representative path for heat flow. For this core, 3.75 cm was adequate. For all other granite samples tested, there was no observable difference between parallel (steady-state cut-bar comparator) and perpendicular (transient needle probe) measurements of λ on the same sample for thicknesses of 1 cm or more.

A comparison between GT-2 λ values in the biotite-granodiorite section of GT-2 and data presented by Birch and Clark²² for selected granitic rocks is shown in Fig. 5-57. The gradual decrease of conductivity with increasing temperatures reflects the classical dependence expected for dense crystalline materials in the anharmonic phonon coupling region. As Birch and Clark²² point out, plots of thermal resistivity ($1/\lambda$) vs temperature are linear for materials of this type. The cross-hatched region of Fig. 5-57 indicates the expected variation of λ in the biotite-granodiorite section. The temperature effect on thermal conductivity is similar for the selected Birch and Clark²² data for tonalite, Rockport and Westerly granite, and quartz monzonite in comparison to the GT-2 cores at 2615 and 2929 m (8580 and 9608 ft). The agreement between GT-2 sample 9608 and quartz monzonite is fortuitous in the sense that the modal compositions are different as shown in Table 5-VIII.

Murphy and Lawton²¹ were able to estimate in situ thermal conductivities of rock contained around the GT-2 and EE-1 boreholes. Basically, they extended

TABLE 5-VIII

MODAL ANALYSIS OF GT-2 ROCKS
(VOLUME PERCENTAGES OF MINERALS)

Sample No.	K-feldspar	Plagioclase	% An	Quartz	Biotite	Chlorite	Muscovite	Myrmekite	Epidote	Amphibole	Opakes	Sphene	Rock Type/Location	Density Ratio
3-2580-43	36 _{±2}	32 _{±2}	34	25 _{±2}	1	3 _{±1}	1				1		Leucocratic Monzogranite gneiss	2.661
12-4918	29 _{±3}	29 _{±3}	30	36 _{±3}	3 _{±1}		1						Leucocratic Monzogranite gneiss	2.648
5964-2A	1	40 _{±3}	38	6	2					47 _{±3}	1		Amphibolite	2.882
6153-3A	22 _{±2}	42 _{±3}	33	28 _{±3}	5 _{±1}		1						Leucocratic granodiorite gneiss	2.635
6153-3B	22 _{±2}	42 _{±3}	33	28 _{±3}	5 _{±1}		1						Leucocratic granodiorite gneiss	2.630
17-6156-1	9 _{±2}	46 _{±3}	37	35 _{±3}	6 _{±1}		1				2		Granodiorite gneiss	2.727
8579-1	21 _{±3}	34 _{±3}	31	29 _{±3}	11 _{±2}			1	1		1	2	Biotite granodiorite	2.723
9608-1	12 _{±1}	43 _{±2}	36	31 _{±2}	10 _{±1}				1		2		Biotite granodiorite gneiss	2.715
Tonalite ^a	-	50	45	28	15					7			Val Verde, CA	2.735
Westerly ^a	33	40	100	19	6								Granite-Westerly, RI	2.643
Rockport ^a	64 ^b	-	-	28						6			Granite-Rockport, MA	2.610
Quartz Monzonite ^a	27	33	27	34	4.5					0.2			Porterville, CA	2.635

^aReference 11.

^bMicroperthite.

Fig. 5-56.

GT-2 core specimen thermal conductivity. (See Table 5-VIII for modal compositions)
 || - cut-bar conductivity comparator.
 ⊥ - transient needle probe.

Fig. 5-57.

Comparison of thermal conductivities for GT-2 biotite granodiorite with those for selected igneous rocks. (See Table 5-VIII for modal compositions.)

the transient line source method described earlier to include effects caused by flowing fluid in the wellbores. A comparison of the conductive heat flux from the rock to the convective heat transported by the wellbore fluid shows that temperature measurements made between 0.25 and 100 h after flow starts, provide suitable data for independently estimating a mean conductivity λ and diffusivity α of the formation. Numerical solutions in the form of dimensionless temperature-time type curves were used to analyze experimental flowing temperature logs of the wellbores. The value of λ was estimated at 2.9 W/m-K and $\alpha = 1.0 \times 10^{-6} \text{ m}^2/\text{s}$ (Ref. 11). By using mean values for $\rho_r = 2700 \text{ kg/m}^3$ and $C_r = 1050 \text{ J/kg-K}$, a λ of 2.8 W/m-K was calculated from the estimate of α . This internal consistency for in situ measurements coupled with the excellent agreement with the laboratory measurements of λ supports the hypothesis that core material, at least in terms of its thermal conduction properties, is representative of the actual material that exists in the reservoir.

5.2.3. Permeability

Because of the important role that the permeability of the granitic rock plays in controlling water loss from an HDR reservoir, a comprehensive laboratory effort was continued in FY77 to understand how temperature and pressure affect permeability and to develop mechanisms for flow in low-permeability, low-porosity crystalline rock. Information of this sort is valuable in analyzing pressure

transient-flow measurement data, as well as in constructing models that describe the flow connection in the GT-2/EE-1 system (see also Secs. 5.3.1. and 5.5.1.).

Detailed permeability measurements have been made on GT-2 core material from depths of 2615 and 2902 m (8580 and 9522 ft) as a function of temperature and pressure. In determining the permeability we had to select a value for the viscosity of the permeating fluid; temperature-corrected values for the viscosity of pure water were used in all cases. The measured permeabilities apply to unfractured rock in a uniform hydrostatic stress environment.

Figure 5-58 shows the influence of effective confining pressure (confining pressure minus pore pressure) upon permeability at 24°C. The decrease in permeability with increasing effective confining pressure is probably caused by a contraction of intergranular pore space. Although differences in the absolute magnitude of permeability are apparent in Fig. 5-58 for different samples, the relative trend with effective confining pressure appears similar, possibly indicating a singular mechanism.

Figures 5-59 and -60 present permeability as a function of temperature at 35 and 110 bars for cores GT-2-8580 and GT-2-9522, respectively. The most striking feature in these figures is the existence of a permeability minimum at a particular temperature. It is postulated that these minima occur at temperatures where the sample crystal morphologies have equilibrated. The increase in permeability on either side of the minimum could then be explained by increases in intergranular pore space. This increase in pore space can be expected to occur as a result of differences in thermal expansion among the various mineral phases and crystallographic directions in individual anisotropic phases. The effects shown in Figs. 5-59 and -60 were reversible, and no hysteresis upon heating or cooling was observed. Therefore, geochemical alteration of the communicating pore structure cannot explain the results.

Such a temperature-permeability relationship may have important implications, especially in view of the fact that the downhole temperature of ~185°C for a given sample is higher than the temperature of the permeability minimum. As heat is removed from the reservoir, the permeability of unfractured rock from which heat is being extracted may initially decrease, thus decreasing the water loss rate from the system. However, this effect may be completely offset by microfracturing of the rock caused by thermal stresses.

In connection with the permeability studies, we have also examined the nature of the connected porosity of the rock using radioactive tracers which were

Fig. 5-58.
Permeability as a function of effective
confining pressure at 24°C.

Fig. 5-59.
Permeability as a function of tempera-
ture for a GT-2 core specimen from
~2617 m (8580 ft) at an effective con-
fining pressure of 35 bars.

Fig. 5-60.
Permeability as a function of tempera-
ture for a GT-2 core specimen from
~2904 m (9522 ft) at an effective con-
fining pressure of 110 bars.

forced through the samples with the same apparatus used to measure permeability. These experiments indicate that flow through the rock is intergranular. No measurable flow through individual crystal grains was observed.

A preliminary study has been carried out in which the permeability was measured before and after a 120-h period of steady flow of distilled water through the sample. The 200°C permeability showed a significant increase (between 50 - 100% over confining pressures ranging from 210 to 7 bars) after 120 h. The

increased permeability in this case is probably due to an increase in the intergranular pore space resulting from mineral dissolution.

5.2.4. Rock-Water Interactions

Research in the area of rock-water interactions during FY77 focused on three specific aspects of importance to the chemical stability and flow characteristics of a fractured HDR reservoir system in hot granite: (1) mineral alteration in hot aqueous environments (partly funded by the DOE Division of Basic Energy Sciences), (2) rock solubility and dissolution kinetics, and (3) enhanced dissolution with chemical additives.

The long-term recirculation of fluids in the active hydrogeochemical environment of an HDR closed heat-extraction loop may lead to partial plugging of flow paths in the fracture by mineral alteration and could severely affect the reservoir lifetime and heat-extraction capacity by reducing the available heat-transfer area. A thorough understanding of the liquid and solid phase changes that may occur, including identification of species and rates of dissolution and reprecipitation, is necessary to predict, as well as to control, the performance of the system. Sections 5.2.4.1 and 5.2.4.2. discuss our laboratory and field work in these areas. In Sec. 5.2.4.3, active chemical treatment is discussed for changing the flow characteristics of the fractured formation. In an effort to reduce the flow impedance of the EE-1/GT-2 fracture system, we pursued methods to selectively dissolve certain components of granite. Before redrilling GT-2, we conducted a sodium carbonate leaching field test (see Sec. 5.3.6.) to reduce the high impedance that existed between GT-2 and EE-1 at that time. The experimental work leading up to the field test is described in Sec. 5.2.4.3. In addition, other methods of chemical treatment involving HCl/HF mixtures and formic acid are discussed.

5.2.4.1. Mineral Alteration. In a laboratory study, many morphological and chemical effects were observed in the reaction of a well-characterized biotite granodiorite in contact with initially distilled water at 300°C and 0.33 kbar for 8 months. Solution samples were taken at 1 day, 2 days, 1 wk, 2 wk, and 1, 2, 4, and 8 months. Rock samples were removed after 1, 2, 4, and 8 months. Eight polished rock disks were mounted on a tantalum pedestal inside a 500-mliter autoclave. The autoclave is part of a circulation system designed for operation at temperatures and pressures up to 500°C and 0.33 kbar (Fig. 5-61).

The granodiorite initially consisted of quartz (23%), microcline (20%, $\text{Or}_{94+2}\text{Ab}_{6+1}\text{An}_{0+1}$), plagioclase (37%, core $\text{Or}_{2+1}\text{Ab}_{73+2}\text{An}_{25+1}$, rim $\text{Or}_{2+1}\text{Ab}_{88+5}$

Fig. 5-61.
Second-generation circulation system. (T_{1-8} are thermocouples.)

An_{10+5}), chloritized biotite (13%), epidote (2%), sphene (2%), apatite (1%), and opaques (2%). The reactivity of phases as shown by scanning electron photomosaics was: quartz $\gg$ microcline $>$ plagioclase $>$ mafics, opaques, and apatite. Figure 5-62 shows a scanning electron micrograph (SEM) photomosaic of a representative section of the rock surface before reaction and after 8-months reaction with initially distilled water. The white sections of Fig. 5-62b represent void where extensive dissolution of quartz occurred.

Major phase morphology and composition were monitored throughout the experiment by scanning electron microscopy and electron microprobe analysis. After 8 months, quartz showed etching several millimeters deep. Plagioclase became much more calcic with time (see Table 5-IX). Plagioclase changed from oligoclase (fresh), to andesine (1 month), to labradorite (2 months), to bytownite (4 months). Microcline showed almost congruent dissolution. Analyses from the most reacted disks indicate the presence of a possibly amorphous alumina-rich phase on a microcline substrate. Biotite and other phases were essentially inert.

Three secondary overgrowths are observed. These, along with proposed structural formulae, are listed in Table 5-X. Overgrowth I (Fig. 5-62), identified as vermiculite based solely upon its composition, appears as a bladed intergrowth on all rock slabs regardless of the duration of the run. It increases in amount with time and is usually associated with the mafic phases such as biotite, epidote, and magnetite. Overgrowth III is identified as a zeolite near thomsonite in composition (Fig. 5-62). It commonly has a sugary texture and grows almost exclusively on plagioclase feldspar. Overgrowth III is most common on the more

Fig. 5-62.

SEM photomosaics of biotite granodiorite (GT-2-9522) before (A) and after 8 months (B) contact with initially distilled water in a closed circulating system at 0.33 kbar and 300°C.

TABLE 5-IX

PROPOSED ALTERATION STRUCTURAL FORMULAE

<u>Plagioclase</u>						
<u>Time</u>	<u>Ca</u>	<u>Na</u>	<u>K</u>	<u>Al</u>	<u>Si</u>	<u>O</u>
Fresh	0.26 $\pm$ 0.02	0.75 $\pm$ 0.01	0.01 $\pm$ 0.01	1.32 $\pm$ 0.02	2.68 $\pm$ 0.02	8
1 month	0.41 $\pm$ 0.12	0.51 $\pm$ 0.14	0.01 $\pm$ 0.02	1.39 $\pm$ 0.12	2.61 $\pm$ 0.14	8
2 months	0.51 $\pm$ 0.02	0.45 $\pm$ 0.06	0.03 $\pm$ 0.02	1.46 $\pm$ 0.08	2.61 $\pm$ 0.08	8
4 months	0.70 $\pm$ 0.06	0.28 $\pm$ 0.06	0.01 $\pm$ 0.01	1.61 $\pm$ 0.06	2.34 $\pm$ 0.08	8
8 months	0.69 $\pm$ 0.04	0.25 $\pm$ 0.04	0.06 $\pm$ 0.02	1.67 $\pm$ 0.04	2.30 $\pm$ 0.04	8

<u>Microcline</u>								
<u>Time</u>	<u>Ca</u>	<u>Na</u>	<u>K</u>	<u>Fe</u>	<u>Ti</u>	<u>Al</u>	<u>Si</u>	<u>O</u>
Fresh	-	0.05 <u>±</u> 0.01	0.93 <u>±</u> 0.01	-	-	1.02 <u>±</u> 0.01	2.96 <u>±</u> 0.01	8
1 month	0.02 <u>±</u> 0.02	0.05 <u>±</u> 0.01	0.93 <u>±</u> 0.02	0.01 <u>±</u> 0.01	0.01 <u>±</u> 0.01	1.02 <u>±</u> 0.01	2.96 <u>±</u> 0.02	8
2 months	0.03 <u>±</u> 0.02	0.06 <u>±</u> 0.01	0.90 <u>±</u> 0.04	0.01 <u>±</u> 0.01	0.01 <u>±</u> 0.01	1.04 <u>±</u> 0.02	2.94 <u>±</u> 0.02	8
4 months	0.06 <u>±</u> 0.04	0.04 <u>±</u> 0.01	0.91 <u>±</u> 0.02	0.03 <u>±</u> 0.01	0.02 <u>±</u> 0.01	1.07 <u>±</u> 0.06	2.90 <u>±</u> 0.03	8
8 months	0.07 <u>±</u> 0.04	0.07 <u>±</u> 0.02	0.89 <u>±</u> 0.06	0.04 <u>±</u> 0.02	0.01 <u>±</u> 0.01	1.09 <u>±</u> 0.02	2.86 <u>±</u> 0.02	8

	<u>Biotite</u>										
<u>Time</u>	<u>K</u>	<u>Na</u>	<u>Ca</u>	<u>Ti</u>	<u>Mn</u>	<u>Mg</u>	<u>Fe</u>	<u>Al</u>	<u>Si</u>	<u>Al</u>	
Fresh	0.78±0.02	0.01±0.01	0.01±0.00	0.00±0.02	0.04±0.01	1.40±0.04	1.16±0.01	0.27±0.02	2.82±0.02	1.18±0.02	0 ₁₀ (OH) ₂
1 month	0.68±0.02	0.04±0.01	0.02±0.01	0.09±0.02	0.05±0.01	1.42±0.08	1.17±0.01	0.27±0.02	2.86±0.04	1.14±0.02	"
2 months	0.72±0.08	0.03±0.02	0.03±0.02	0.10±0.02	0.05±0.01	1.45±0.10	1.23±0.04	0.14±0.00	2.80±0.06	1.20±0.08	"
4 months	0.65±0.08	0.03±0.01	0.03±0.02	0.08±0.02	0.05±0.01	1.42±0.08	1.17±0.04	0.26±0.06	2.83±0.08	1.17±0.06	"
8 months	0.73±0.06	0.02±0.01	0.03±0.01	0.00±0.01	0.05±0.01	1.39±0.04	1.28±0.04	0.21±0.02	2.77±0.04	1.23±0.02	"

TABLE 5-X
OVERGROWTH PHASES

Overgrowth I. Vermiculite

Overgrowth II. Thomsonite

Overgrowth III. Ashcroftine

reacted rock cores. Overgrowth II is tentatively identified as the zeolite, ashcroftine. Its morphology consists of thin needles or prisms growing in patches exclusively on a plagioclase substrate. Overgrowth II is most abundant in the least reacted rock cores but persists on the latter disks. Figure 5-63 shows the percent weight loss with time on log-log coordinates.

Fig. 5-63.
Percent rock weight loss as a function of time.

Weight loss is empirically represented by a square-root dependence on time (t) with a correlation coefficient (r^2) of 0.99. Thus,

$$\frac{M_0 - M}{M_0} = kt^{0.54 \pm 0.10} \quad (95\% \text{ confidence limits}) \quad , \quad (5-34)$$

where

k = 0.0012 = dimensionless constant

t = time, hours

M_0 = initial rock sample mass ($t = 0$), grams

M = rock sample mass at time t , grams.

Differentiation of Eq. (5-34) indicates that the rate of change of weight loss with time ($-dM/dt$) should decrease proportionally to $t^{-0.46 \pm 0.10}$. Silica concentrations contained in solution samples from the cold portion of the circulating system are plotted in Fig. 5-64 as $\log [\text{SiO}_2]$ (ppm) vs $\log t$ (h). Silica represents about 90% of the total dissolved solids. The behavior shown here is quite different from that shown in Fig. 5-63. A definite steady-state concentration is reached sometime before 5800 h. The decreasing rate of change of SiO_2 concentrations ($d[\text{SiO}_2]/dt$) vs time corresponds to the logarithmic behavior observed for the closed-system experiments described in the following subsections. A companion set of experiments, reacting this biotite granodiorite in a closed system, shows that the solution composition equilibrates with the rock surface, or at least approaches steady state in the circulating system in spite of its limited residence time in the rock reactor. The most important conclusion drawn from this experimentation is that silica activity is apparently buffered to a lower level (700 ppm at 300°C) than would be predicted from the simpler quartz-water system under the same conditions (860 ppm).

Because the weight loss continues to increase even after the aqueous silica concentration levels off (compare Figs. 5-63 and -64), a substantial amount of mass transport is occurring even after 6000 h and may represent an approach to a steady rate of transport. For this to occur, a finite concentration difference

Fig. 5-64.
Silica concentration as a function of time.

must exist between the hot and cold sections of the apparatus to provide the necessary concentration, or activity, driving force for mass transport to occur. Consequently, the actual hot solution will contain a silica concentration between 700 and 860 ppm. The buffering that does occur is caused by multicomponent reactions between the primary phases (quartz, feldspars, etc.) with the initial solution yielding silica-bearing overgrowths. These synthesized overgrowths do not seem to be abundant enough to cause a circulation problem in the rock reservoir. At temperatures of 250°C and below this buffering effect did not appear to cause any pronounced deviation from a silica concentration controlled by a quartz-water system. In fact, laboratory and field measurements of silica concentration at 200 and 185°C indicate that for practical engineering purposes the silica concentration approaches a quartz-water system solubility limit corresponding to the rock-water temperature. This, of course, is a simplification of the real situation; because of the polyminerallic nature of the rock samples, one would anticipate that the silica activity in the liquid phase would not be controlled by a binary quartz-water system.

Some preliminary powder x-ray work was done on vein fillings from core samples taken at the bottom of GT-2 and EE-1 after exposure in the laboratory to circulating water and sodium carbonate solutions. Vein fillings in cores from the bottom of GT-2 contained chlorite. The x-ray intensities indicate 7 Å and 14 Å chlorite. The x-ray patterns also suggest the presence of small amounts of minnesotaite (an iron talc) and xonotlite (a calcium silicon oxide hydrate). Vein fillings in cores from the bottom of EE-1 were primarily 14 Å chlorite. The 7 Å chlorite is thought to be a metastable low-temperature alteration possibly produced by reaction of rock with water under flow or static conditions. The minnesotaite and xonotlite are alterations produced in the sodium carbonate flow experiments. (See also Sec. 5.3.6.) Identification of phases

other than chlorite is sketchy and needs more detailed work to confirm their presence.

In the spring of 1977, a 10-cm-long rock fragment was recovered by a tool from near the bottom of EE-1. This fragment was apparently broken from the side of the wellbore when the tool became snagged. Because this fragment showed intensive evidence of in situ alteration, we examined it in detail.

As shown in Figs. 5-65 and -66, the fragment is bounded by a section of the wellbore, two altered fracture planes, and a freshly broken surface. The most intensely altered fracture surface has a dip of 65° , thus making an angle of 25° with the wellbore. A 45° dipping fracture surface is less intensely altered or coated. The fragment, designated EE-1-BT, closely resembles the foliated biotite granodiorite from Core 27 in GT-2 at 2928 m (9607 ft). Quartz, plagioclase, K-feldspar, and biotite are recognizable at low magnifications as major constituents, with sphene, opaques, and dark red garnet present in trace amounts. Quartz grains on the fracture surfaces show some evidence of pitting or dissolution. No such pits were observed in the quartz on the freshly broken surface. Dissolution of minerals, possibly calcite, from small fractures has also occurred. Striations or slickensides are present on the 65° dipping surface, but there is no way to determine when this occurred except that it was postalteration.

The alteration consists of a thin (<1 mm) green encrustation. Under low magnification, several different mineral phases are observable. These were

Fig. 5-65.
End and front view of altered sample recovered from bottom of EE-1.

Fig. 5-66.
Altered sample recovered from bottom of EE-1.

identified by x-ray diffraction to be chlorite, minnesotaite, and xonotlite. Calcite and biotite were also identified as alteration products with the microprobe and SEM. In addition, the surface of the alteration layer was examined with SEM. The quartz has been strongly attacked and closely resembles photo-mosaic SEM photographs of quartz in the altered cores from the circulation experiments (Fig. 5-62). Elemental mapping was used to show that isolated calcite crystals rest on top of the chlorite and minnesotaite.

Primary biotite in the rock fragment appears to be stable under the conditions of the in situ leaching experiments. The chlorite seems to be "plating" all of the minerals, and at least some of the iron in this mineral is probably derived from the casing. According to the literature, minnesotaite results from the silication of chlorite. This seems reasonable when the high SiO_2 content of the Na_2CO_3 solutions is considered. (See also Sec. 5.3.6.)

5.2.4.2. Rock Solubility and Dissolution Kinetics. At least seven major parameters control the dissolution of reservoir rock: (1) rock composition and microstructure, (2) inlet fluid composition, (3) temperature, (4) fluid velocity, (5) residence time, (6) rock surface area/fluid volume, and (7) pH. In the in situ environment the rock composition and microstructure, temperature, and ratio of rock surface area to fluid volume are defined. Cores extracted from GT-2 and EE-1 provide some flexibility in studying individual mineral-water interactions; but in the field, one is forced to examine the gross rock-matrix-water interactions. Fluid velocity and residence time can be varied only in a relative sense in the field because absolute values for porosity and fracture surface area are not known. Laboratory experiments conducted on core material have the advantage that all of the parametric effects listed above can be studied on an individual basis.

Until recently field geochemical experiments have consisted of injecting fresh water into one borehole, circulating it through the EE-1/GT-2 fractured region, and returning the fluid to the surface in the second borehole with no recirculation of the water. By August 1976, over 5.6×10^6 liters (1.5×10^6 gal) had been injected with a large fraction recovered and many samples analyzed to determine inlet and outlet fluid composition. Typical results are given in Table 5-XI for the major cations and anions present in the injected and recovered water. Titration, selective ion electrodes, atomic absorption, and other spectrophotometric methods were used for analysis. The values given in Table 5-XI for water circulated through the reservoir correspond to a mean

TABLE 5-XI

GEOTHERMAL FLUID COMPOSITION FOR EXPOSURE TO BIOTITE GRANODIORITE
(2804 - 2926 M (9200-9600 FT) IN THE EE-1/GT-2 SYSTEM)

Species	Injected Water (ppm)	Water After ~14-h Exposure In Situ ^a (ppm)	Water After 24-h Exposure Lab Core Samples (ppm)
SiO ₂	42-50	220-260	180-220
Na	12-60	240-300	36
K	3-8	25-40	15
Ca	13-23	14-16	4
Mg	1-5	0.3	0.08-0.20
Fe	0.3-1.0	2-6	1.3-3.3
Al	<1 ^b	0.2-0.6	1.6-3.2
F	1	12-14	12
Cl	3-10	310-400	4-5
SO ₄	10-20	80	<100
HCO ₃	200-280	180	~150
CO ₃	<10	~0	~0
S	~0	1-2	<1
PO ₄	<0.1	0.2-0.5	~0.1

^aAfter 5.7×10^6 liters (1.5×10^6 gal) circulated.

^b< means below detection limits.

residence time of 14 h. (See also Sec. 5.3.5.) The total dissolved solids level increases from ~400 ppm for the injected water to ~1200 ppm for the returned water. The aqueous silica (SiO₂) concentration reaches a value approximately equal to the saturation concentration or solubility of quartz at 200°C.

Experiments using core material are conducted in three different ways: (1) agitated teflon-lined autoclave batch systems with crushed core or drilled cuttings exposed to fluid under its vapor pressure at temperatures up to 250°C, (2) flowing systems which expose crushed core or prepared slabs of core material to circulating fluid maintained at pressures of 10 - 69 MPa (1300 - 10 000 psi) at

temperatures up to 300°C, and (3) permeation systems which use a pressure gradient to force fluid to penetrate through a core specimen maintained at a fixed confining pressure at temperatures up to 300°C. Results are shown in Table 5-XI for a 24-h exposure of 1.0 g of 16- by 24-mesh (~ 0.85 -mm-diam) crushed core [2900 m (9515 ft) - see Table 5-VIII] material to 15 g of water at 200°C.

In comparing these laboratory measurements with the in situ fluid composition, both SiO_2 concentrations approach the saturated quartz condition and imply a similar controlling mechanism of rock dissolution. The difference in SiO_2 concentrations for 14- vs 24-h exposure is not significant in view of the uncertainties surrounding the value of exposed rock surface area in the in situ environment vs the laboratory measurements. Similar pH values of 6.8 - 8.0 are observed for field and laboratory fluids. However, the much higher values for chloride, sodium, calcium, and potassium observed in the field are possibly caused by the mixing of indigenous pore fluid with circulating water contained in the fractured EE-1/GT-2 reservoir. A steady decline in the total dissolved solids (particularly chloride, sodium, calcium, and potassium) level has been observed as more and more fresh water is circulated. This could be expected as the pore fluid source of dissolved salts is depleted. Recent circulation experiments have shown that the total dissolved solids (TDS) level is between 400 - 600 ppm with about 200 ppm of SiO_2 after 100 h of recirculation. The conductivity of this fluid is about 350 $\mu\text{mho/cm}$ compared to ~ 290 $\mu\text{mho/cm}$ (~ 250 ppm TDS) for the initial feed water that is injected in the system. The agreement between laboratory and in situ fluoride concentrations suggests that the source of fluorine is active dissolution of rock rather than from pore fluid.

The rate of dissolution for a closed-vessel experiment with initially distilled water follows the behavior expected for a solubility-limited transport reaction as was observed for the closed circulation loop described earlier (Fig. 5-61). A quantitative description of the kinetics is presented below.

5.2.4.3. Enhanced Dissolution with Chemical Additives. Laboratory experiments conducted during the past year at LASL have demonstrated that aqueous solutions (0.1 - 4.0 N) of sodium carbonate (Na_2CO_3) react with EE-1/GT-2 core specimens to dissolve SiO_2 primarily by attacking the quartz component of the granite. This "selective" attack of quartz is also true for pure water, as presented previously.

The reaction is sufficiently irreversible to result in essentially stoichiometric conversion of crystalline silica [$\text{SiO}_{2(c)}$] into a soluble form. Na_2CO_3

acts to buffer the solution into the moderately basic region ($\text{pH} > 10$) and thus provides an active source of hydroxide ions (OH^-) which can react with dissolved silicic acid $[\text{Si}(\text{OH})_4]$ to form soluble metasilicates,²⁵ thus increasing the effective solubility of silica.

The rate and final saturation concentration achieved increase as the pH or OH^- concentration increases. Thus, concentrated sodium hydroxide (NaOH) solutions would result in faster dissolution rates because of the higher OH^- concentration. However, using dilute Na_2CO_3 (aq) as the reactant to induce dissolution is advantageous for a first experiment in the EE-1/GT-2 system because the reaction rates are slow enough to permit control of the experiment and adequate interpretation of the results.

To optimize the design of a field experiment for carbonate leaching, we performed a series of laboratory tests to collect data on the reaction kinetics of Na_2CO_3 solutions on granite and on the fluid-flow characteristics expected in the reservoir. (See also Secs. 5.3.5. and 5.3.6.) In effect, we would like to control the location and extent of silica dissolution in the system. Reaction kinetic data tell us how fast silica dissolves as a function of time, and fluid residence-time data collected in the EE-1/GT-2 reservoir tell us how long the reacting fluid would be exposed to the reservoir rock. By combining this information we can select solution concentration and volumes for specified flow rates to ensure that the carbonate will not be expended before it reaches the zone of high impedance.

Because the chemical dissolution reaction involves liquid and solid phases, one would expect that the reaction rate, with surface kinetics controlling, would be proportional to the ratio of rock surface area to fluid volume (a^*). Gas absorption and mercury porosimeter measurements were used to estimate surface areas accessible to the fluid. Experiments were done with the agitated autoclave batch vessels described earlier. Kinetic runs at 200°C with 0.1 - 4.0 N Na_2CO_3 and pure-water solutions were made on core slabs and drill cuttings. For core slabs, $a^* = 55 \text{ cm}^2 / 90 \text{ cm}^3 = 0.6 \text{ cm}^{-1}$ based on nominal area and liquid volume. For

cuttings, 1 g of 16- by 24-mesh samples were used in 15 cm³ of liquid, with a nominal $a^* = 2 \text{ cm}^{-1}$. Solution samples were taken at different exposure times up to 120 h and analyzed for aqueous silica by atomic absorption and the silicomolybdate spectrophotometric method.²⁶ When core slabs were used, sample weight losses were also determined. The time dependence of weight loss or aqueous solution concentration build-up was then used to determine dissolution rates. We fit a simple model to weight-loss and SiO₂-concentration rate data to yield the instantaneous dissolution rate R as a function of a^* and the difference between the saturated SiO₂ concentration, corresponding to the initial Na₂CO₃ concentration, and the SiO₂ concentration at a particular time t :

$$R = \frac{d[\text{SiO}_{2(\text{aq})}]}{dt} = \frac{-1}{V} \frac{dM}{dt} = k_d^* a^* [\text{SiO}_{2(\text{aq})}^{\text{sat}} - \text{SiO}_{2(\text{aq})}] \quad , \quad (5-37)$$

where V = liquid volume, cm³
 k_d^* = dissolution rate constant, cm/s
 a^* = ratio of accessible rock surface area to fluid volume = S/V , cm⁻¹
 $\text{SiO}_{2(\text{aq})}^{\text{sat}}$ = aqueous saturation concentration of silica, g/liter or ppm
 $\text{SiO}_{2(\text{aq})}$ = aqueous concentration of silica, g/liter or ppm
 M = core slab mass, grams
 t = time.

The rate constant k_d^* is determined empirically and depends on rock type, temperature, flow rate, and Schmidt number. The dissolution rate R is expressed as a rate of sample weight loss ($-dM/dt$) or as a rate of SiO₂ concentration increase ($d[\text{SiO}_{2(\text{aq})}]/dt$). If we assume that essentially all of the sample weight loss is due to silica dissolving, then by using a simple material balance, Eq. (5-37) can be rewritten:

$$\frac{dM}{dt} = \frac{dW}{dt} = k_d^* a^* (W^\infty - W) \quad (5-38)$$

where

W = weight loss of sample at time t , grams
 W^∞ = weight loss of sample as $t \rightarrow \infty$ (i.e., saturation), grams.

Typical weight-loss data collected by R. Charles for EE-1/GT-2 granite core slabs are plotted in Fig. 5-67. The theoretical lines shown are obtained by integrating Eq. (5-38); an appropriate value for $k_d^* a^*$ is determined by plotting the initial rate ($t \rightarrow 0$) as a function of W_d^∞ . Figure 5-68 shows initial dissolution rate for core slabs and cuttings as a function of carbonate concentration. The nonlinear concentration dependence shown is caused by a nonlinear dependence of $[\text{SiO}_2(\text{sat})]$ on carbonate concentration. By using experimental values of initial dissolution rate for cuttings plotted as a function of $[\text{SiO}_2(\text{sat})]$, a linear relationship corresponding to Eq. (5-37) results, as shown in Fig. 5-69. A similar relationship was determined for the core slab data.

The kinetic dissolution model developed was incorporated into a general reservoir dissolution model to design and analyze the field test of carbonate leaching at Fenton Hill. (See Sec. 5.3.6. for details.)

In addition to the use of basic solutions for reservoir improvement, acidic solutions consisting of hydrochloric/hydrofluoric acid mixtures and formic acid are under investigation. LASL has been assisted in a preliminary study by C. Crowe of Dowell Laboratories, Tulsa, Oklahoma. Initially experiments focused on increases in fracture permeability or conductivity that might be expected by dissolution of calcite (CaCO_3) with hydrochloric (HCl) and formic (HCOOH) acid solutions. A Hassler-type apparatus, using a cylindrical core sample, was set up to flow acid solutions at high temperature through a simulated fracture, which initially was held closed by maintaining a confining pressure around the sample. Measurements of fracture conductivity could be made directly, and the acidized surfaces of the rock could be examined in detail after the experiment was completed.

Tijeras Canyon, New Mexico, granodiorite and GT-2 biotite-granodiorite reservoir rock that have been subjected to various acid treatments are being examined by optical and SEM microscopy. Semiquantitative and morphological studies on the SEM will help predict relative attack and physical character of breakdown of the major mineral constituents as well as surficial by-products of the reactions. These continuing studies will contribute information needed for choosing the appropriate type and concentrations of chemical leachant for optimal design of an acid treatment for the GT-2/EE-1 system.

Fig. 5-67.

Core slab weight loss at 200°C as grams per nominal surface area (cm²) as a function of time for three sodium carbonate concentrations. A 55-cm² slab was used in 90 cm³ of solution. The theoretical lines shown correspond to an integration of Eq. (5-38).

Fig. 5-68.

Initial dissolution rate as a function of initial sodium carbonate concentration at 200°C. Accessible rock surface areas listed.

Fig. 5-69.

Initial dissolution rate as a function of silica saturation concentration.

5.3. Field Studies of Reservoir Properties (R. L. Aamodt; L. A. Blatz; D. W. Brown; J. Counsil; H. N. Fisher; C. O. Grigsby; C. E. Holley, Jr.; R. G. Lawton; H. D. Murphy; R. M. Potter; J. W. Tester)

5.3.1. Pressure-Transient Flow Testing

5.3.1.1. Introduction. During the early phases of flow injection, as discussed in the previous annual report,² the pressure resulting from the injection of water into the reservoir at a constant rate was found to increase with the square root of time. Such behavior conformed to a reservoir model consisting of a fracture with infinite hydraulic conductivity, compared to the surrounding rock. Thus, one-dimensional transient diffusion of the injected water into the rock perpendicular to an isobaric, planar fracture adequately describes the process.

Later phases of flow injection revealed a deviation from the linear relationship between pressure and the square root of time, with the pressure asymptotically approaching some maximum value dependent upon the injection rate. This behavior was attributed to a pressure-dependent rock permeability and compressibility (porosity), and in fact, the pressure dependency was qualitatively like that observed during laboratory testing of granite core material or specimens similar to the Fenton Hill reservoir rock²⁷ (Secs. 3.3.2. and 5.5.5.).

The agreement between the model and many repeated field observations made this approach appear quite plausible, but we also recognized that this model is not necessarily unique nor correct, and that other solutions or models are possible. For this reason, pressure-transient analysis (PTA) methods - well known in the petroleum engineering field - were applied to several flow experiments conducted this year. These analysis techniques lead to estimates of the product of permeability and formation thickness, kh , and the product of porosity, compressibility, thickness, and fracture half-length squared, $\phi c_t h x_f^2$, for the fractured reservoir. Also, estimates of fracture volume and the fracture porosity-compressibility product, ϕc_t , as a fraction of total ϕc_t were made. These analyses assume either radial flow from an unfractured well or linear flow from infinite-conductivity or constant-flux fractures fully penetrating a rock formation and constant properties. Because these assumptions may not accurately describe actual reservoir conditions, the results must also be viewed with some skepticism until they are proven useful for predicting future flow-rate/pressure/time relations. Despite these limitations the initial results lead to interesting observations, which often complement our earlier views of the Fenton Hill reservoir (see Sec. 5.5.1.).

5.3.1.2. Summary. Major results of this PTA study are listed in Table 5-III. Experiment 172A is believed to provide more reliable answers than the others because it was influenced less by storage and near-wellbore impedance effects. The kh value during the first injection period of 172A varied from 37 to 68 md-m (120 to 220 md-ft). The value of $\phi c_t h X_f^2$ varied from 0.110 to 0.17 m³/bar (0.26 to 0.40 ft³/psi). A multirate analysis for all three flow periods showed that kh appeared to increase from 41 to 80 md-m (136 to 261 md-ft). When the bottom-hole pressure was increased to 83 bars (1200 psi), the fracture volume was crudely estimated from type-curve matching to be 44 m³ (1560 ft³). Based upon self-propping mechanisms for the fracture opening and this volume, the total fracture area is estimated to be in the range of 44 000 - 220 000 m² (4.7 - 23.7 x 10⁵ ft²). From the semilog analysis, the fracture porosity-compressibility product $(\phi c_t)_f$ was roughly estimated to be 72% of total porosity-compressibility $[(\phi c_t)_f + (\phi c_t)_{ma}]$.

The kh value during the first injection period of Experiment 172C was lower, 21 md-m (69 md-ft). The value of $\phi c_t h X_f^2$ was much lower, averaging 0.013 m³/bar (0.032 ft³/psi). In a multirate analysis for all four flow periods of Experiment 172C, the kh product again increased from 23 to 98 md-m (74 to 323 md-ft) when the bottom-hole pressure increased by 83 bars (1200 psi). The kh showed a single step increase and remained constant at the three higher flow rates and pressures. However, the skin effect appeared to increase for the second flow rate and then decrease for the third and fourth flow rates.

5.3.1.3. Detailed Analysis of Experiment 172A. As an example of the approach, the details of the PTA calculations are given for data from Experiment 172A. In this experiment, well GT-2B was shut-in at the wellhead and water was injected into EE-1. A rented positive-displacement pump truck was used to inject 3.7 liters/s (59 gpm) with step increases to 6 and 9 liters/s (95 and 142 gpm). The first constant injection period was analyzed using log-log, semi-log, and square root of time methods. The data for the three rates were then analyzed by a multirate technique. The interference data between wells were also reviewed.

Log ΔP vs log Δt . The bottom-hole pressure increase, ΔP , vs time, Δt , is shown plotted on log-log paper in Fig. 5-70. These data can be matched with the infinite hydraulic conductivity and constant-flux vertical-fracture type curves (presented by H. J. Ramey, LASL Well Testing Short Course).

TABLE 5-XII^a

RESULTS OF PRESSURE-TRANSIENT ANALYSIS

Expt.	Well Data	Flow Rates	Analysis	kh (md-m)	$\phi c_t h X_f^2$ (m ³ /bar)	$k \phi c_t h^2 X_f^2$ (md-m ⁴ /bar)
172A	EE-1	1st	Log ΔP vs log Δt			
			Infinite conductivity	37	0.17	6.1
			Constant flux	68	0.11	7.2
			Infinite conductivity with storage	42	0.12	5.1
"	"	"	ΔP vs $\sqrt{\Delta t}$	--	--	6.7
"	"	"	ΔP vs log Δt	60	--	--
"	"	All 3	Multirate			
			A	41	--	--
			B	80	--	--
"	GT-2B	1st	Interference	52	--	--
172C	GT-2B	1st	Log ΔP vs log Δt			
			to = pump start			
			Infinite conductivity	19	0.008	0.20
			Constant flux	20	0.013	0.40
			to = initial pressure rise			
			Infinite conductivity	22	0.008	0.17
			Constant flux	23	0.014	0.31
"	"	"	ΔP vs $\sqrt{\Delta t}$	--	--	0.55
"	"	"	ΔP vs log ΔP	21	--	--
"	"	All 4	Multirate			
			A	23	--	--
			B	98	--	--
			C	98	--	--
			D	98	--	--
"	EE-1	1st	Interference	46	--	--

^aFracture area $A = h(2X_f)$. For a square fracture, $h = 2X_f$ or $A = 4X_f^2$.

$$\beta = \phi c_t, \text{ then } A\sqrt{K\beta} = \left[4(kh \cdot \phi c_t h X_f^2) \right]^{1/2} \quad \text{and} \quad \frac{\beta A}{K} = 4 \left[\frac{\phi c_t h X_f^2}{kh} \right].$$

Fig. 5-70.
Pressure response, log (pressure) and log (time) coordinates.

A slope of one-half on the $\log \Delta P$ -vs- $\log \Delta t$ plot is present from 0.8 to 10 min and suggests linear flow from the fracture into the formation. Data from this time period should provide the correct straight line on a ΔP vs $\sqrt{\Delta t}$ graph. Data before 0.8 min may be influenced by wellbore and fracture storage. The correct straight line on a ΔP -vs- $\log \Delta t$ graph, indicating radial flow, is expected at a Δt twice as long as the end of the linear flow time. The semilog straight line is therefore expected at a Δt of 20 min. This information is useful for the interpretation of the ΔP -vs- $\sqrt{\Delta t}$ and ΔP -vs- $\log \Delta t$ graphs.

Type-curve matching provides nonunique answers because more than one match is possible. It must be stressed that data from the real system are being matched to data computed for an idealized system. The fracture-flow type curves assume a vertical fracture of height h , half fracture length from the wellbore to the fracture tip X_f , and an otherwise homogeneous formation of area $(2X_e)^2$.

The field data match the infinite conductivity fracture curve for $X_e/X_f = \infty$. In other words, no boundary effects are present. A match point with a measured time Δt of 118 min, a dimensionless time $t_{D,f}$ of 1, a pressure change ΔP of 28 bars (410 psi), and a dimensionless pressure change P_D of 1, results in the estimate:

$$kh = 37 \text{ md-m (120 md-ft)} \quad (5-39)$$

$$\phi c_t h X_f^2 = 0.17 \text{ m}^3/\text{bar (0.41 ft}^3/\text{psi)} . \quad (5-40)$$

Definitions of the dimensionless parameters are listed in Table 5-XIII. Also shown are formulas for calculating the kh product and skin effect. In these expressions q is the flow rate; μ is the downhole water viscosity, 1.4×10^{-4} Pa-s (3×10^{-6} lb-s/ft²); and B is the formation volume factor for water, 1.11.

The field data from the first injection period of Experiment 172A also appear to match the constant flux (over the fracture face) type curve for $X_e/X_f = 2$. This suggests that either a boundary is present or, possibly, that the infinite-conductivity, rather than the constant-flux, model is appropriate. The match point with the constant-flux type curve results in:

$$kh = 68 \text{ md-m (222 md-ft)}; \phi c_t h X_f^2 = 0.107 \text{ m}^3/\text{bar (0.260 ft}^3/\text{psi)} . \quad (5-41)$$

If we assume that the data before 0.8 min are influenced by storage, we can use results presented by Ramey and Gringarten²⁸ to prepare a "high-volume conductivity fracture" type curve. A different match was obtained and the following estimates were then made:

$$kh = 42 \text{ md-m (138 md-ft)}; \phi c_t h X_f^2 = 0.121 \text{ m}^3/\text{bar (0.295 ft}^3/\text{psi)} . \quad (5-42)$$

The maximum credible dimensionless storage constant C_D from the match for a case of no boundary effects ($X_e/X_f = \infty$) is:

$$C_D = \frac{C}{2\pi\phi h c_t X_f^2} = 0.01 . \quad (5-43)$$

TABLE 5-XIII

DEFINITIONS AND FORMULAE

Analysis	Formulae
Log ΔP vs log Δt	$P_D = \frac{2\pi kh \Delta P}{\dot{q}_B \mu} \quad \text{or} \quad kh = \frac{\dot{q}_B B}{2\pi} \left(\frac{P_D}{\Delta P} \right)$ $t_{Df} = \frac{kt}{\phi \mu c_t \chi_f^2} \cdot \frac{h}{h} \quad \text{or} \quad \phi c_t h \chi_f^2 = \frac{(kh)}{\mu} \left(\frac{\Delta t}{t_{Df}} \right)$ $t_D / r_D^2 = \frac{kt}{\phi \mu c_t r^2}$
ΔP vs $\sqrt{\Delta t}$	$k \phi c_t \chi_f^2 h^2 = \frac{\mu}{\pi} \left(\frac{\dot{q}_B}{m_f} \right)^2$
ΔP vs log Δt	$kh = \frac{0.183 \dot{q}_B \mu}{m} \quad (\text{where } m = \text{slope of } \Delta P \text{ vs log } \Delta t \text{ curve})$
Multirate	
$\frac{P_i - P_{wf}}{\dot{q}_N}$ vs.	$kh = \frac{0.183 B \mu}{m'} \quad (\text{where } m' = \text{slope of multirate curve})$
$\sum_{j=1}^N \left[\left(\frac{\dot{q}_j - \dot{q}_{j-1}}{\dot{q}_N} \right) \log (t - t_{j-1}) \right] \quad s = 1.1513 \left[\frac{b}{m'} - \log \left(\frac{k \Delta t}{\phi \mu c_t r_w^2} \right) - 0.350 \right]$	

This yields an estimate of 7.6 liters/bar (0.139 gal/psi) for the storage coefficient of the total system. The relationship between the total storage and the well and fracture storage is:

$$C = C_w + C_f \quad \text{or,}$$

$$C = c_w V_w + c_f V_f, \quad (5-44)$$

where c is compressibility and V is volume. Using the appropriate water properties and the volume of the wells, we then estimated that the fracture volume is about 44 m^3 (1560 ft^3 or $11\,700 \text{ gal}$). This estimate is in excellent agreement with volume estimates based upon residence time studies that used sodium-fluorescein dye (see Sec. 5.3.4.). Furthermore, roughness measurements on a fractured core surface indicate that the self-propped fracture width is in the range $0.2 - 1 \text{ mm}$. Using the volume cited above, the fracture area (one side only) can be estimated to range from $4.4 \times 10^4 \text{ m}^2$ to $2.2 \times 10^5 \text{ m}^2$ (4.7 to $23.7 \times 10^5 \text{ ft}^2$). If the fracture is penny-shaped the computed radius ranges from 120 to 260 m (390 to 850 ft). For comparison, the fracture radius was estimated to be 140 m , based upon measurements of the linear diffusion parameter ($A\sqrt{k\beta}$). From the redrilling and fracture intersection points we know that the fracture radius must be at least 90 m .

ΔP vs $\sqrt{\Delta t}$. Deciding upon the correct straight line through the data points of a ΔP -vs- $\sqrt{\Delta t}$ plot (Fig. 5-71) is difficult. If the system is static before the test, then ΔP should be zero when Δt is zero. However, the $\log \Delta P$ -vs- $\log \Delta t$ plot (Fig. 5-70) indicated linear flow from 0.8 to 10 min . Therefore, using the slope, $4.3 \text{ bars}/\sqrt{\text{min}}$, and the appropriate formula of Table 5-XIII, we estimate that

$$k\phi c_t \chi_f^2 h^2 = 6.86 \times 10^{-15} \text{ m}^6/\text{bar} \text{ (} 54 \text{ md ft}^4/\text{psi) } . \quad (5-45)$$

The square root of this parameter is the area/square root of the rock permeability/compressibility product $A\sqrt{k\beta}$, which is $82 \times 10^{-8} \text{ m}^3 \cdot \text{bar}^{-1/2}$, or about one-half the value obtained before redrilling GT-2.

ΔP vs $\log \Delta t$. The plot in Fig. 5-72 of bottom-hole pressure change vs $\log$ (time) is linear from 18 to 80 min with a slope m of 20 bars (284 psi) per $\log$ cycle. Using the appropriate formula from Table 5-XII, we estimate kh as,

Fig. 5-71.
Pressure response, pressure and (time)^{1/2} coordinates.

Fig. 5-72.
Pressure response, pressure and log (time) coordinates.

$$kh = 60 \text{ md-m (200 md-ft)} \quad .$$

(5-46)

Multiple rate. The kh product was determined from the straight-line slopes of plots (Fig. 5-73) of

$$\frac{P_i - P_{wf}}{\dot{q}_N} \text{ vs } \sum_{j=1}^N \left[\left(\frac{\dot{q}_j - \dot{q}_{j-1}}{\dot{q}_N} \right) \log (t - t_{j-1}) \right] \quad .$$

(5-47)

Fig. 5-73.
Pressure response, multirate injection test.

This equation is valid for long-term radial flow and does not necessarily model a fractured system.

For the first two flow rates (line A in Fig. 5-73) it appears that $kh = 41$ md-m (136 md-ft). For the third flow rate (line B), $kh = 80$ md-m (261 md-ft); kh apparently increases sometime between the first and second data points during the third flow period (line B). In other words, at a bottom-hole pressure change of 83 bars (1200 psi) the permeability increases. Because intercept b increases and slope m decreases at the higher pressure, the skin effect s appears to increase.

5.3.2. Flow Impedance

The historical summary of the flow impedance between the two wellbores is shown in Fig. 5-74. Before the redrilling of GT-2 the impedance to flow circulation was due primarily to the highly impermeable rock separating the parallel fractures created in GT-2 and EE-1. Because the permeability of this rock is pressure dependent, the measured impedance was a transient function of the pressure level at each of the wells. The circled data points of Fig. 5-74 represent the initial impedances at zero pressure; the vertical bars below some of these points represent the full range of transient impedance observed during some of the long-term, high-pressure pumping tests.

Events previous to Experiments 120 and 122A were discussed in detail in Ref. 2. The large change in impedance achieved during Experiment 133 was caused by pressurizing GT-2 above its fracture-extension pressure. This resulted in a

Fig. 5-74.
Specific impedance.

large increase in the GT-2 fracture area and a subsequent decrease in impedance. Unfortunately, the fracture propagated into the unpressurized annulus behind the GT-2 production tubing. This annulus extends to the surface and thus could not be pressurized because of the possibility of breaking down the formation at a very shallow and permeable interval, which would result in large water losses. Thus, further impedance reductions by fracture extension in GT-2 was considered too risky.

Experiment 137/138 was an attempt to reduce the impedance by selectively leaching the quartz in the rock with a 1 N solution of sodium carbonate (Na_2CO_3) injected into EE-1. The details of reaction chemistry and kinetics are given in Sec. 5.3.6. In summary, the experiment actually led to a slight increase in impedance, probably because the concentration of Na_2CO_3 was not high enough and not enough solution was injected.

Detailed discussions of explosive fracturing had been under way, but these eventually led to the conclusion that even the use of shaped charges to perforate the 15 m (50 ft) of dense granitic rock separating the fractures was practically infeasible. Instead, we decided to sidetrack the GT-2 wellbore at a depth of about 2500 m (8200 ft) and to redrill to connect directly with the fracture originating from EE-1 at 2750 m (9030 ft). The first redrilling path, GT-2A, was apparently drilled too high above the EE-1 fracture. Efforts to extend the

EE-1 fracture upward into GT-2A were unsuccessful, either because the fracture was slightly off vertical (4°) and thus its upward path missed the GT-2A trajectory, or possibly because an intrinsic gneiss forming a contact with the native granodiorite at 2600 m (8540 ft) acted as a "cap" rock so that the fracture was forced to extend laterally rather than upward (see Sec. 5.4.). In any event, the impedance was reduced only to 44 bar-s/liter (40 psi/gpm), still too large for a viable heat-extraction experiment.

Beginning May 18, 1977, a second drill path, GT-2B, was sidetracked. Its target was an intersection of the EE-1 fracture at 2650 m (8700 ft), or 61 m (200 ft) below the GT-2A target. Because of difficulties in directionally drilling with the Dyna-Drill, this path did not result in as much deviation (lateral movement) as planned, so that although a very significant reduction in impedance was observed, the intersection is not actually with the main hydraulic fracture but rather with several communicating slanting fractures or joints in the rock. The depths of these flow connection points were measured with a shut-in temperature survey (Sec. 5.1.6.) and are conceptually illustrated in Sec. 5.4. In addition, the relative flow rate communicated by each connection was calculated from temperature surveys taken in GT-2 while water was injected (Sec. 5.1.6.).

After a high-pressure treatment (Experiment 166) at GT-2B to promote "self-propping" of the GT-2B flow communication paths, the overall flow circulation impedance was 11 bar-s/liter (10 psi/gpm), which is sufficient for a 5-MW nominal power extraction experiment. However, recent experiments 172A and 172C, conducted on August 8 and 18, 1977, have indicated that a large fraction of the total impedance, about 8 bar-s/liter (7 psi/gpm), is attributable to the flow paths that connect GT-2B to the main hydraulic fracture system. Thus, these impedances are highly local in nature and may be reducible with further stimulation. The impedance of the main hydraulic fracture is about 3 bar-s/liter (3 psi/gpm), which is consistent with self-propping mechanisms based on the roughness measured on old and new fracture surfaces of GT-2 core specimens. The flow capacity of the fracture is estimated to be 1 d-m (3 d-ft), which is about the same had the fracture been sand-propped with -10/+20 mesh sand particles at the same fracture closure stress. (See Secs. 5.5.2. and 5.5.5.).

5.3.3. Fluid Losses

The rate at which make-up water must be added to a circulating geothermal energy extraction system is of special interest. If consumption is high,

modifications of the system such as adding a downhole pump (to lower fluid pressure to that of the surrounding water table) may be necessary. This will reduce or eliminate water loss and reduce the probability of generating small seismic disturbances. Considerable experience has been obtained with the EE-1 and GT-2 fractures pressurized for a few hours or tens of hours, and the final EE-1/GT-2B circulation system has been operated for 90 h, with the results shown in Fig. 5-75. Water losses appear to be trending toward some low value less than 1 liter per second (<20 gpm). It is important to note that the water loss should depend on the pressure in the fracture and on the time for which it has been applied, but should be almost independent of the circulating flow rate (except for a transient effect when the flow rate is changed and fracture volume changes or the fracture extends). The maximum circulating flow rate is determined by the limiting (maximum) pressure at which the fracture can be operated without extension, divided by the flow impedance. If this impedance is reduced, the water losses may increase or decrease slightly because of changes in the pressure distribution inside the fracture. (If the impedance reduction takes place near the exit, water loss will be reduced.) As a first approximation, water loss is independent of flow rate. The EE-1/GT-2 fracture system has become rather complex. It contains several fractures which are probably pressurized during a circulation experiment, with consequent water losses, but which are not useful for heat extraction. A newly created system of the same heat-extraction capability should have lower water loss than the present system.

5.3.4. Hydraulic Fracturing (Fracture Size and Stability, Earth Stress)

5.3.4.1. Fracture Stability. One way of reducing the flow impedance in a hydraulic fracture is to operate at a pressure slightly below the fracture extension pressure, to obtain the greatest practicable width. Even if this criterion is met, however, the fracture may not be open over its full area. In fact, for any given linear rate of change of the least principal stress with depth, we can calculate the largest vertical span over which a water-filled fracture will remain open without fracture extension. Both the internal fluid pressure, which acts to hold the crack open, and the external earth stress normal to the fracture face, which tends to close the fracture, are functions of depth. Unless they vary identically with depth, one or the other will become sufficiently large, at some fracture radius, to close or extend the fracture. The surface pressure may be adjusted so that the fracture grows at one end just as it begins to close on the other, thereby achieving the maximum open vertical span

Fig. 5-75.

Water loss rate vs log (time), Experiment 176. The step increase on the right corresponds to an input flow increase while the pressure exceeded fracture extension pressure.

possible. This is defined as the maximum stable fracture, that is, the largest open fracture which is not changing length by closing at one end or growing at the other.

5.3.4.2. Stability Calculations. Consider a vertical fracture in the xy plane, where y is positive downward. Because of the force of gravity, the pressure P in a fluid which fills the fracture increases with depth

$$dP/dy = A. \quad (5-48)$$

The least principal stress S is normal to the crack face. If it also increases linearly with depth, then, when the crack is closed

$$dS/dy = B. \quad (5-49)$$

Two-dimensional calculations. Secor and Pollard²⁹ solved the problem of the maximum stable two-dimensional fracture. In their notation the half-width, $L/2$, of the largest stable fracture is

$$\frac{L}{2} = \left(\frac{|K_C|}{\sqrt{\pi}|A-B|} \right)^{2/3}, \quad (5-50)$$

where K_C is the fracture toughness of the rock. If α is the energy expended in creating unit area of new fracture surface and if E and ν are Young's modulus and Poisson's ratio for the rock, then for a two-dimensional fracture,³⁰

$$|K_C| = \left[\frac{\alpha E}{1-\nu^2} \right]^{1/2}. \quad (5-51)$$

Using values of $\alpha = 100 \text{ J/m}^2$, $E = 8 \times 10^{10} \text{ Pa}$, and $\nu = 0.25$, Secor and Pollard found that $L/2$ varied from $3 \times 10^3 \text{ m}$ to 30 m as $|A-B|$ varied from 10 to 10^4 Pa/m . When the length of the fracture is larger than this value, the fracture will propagate upward or downward as $B > A$ or $A > B$, as was shown by Weertman³¹ for water-filled crevasses in glaciers.

Three-dimensional calculations. Y. C. Hsu and F. Santossa³² solved the analogous problem of the largest penny-shaped crack that would be stable for a given value of $|A-B|$. Their calculations indicate that the largest stable radius for the three-dimensional crack is $\sqrt{2}$ times the corresponding $L/2$ discussed above.

Realistic stress gradients. The mean value of $B-A$ can be calculated by dividing the surface pressure required to extend a fracture by its depth. If this is done for depths of 2000 m (6562 ft) in GT-2 and 2760 m (9055 ft) in EE-1, the mean value of $B-A$ to those depths is 7654 Pa/m and 3498 Pa/m , respectively. Figure 5-76 shows the maximum stable fracture radius of a penny-shaped fracture. By assuming the values of E , α , and ν given above, the three-dimensional analogy to Eq. (5-50):³²

$$a_m = \left[\frac{3\sqrt{\pi}}{2} \frac{|K_C|}{|B-A|} \right]^{2/3}, \quad (5-52)$$

Fig. 5-76.

Maximum stable fracture radius of a penny-shaped fracture.

and

$$|K_C| = \left[\frac{2\alpha E}{1-\nu^2} \right]^{1/2} \quad (5-53)$$

The expression for K_C may be derived from Eq. (50) of Ref. 33:

$$P - S = \frac{K_C}{2} \left(\frac{\pi}{a} \right)^{1/2}, \quad (5-54)$$

and Sack's equation for fracture extension pressure:³³

$$P - S = \left[\frac{\pi\alpha E}{2(1-\nu^2)} \right]^{1/2} \quad (5-55)$$

From Fig. 5-76 and the mean $|B-A|$ values given above, the maximum stable radius at 2000-m (6560-ft) depth is ~50 m (165 ft), and at 2760 m (9055 ft) it is ~85 m (280 ft). The local stress may differ from the mean. If the least principal horizontal stress could be measured at numerous points along a wellbore, it might be possible to create large, stable fractures in regions where B and A were approximately equal. The value of A could be adjusted over a limited range by varying the density of the heat-extracting fluid. In general, however, it will not be possible to hold fractures open by pressure alone.

Resistance to flow along the face of the fracture may be reduced by proppants, chemical leaching, or explosives, and eventually by shrinkage of the rock as it cools. In the EE-1/GT-2 system the phenomenon of "self-propping" (the failure of a newly opened fracture to reclose tightly) appears to eliminate the necessity for holding the fracture open by pressure. Further experiments at new locations will be required to see if self-propping can generally be expected.

5.3.5. Residence-Time Distribution Studies

Work continued in FY77 on the development of dye tracer techniques to characterize the fracture system volume and fluid residence-time distribution (RTD) within the reservoir.² Two sets of field experiments were conducted. In all cases, a pulse of sodium-fluorescein dye, about 400 liters (100 gal) of 200- to 300-ppm solution, was injected into EE-1, pumped down the EE-1 wellbore, through the fractured zone, and up the GT-2 wellbore. The dye concentration was monitored spectrophotometrically at the surface as a function of time and volume throughput. The first experiment set occurred before and after the sodium carbonate leaching experiment conducted in November 1976. The purpose of the preleaching experiment was to obtain RTD data that could be used in the design of the leaching test (see Sec. 5.3.6.) and to evaluate the condition of the fracture system before leaching was attempted. The postleaching dye study was to identify any changes in the RTD that may have occurred. The results for the pre- and postleaching tests are given in Fig. 5-77 A and B. In both cases, a constant EE-1 surface injection pressure of 83 bars (1200 psi) was maintained with GT-2 fully vented; a 200-ppm, 400-liter (100-gal), slug of sodium-fluorescein was used; and about 22 - 37% of the dye was eventually recovered at GT-2 under system impedances ranging from 14 to 19 bar-s/liter (13 to 17 psi/gpm).

The second set of experiments (see Fig. 5-77 C and D) was designed to characterize the redrilled GT-2B/EE-1 system before extensive heat-extraction experiments began. Two sodium-fluorescein dye tracer studies were conducted as a part of Experiment 176. In each case, a 400-liter (100-gal) slug of 300-ppm sodium-fluorescein dye solution was injected into EE-1, pumped through the fracture system, and sampled and analyzed as it returned to the GT-2 wellhead. The first dye experiment was started during the changeover to closed-loop operation, after 34 h of open-loop operation. Pumping began into EE-1 at an average flow rate of 9.5 liters/s (150 gpm). After about 20 000 liters (~5257 gal) had been pumped behind the dye front, as it left the EE-1 wellbore and entered the fracture, a leak (valve opening) in the EE-1 injection line necessitated a pump

A

B

C

D

Fig. 5-77.
Sodium-fluorescein dye tracer results. A and B are for the GT-2/EE-1 system before redrilling and C and D are for the redrilled system.

shutdown followed by a shut-in of GT-2 and EE-1. Pumping resumed in GT-2 after about 3 h with the front edge of the dye observed about 2.7 h later, corresponding to a minimum fracture volume of 15 370 liters (4060 gal) or residence time of about 40 min. A mean EE-1 surface injection pressure of 69 bars (1000 psi) was calculated for this first experiment, but the system shutdown resulted in a pressure variation from 1100 to 900 psi while most of the dye was in the fracture. The RTD curve is shown in Fig. 77C. Seventy percent of the dye was recovered at GT-2.

The second dye experiment of this set (D) was performed without shutdowns. Pumping of the dye slug began at 0217 MDT on September 30, 1977, with an average rate of 9.5 liters/s (150 gpm). The dye front entered the fracture at 1106:30 MDT and was first seen at GT-2 at 0755 MDT, corresponding to a minimum fracture volume of 10 000 liters (2500 gal) or residence time of 25 min. The EE-1 surface injection pressure was ± 1350 bars (± 20 psi) while most of the dye was in the fracture. In this experiment only 40% of the dye was recovered at GT-2.

We do not yet understand the cause of the different recoveries between experiments C and D. The mean pressure levels were different, 70 vs 93 bars (EE-1 surface pressure). At the higher pressure, the permeation water loss rate was higher (30 gpm vs 20 gpm out of 150 gpm) but not high enough to account for the difference between 40 and 70% recovery of dye. Possibly, additional fresh rock surface area (with minimal additional volume) was exposed to the dye, resulting in losses by absorption, or mixing and dilution by returning permeation flow obscured the estimation of recoveries by providing a long concentration "tail" with concentration levels below detection.

To evaluate these residence-time distributions we used a simple normalization procedure. Normalized concentrations (C_θ) plotted in Fig. 5-77 correspond to:

$$C_\theta = C_i / \left[\frac{1}{\bar{V}} \int C_i dV \right] , \quad (5-56)$$

where

C_i = measured output dye concentration, ppm

$\bar{V}$ = mean fracture-system volume

V = fracture-system volume corresponding to C_i .

TABLE 5-XIV
RESIDENCE-TIME DISTRIBUTION RESULTS

Experiment	$\bar{P}_{EE-1}$		$\bar{V}$		$\bar{\tau}$	σ_{θ}^2
	(bars)	(psi)	(liters)	(gal)		
Preleaching Expt. 137	83	1200	34 500	9115	10	0.241
Postleaching Expt. 138	83	1200	37 950	10 025	11	0.345
#1, Expt. 176	69	1000	37 600	9933	1.5	0.348
#2, Expt. 176	93	1350	35 480	9373	1.4	0.467

$$\bar{V} = \text{mean volume} = \int V C_i dV / I$$

$$I = \int C_i dV = \text{dye recovery normalization integral}$$

$$\bar{\tau} = V / \bar{q}_{GT-2} = \text{mean residence time}$$

$$\bar{q}_{GT-2} = \text{average flow rate at GT-2}$$

$$\sigma_{\theta}^2 = C_{\theta} \text{ distribution variance} = \int V^2 C_i dV / \bar{V}^2 - 1$$

The integral term I represents the total amount of dye recovered. In Table 5-XIV mean volumes, residence times, and normalized variances for the dye tracer measurements made during Experiment 176 are compared with results obtained before redrilling.

Figure 5-78 and Table 5-XIV show that the RTD characteristics of the GT-2/EE-1 system have not undergone any dramatic change caused by the redrilling operation, nor is there any statistically significant difference (95% confidence level) between the RTD for the 69-bar (1000-psi) vs the 93-bar (1350-psi) case in Experiment 176. The main features are: (1) no short-circuit flow, minimum volume about 12 800 liters (~3200 gal), (2) mean volume of the fracture system is 35 000 - 38 000 liters (9000 - 10 000 gal), (3) very dispersed flow indicates considerable mixing occurs in system (widely different from the near-plug flow

that might be expected for a single, flat planar fracture with no buoyant circulation). All of these features are encouraging from a heat-extraction point of view. The system must be larger than an equivalent 0.2-mm (8-mil) -wide plane fracture having a 100-m (330-ft) radial extent corresponding to the separation between the main inlet and outlet points in GT-2 and EE-1. This may be a result of a wider fracture, a larger radius fracture (~300 m or 985 ft), and/or a significantly more complex flow path for fluid. The large amount of dispersion observed requires considerable mixing within the fractured region. It is important to emphasize that tracer studies of this type do not directly determine the surface area of rock exposed to circulating fluid. A large dispersed flow volume does not necessarily guarantee a large fracture surface area.

Efforts are under way to develop an empirical model with multiple flow paths that will describe the observed RTD, consistent with the geometric constraints presented in Sec. 5.4. A parallel, dispersed-flow system with multiple porous zones characterized by individual dispersion coefficients, volumes, and flow rates is being used.

5.3.6. Chemical Leaching with Na₂CO₃

5.3.6.1. Treatment Design. By superimposing fluid residence data collected on the EE-1/GT-2 fracture system (Sec. 5.3.5.) with dissolution kinetic data (Sec. 5.2.4.), we can estimate the concentration response of reaction products for a given input of sodium carbonate. The superposition is accomplished by using the empirical kinetic dissolution equation developed in Sec. 5.2.4:

$$\frac{d[\text{SiO}_2]_{\text{aq}}}{dt} = k_d^* a^* ([\text{SiO}_2]_{\text{aq}}^{\text{sat}} - [\text{SiO}_2]_{\text{aq}}) \quad , \quad (5-57)$$

which can be rewritten as

$$\frac{dC}{dt} = -k_d^* a^* (C_{\infty} - C) \quad , \quad (5-58)$$

where

$$C = [\text{SiO}_2]_{\text{aq}}$$

$$C_{\infty} = [\text{SiO}_2]_{\text{aq}}^{\text{sat}} = f [\text{initial Na}_2\text{CO}_3 \text{ concentration}] \text{ (see Sec. 5.2.4.)}$$

and the empirical RTD developed in Sec. 5.3.5.

$$C_{\theta} = f(\theta) = C_i / \frac{1}{V} \int_0^{\infty} C_i dV \quad (5-59)$$

The degree of completion or extent of reaction α can then be expressed by combining Eqs. (5-58) and (5-59) and by using a cumulative distribution function format, because the sodium carbonate is added as a step input rather than as a pulse.

$$\alpha \equiv \frac{C}{C_{\infty}} = \int_0^{\theta} [1 - \exp [-k_d^* a^* \tau \theta]] C_{\theta} d\theta \quad (5-60)$$

with

$$\theta = \frac{t}{\tau} = \frac{t\dot{q}}{V} \quad (5-61)$$

where

t = time

$\dot{q}$ = flow rate

V = mean system volume

τ = mean residence time

k_d^* = kinetic dissolution rate parameter

a^* = surface area/volume ratio.

To quantify this estimate, we must know the magnitude of the dimensionless rate parameter group $k_d^* a^* \tau$ in Eq. (5-60) as well as the initial concentration and amount of Na_2CO_3 added. Figure 5-79 shows the dimensionless concentration response C/C_{∞} vs dimensionless time or volume θ for various values of E .

The dimensionless parameter $E \equiv k_d^* a^* \tau$ shows the effect of the first-order kinetic rate constant k_d^* , the in situ surface area to fluid volume ratio a^* , and the mean residence time τ on the extent of reaction α for a given value of θ . When $\alpha = 1.0$, a new solubility limit for silica is reached corresponding to exhaustion of the ability of the carbonate to provide free hydroxide for forming soluble metasilicates (see Sec. 5.2.4.). Figure 5-79 can be used to predict a

Fig. 5-78.

Composite of sodium-fluorescein dye tracer results. Experiment 176 results are for the redrilled GT-2B/EE-1 system.

Fig. 5-79.

Dimensionless concentration (C/C_∞) of reaction product as a function of dimensionless time or volume $\theta = t/\bar{t} = V/\bar{V}$ for different values of the dimensionless reaction rate parameter E .

mean system a^* from known values of k_d^* , τ , and the output response of $\text{SiO}_{2(\text{aq})}$ concentration. Consequently, qualitative characteristics of the GT-2/EE-1 flow impedance can be identified, that is, whether the major fraction is contained in the low matrix permeability of rock between overlapped parallel fractures with a high a^* vs an internal flow resistance in the hydraulic fracture itself with a lower a^* . Based on laboratory reaction rate and permeability measurements, a composition of 1 N Na_2CO_3 was selected for the field test.

5.3.6.2. Field Test Procedure and Results. In a residence-time distribution study (Experiment 137) to evaluate precisely the condition of the fracture system before leaching, about 1000 m^3 (275 000 gal) of water were pumped through the system. Then 190 m^3 (50 000 gal) of 1 N Na_2CO_3 solution - about five fracture-volumes - were pumped through in a 25-h period at a constant EE-1 injection pressure of 83 bars (1200 psi). Finally, the system was thoroughly flushed with fresh water and the dye-injection residence-time study was repeated. About 1000 kg (1 ton) of silica were dissolved and removed from the reservoir, but with no significant effect on system volume or residence-time distribution of the fluid. Unexpectedly, however, instead of reducing flow impedance, the chemical treatment increased it slightly, from about 82 bar-s/liter (75 psi/gpm) during preleach circulation to about 98 to 110 bar-s/liter (90 to 100 psi/gpm)

during postleach flushing. Because these measurements were made at pressures too low to inflate the hydraulic fracture, one possible explanation is that the self-propping is primarily by quartz grains which, being stressed, were sufficiently dissolved to permit partial closure of the fractures. An alternative explanation is that, because there was considerable attack of the cement behind the EE-1 casing, the fractures were partially plugged by residual fines from the cement. Preliminary indications are that the lower connection in EE-1 at ~2943 m (9650 ft) was sealed off. Plugging by mineral alteration is a third possibility, although this did not occur during leaching and permeability experiments on core samples in the laboratory (see Sec. 5.2.4.). To the contrary, laboratory permeability tests run at 200°C with a constant concentration of Na_2CO_3 as the permeating fluid resulted in increases in permeability and, in fact, for exposures of up to 30 h with a 1 N Na_2CO_3 solution, a dramatic (>100 fold) increase occurred.

Conceptually, the form of the silica concentration response vs fracture throughput volume as shown in Fig. 5-80 corresponds to a rapid rate of reaction in Fig. 5-79 with a large value of E. This is probably caused by a large value of a^* , indicative more of granite matrix attack by the reacting fluid as it penetrates across a set of parallel fractures than of fracture-face attack (see Fig. 5-81).

If dissolution on the faces of the hydraulic fracture was the main mechanism, one would expect that a^* would have a minimum value, equal to $3/2b$, for elongated, elliptical-shaped cracks where b is the mean width. For a self-propped fracture in this rock, widths of 0.2 - 1.0 mm (8 - 40 mils) are estimated (see Secs. 5.3.1. and 5.5.3.). The same principle could be applied to flow in the matrix via communicating microcracks except that b is probably $\leq 10^{-3}$ mm, as shown by work done by Simmons and Cooper³⁴ on GT-2 core material. Consequently, the ratio of E's can be estimated:

$$\frac{E(\text{matrix})}{E(\text{fracture face})} = \frac{k_d^* a^* (\text{matrix}) \tau}{k_d^* a^* (\text{fracture face}) \tau} \approx 10^3 \quad (5-62)$$

and a distinct difference in C/C_∞ vs θ should be observed.

Before estimates of E or a^* can be made, an appropriate value of C_∞ must be established. Normally, only the initial Na_2CO_3 concentration would be required to estimate C_∞ (see Sec. 5.2.4.), but because of internal pressure changes within the fracture system caused by hydrostatic density gradients in the wellbores, a

Fig. 5-80.

Aqueous silica concentration vs through-put volume in response to a 190-m^3 ($50\,000\text{-gal}$) injection of $1\text{ N Na}_2\text{CO}_3$. Wellbore effects have been subtracted.

Fig. 5-81.

Conceptual cross section of EE-1/GT-2 system after carbonate leaching.

$1\text{ N Na}_2\text{CO}_3$ concentration was apparently never sustained in the fracture. For example, the Na^+ concentration reached only $11\,000\text{ ppm}$ and $\text{CO}_3^{2-}/\text{HCO}_3^-$, $18\,900\text{ ppm}$. Neither Na^+ nor $\text{CO}_3^{2-}/\text{HCO}_3^-$ attained the levels of $23\,000$ and $30\,000\text{ ppm}$, respectively, which would be expected for a $1\text{ N Na}_2\text{CO}_3$ solution (see Figs. 5-82, -83, and -84). Although the shape of the concentration-volume curve was approximately what was expected for a residence-time distribution given by Fig. 5-76 of Sec. 5.3.5., material balance results for Na^+ and $\text{CO}_3^{2-}/\text{HCO}_3^-$ indicated that only 35% (Na-basis) and 46% ($\text{CO}_3^{2-}/\text{HCO}_3^-$ -basis) of the injected material was recovered.

Peak concentration data and material balance results for Na^+ and $\text{CO}_3^{2-}/\text{HCO}_3^-$ combined with the preleaching and postleaching dye studies (see Sec. 5.5.5.) were used to develop a weighted average characteristic Na_2CO_3 concentration in the formation, which was then used to estimate a C_∞ or $[\text{SiO}_2]_{\text{aq}}^{\text{sat}}$ of $4500 \pm 800\text{ ppm}$. With SiO_2 concentrations determined by atomic absorption (Fig. 5-80), C/C_∞ ratios were calculated and compared to the C/C_∞ - vs - θ curves of Fig. 5-79. A range of $1.5 - 5$ was calculated for E based on the uncertainty in C_∞ values.

Because of problems with SiO_2 depositing on the walls of the sample bottles, measured SiO_2 concentrations shown in Fig. 5-80 are probably conservatively low; consequently, C/C_∞ values and the resulting E's should be viewed as lower limits.

The similar shapes of the concentration-volume throughput profiles (Figs. 5-80 and 5-83 through -86) for Na^+ , $\text{CO}_3^{-2}/\text{HCO}_3^-$, SiO_2 , F^- , and H^+ (pH) indicate similar dispersive flow and reaction mechanisms for each species. For those figures in which the species concentration is plotted as a function of volume throughput, the wellbore volumes have been subtracted. Thus, the response at zero volume corresponds to a time when the 190-m^3 (50 000-gal) slug of Na_2CO_3 solution first reaches the EE-1/GT-2 fracture system.

The observed F^- response, from a background level of 12 - 15 ppm to a peak concentration of 175 ppm with sustained levels from 140 to 160 ppm while the 190-m^3 (50 000-gal) carbonate slug was flowing through the system, verifies the reaction is with the formation. The soluble fluoride was possibly produced from a fluoride-rich biotite of CaF_2 -enriched section of the EE-1/GT-2 fracture system. Furthermore, the high F^- concentrations achieved during leaching resulted in the dissolution of about 42 kg (92 lb) of fluoride from the formation and could not be attributed to other sources (such as the decomposition of the casing cement in EE-1).

The electrical conductivity of the effluent solution of Fig. 5-87 also behaves as expected for the levels of dispersion measured in the system. In addition, the maximum conductivity measured was about 45 000 $\mu\text{mho/cm}$, still below the nominal 64 000- $\mu\text{mho/cm}$ value for the 1 N Na_2CO_3 feed and thus providing further evidence that the carbonate concentration never reached 1 N in the formation.

Figures 5-88 and -89 provide additional information on fluid composition before and during the carbonate leaching test. In addition to the increase observed for aqueous SiO_2 (Fig. 5-82), K^+ , PO_4^{-3} , F^- , and SO_4^{-2} showed considerable increases in concentration, whereas Cl^- increased only slightly. This may be due to increased dissolution rates of other components of the reservoir rock, such as microcline, whereas the Cl^- level is due more to a pore fluid rather than a dissolution source. However, decreases in Ca^{+2} , $\text{Fe}^{+2}/\text{Fe}^{+3}$, Al^{+3} , and Mg^{+2} concentrations were observed, which is consistent with the formation of iron talcs (for example, minnesotaite) and a calcium silicon oxide hydrate (xonotlite), and other alteration products as described in Sec. 5.2.4.

Fig. 5-82.

Background and peak concentrations of indicated species contained in fluid circulated through the GT-2/EE-1 fracture system before and during the sodium carbonate leaching field test (Experiments 137 and 138).

Fig. 5-83.

Na⁺ concentration vs fracture volume³ throughput in response to a 190-m³ (50 000-gal) injection of 1 N Na₂CO₃. Atomic absorption used for analyses.

Fig. 5-84.

Carbonate and bicarbonate (CO₃⁻²/HCO₃⁻) ion concentration vs fracture volume³ throughput in response to a 190-m³ (50 000-gal) injection of 1 N Na₂CO₃. Titration used for analyses.

Fig. 5-85.

Fluid pH vs fracture volume throughput in response to a 190-m³ (50 000-gal) injection of 1 N Na₂CO₃.

Fig. 5-86.

F^- concentration vs fracture volume throughput in response to a 190-m^3 ($50\,000\text{-gal}$) injection of $1\text{ N Na}_2\text{CO}_3$. Select ion electrode used for analysis.

Fig. 5-87.

Electrical conductivity of the returned fluid vs fracture volume throughput in response to a 190-m^3 ($50\,000\text{-gal}$) injection of $1\text{ N Na}_2\text{CO}_3$.

Fig. 5-88.

Background and peak concentrations of species contained in fluid circulated through the GT-2/EE-1 fracture system before and during the sodium carbonate leaching field test (Experiments 137 and 138).

Fig. 5-89.

Background and peak concentrations of species contained in fluid circulated through the GT-2/EE-1 fracture system before and during the sodium carbonate leaching field test (Experiments 137 and 138).

Apart from the useful aspects of the data obtained, the phase I sodium carbonate dissolution attempt to decrease impedance in the GT-2/EE-1 system was unsuccessful. Of course, additional leaching with sodium carbonate or sodium hydroxide could have eventually resulted in substantial increases in matrix permeability, causing a breakthrough effect and a substantial decrease in impedance (see Fig. 5-81). Another possible approach would be acid treatment to dissolve calcite, the major secondary mineral that fills and seals old fractures in the crystalline rock. However, as a result of successful development of more sophisticated downhole instruments and wellbore- and fracture-mapping techniques, the geometry of the underground circulation loop became better understood (see Sec. 5.1.). Accordingly, instead of additional chemical treatments, the next improvement effort was to redrill with the hope of creating a single, low-impedance fracture system connected to the two boreholes.

5.4. Reservoir Geometry Modeling (R. L. Aamodt, J. N. Albright, A. E. Batchelor, H. N. Fisher, H. D. Murphy, R. M. Potter, R. W. Spence, J. W. Tester)

The fracture system that originates at 2752 m (9030 ft) TVD* in EE-1 with a major connection to the GT-2B borehole at 2665 m (8745 ft) TVD, will be the source of heat for the major heat-extraction experiment. Figure 5-90 shows one possible interpretative model of this system, which encompasses the accumulated results of ranging and flow experiments and assorted geophysical logs.

The main flow path is shown as a near-vertical, hydraulically activated fracture lying between the GT-2A and GT-2B wellbores, with an orientation of approximately northwest-southeast and terminating somewhere near the contact between the gneiss and granodiorite. The main connection from the GT-2B wellbore to this vertical fracture is through a short, inclined ($\sim 30^\circ$) cross fracture, possibly a hydraulically activated natural feature. Evidence for this structure and its location comes from the nature of the intersections observed along the GT-2A and GT-2B wellbores during redrilling, temperature logs, flow and acoustic experiments, and the structure of the core at 2665 m (8745 ft) TVD.

Numerous inclined fractures are shown in Fig. 5-90, intersecting both this main feature and the several boreholes. One of these fractures is shown as the connecting fracture described above. These flow paths are to explain the numerous well-defined anomalies in temperature logs during flow and related pressure drops during redrilling. Also shown in Fig. 5-90 are anomalies in the service company's wellbore logs, which appear to support the existence of these fractures, either before the original pressurization or to show the effects of flow from them after pressure stimulation. This set of inclined fractures appears to be roughly parallel with the contact, and their origins may arise from stresses accompanying the intrusion of the granodiorite. Their inclination of $\sim 30^\circ$ from the vertical would permit lateral movement of water at a much higher permeability than would be available through the undisturbed matrix. Such a system would provide a model to explain the flow between the EE-1 and GT-2 fractures. Further substantiation for such a model is an interpretation of the history of the acoustic cement-bond logs taken in EE-1. They have shown a steady deterioration in the bonding of the cement at several depths that correlate reasonably well with the intersections of the inclined fracture set with the EE-1 wellbore.

* True vertical depth measured from 2652 m (8700 ft) SL.

Professor K. Aki (MIT) has examined the acoustic signals arising from the fracture experiments in GT-2 and has deduced their source mechanism. If the principal stress is vertical,* they are dip-slip events arising from inclined surfaces striking about northwest-southeast. Pressurization of the fracture set shown in Fig. 5-90 would provide the activation for and the geometric characteristics of his mechanism. (See also Sec. 5.1.).

*The proximity of the Fenton Hill site to the Valles Caldera and the Rio Grande Rift System strongly suggests a vertical principal stress.

Fig. 5-90.
Interpretative geophysical model of the EE-1/GT-2 system (elevation, as viewed from 125°).

5.5. Reservoir Performance Modeling (R. L. Aamodt, D. W. Brown, H. N. Fisher, Y. C. Hsu, R. G. Lawton, H. D. Murphy, R. M. Potter, J. W. Tester)

5.5.1. Permeability-Porosity Models of the Flow System

Hydraulic fractures were established and enlarged during October 1975 in granite at a depth of about 2900 m (9000 - 10 000 ft) in GT-2 and EE-1. A distinct fracture system was established at each borehole. Microseismic, acoustic ranging and other experiments indicated that, at a depth of 2900 m, the boreholes are separated by as little as 10 m (30 ft), but the fracture system itself is very complex, consisting of multiple interconnected high-conductivity zones (see Sec. 5.4.). As is the case in other formations, the main fractures are presumed to be nearly planar and perpendicular to the direction of the least principal earth stress (S_3) with interconnections determined by weakly cemented smaller fractures. For the purpose of modeling permeation and porosity in the reservoir, the total system can be viewed as consisting of two planar, parallel fractures connected by a homogeneous matrix. However, the possibility that one fracture system (EE-1) consists of two distinct fractures has not been confirmed by the present analysis.

Many pressurization and flow experiments were performed on each fracture system and on the combined system before the redrilling of GT-2. They have provided considerable data on the interdependence of pressure, total flow, flow between the fractures, and flow into the surrounding formation. The data are complicated by changes occurring in the fracture geometry under pressurization, the main effects being the extension of the areas of the fractures. The data indicate that, once a fracture is established, it remains open with a constant area and a width sufficient to allow flow into the fracture at low impedance. The response of the flow to pressure, then, is governed by fluid permeation through the porous rock surrounding the fractures.

The present analysis is based on the one- and two-dimensional time-dependent diffusion equations governing the flow of water and hence the transient pore pressure P in the granite. Early in the pressurization of either fracture the flow is one dimensional; at some later time, determined by the rock properties and the dimensions of the system, the extent of the pore pressure field becomes comparable to the dimensions of the fractures and the two-dimensional equation governs. In this case the fractures are assumed to have cylindrical symmetry about an axis parallel to S_3 and to have radii determined by equating the calculated areas to that of circles. During all experiments, only total flow and pressure for the two wells were measured; therefore, the system parameters of

both fracture areas, the separation distance between the fractures, and rock permeability k and porosity θ or pore compressibility ($\beta = d\theta/dP$) cannot be uniquely determined. Some use must be made of other measurements of system dimensions. The fracture areas and the separation implied by the microseismic and acoustic ranging studies are used to determine an approximate permeability, porosity, and pore compressibility. This permeability is then compared with that determined in the laboratory for flow through the microstructure. The Kozeny-Carmen model,³⁵ which relates permeability porosity and crack (or pore) spacing is then used to further characterize the pore geometry.

The importance of the pressure dependence of the rock properties was previously discussed.² However, the pressure dependence of all three related quantities, permeability, porosity, and pore compressibility, must be determined to fit the data with solutions of the nonlinear diffusion equation. The complicated nature of this pressure dependence - and the fact that each depends on the rock elastic moduli, pore geometry, and the earth stresses - required the construction of a model for porosity. This model takes into account the nonlinear expansion of the pores; the pore volumes must increase by several factors, and the linear theory³⁶ is inadequate. The theoretical porosity and permeability are obtained through the use of a "stiffened-gas" equation of state. The theoretical permeability produces a good fit to the laboratory measurements of core permeability of the microstructure of the cores from the GT-2 boreholes. Also, the permeability and compressibility provide good fits in the in situ flow measurements when they are used in the nonlinear diffusion equation.

During some of the experiments, steady-state flow was observed in two modes. Steady-state flow between the fractures is characterized by constant pressure within the fracture into which the water is being pumped, and by constant pressure within and constant flow out of the other fracture. Steady-state flow into the infinitely permeable formation can be approached at constant pressure. These modes of flow provide additional information on the permeability and its dependence on pressure. A detailed analysis, now in progress, of the transition from one- to two-dimensional flow will also require the introduction of an anisotropic permeability. Preliminary calculations indicate that time required to establish steady-state flow into the infinite medium is consistent with observations.

The value of viscosity used in the analyses was that of water at 200°C, namely 1.4×10^{-4} Pa-s (9.4×10^{-5} lb/s-ft).

5.5.1.1. Theory. Assume that the average flow velocity is determined by the Darcy equation,

$$\bar{v} = - \frac{k}{\mu} \nabla P \quad (5-63)$$

where k is the permeability tensor, μ the viscosity, and P the pore pressure. The continuity equation is

$$\nabla \cdot (\rho \bar{v}) + \frac{\partial(\rho \theta)}{\partial t} = 0 \quad (5-64)$$

with ρ the fluid density and θ the porosity. The pressure then, is the solution to³⁵

$$\nabla \cdot \frac{\rho k}{\mu} \nabla P = \frac{\partial(\rho \theta)}{\partial t} = \frac{d(\rho \theta)}{dP} \frac{\partial P}{\partial t} . \quad (5-65)$$

The density of the permeating fluid ρ can be expanded as $\rho = \rho_0(1 + \beta_w P)$. Then because $\beta_w \sim 5.0 \times 10^{-4} \text{ MPa}^{-1}$ for the compressibility of water

$$\frac{d(\rho \theta)}{dP} = \theta \beta_w \rho_0 + \rho_0 \frac{d\theta}{dP} . \quad (5-66)$$

Here, $d\theta/dP$ depends on the properties of the rock, which is about 20 times less compressible than water. So it is not clear which term, if either, of Eq. (5-66) will dominate. Similar considerations hold for the left-hand side of Eq. (5-65). We will assume here that the term $\theta \beta_w \rho_0$ in Eq. (5-66) will not dominate and that ρ can be considered constant. This assumption must be justified later. For now

$$\nabla \cdot (k \nabla P) = \mu \frac{d\theta}{dP} \frac{\partial P}{\partial t} . \quad (5-67)$$

The related quantities k , θ , and $\beta = d\theta/dP$, and, in particular, their dependence on pressure cannot be determined exactly because they also depend on the pore volumes, shapes, orientations, and distribution in space, which are not known. In addition, each depends on the three components of stress, which in

turn are determined by the in situ earth stresses and, to some extent, the pore pressure. The linear Biot theory in which the porosity depends linearly on the pore pressure and mean stress is described in detail in Ref. 36. In the situation under consideration the data indicate that the pore compressibility changes by many factors and the linear theory must be replaced by one that takes this into account. The use of a stiffened-gas equation of state and the assumption that the change in pore volume is proportional to the volumetric strain give for the porosity

$$\theta = \theta_0 / [1 - CP]^{1/\gamma}, \quad (5-68)$$

where

γ = adiabatic constant (Ref. 37)

$C = k/H(s+P_0)$

s = stress

k = (bulk modulus)⁻¹

H = constant that relates volumetric strain to pore pressure P ,

and for constant C ,

$$\beta = d\theta/dP = \frac{\theta_0 C}{\gamma(1 - CP)^{1+1/\gamma}}. \quad (5-69)$$

If the Kozeny-Carmen relation³⁵ is used to obtain the pressure dependence of the permeability, that is, $k \propto \theta^3$, then

$$k = \frac{k_0}{(1 - CP)^{3/\gamma}}. \quad (5-70)$$

Application of Eq. (5-70) to the real situation requires that anisotropic stresses be incorporated. Several simplifying assumptions are made, based on the fact that the principal stresses obey the inequality, $S_1 > S_2 > S_3$. The porosity will be determined by the smallest stress, S_3 , and the permeability for flow parallel to S_3 will be determined by S_2 . Also, if the rock is considered to consist of bound harmonic oscillators, each with $N = 3^\circ$ of freedom, then $\gamma \sim (N + 2)/N = 5/3$.

Then

$$\theta = \frac{\theta_0}{(1 - C_3 P)^{0.6}} , \quad (5-71)$$

$$k_2 = \frac{k_0}{(1 - C_2 P)^{1.8}} , \quad (5-72)$$

and

$$\beta = \frac{\beta_0}{(1 - C_3 P)^{1.6}} , \quad (5-73)$$

where $C_2 < C_3$.

5.5.1.2. The Permeability of the GT-2 Microstructure. The permeability of the microstructure of several cores from GT-2 has been measured as a function of confining pressure P_c and pore pressure (Sec. 5.2.3.) under isothermal conditions. The data plotted in Fig. 5-91 indicate that the permeability depends only on $P_e = P_c - P$; that is, $k/H \sim 1$. By use of the appropriate simplifications to the equation of state,

$$k = \frac{k_0}{(1 + P_e/P_0)^3} . \quad (5-74)$$

The solid curves of Fig. 5-91 were fit to each set of data by adjusting k_0 and P_0 . The values of P_0 obtained range from 15.1 to 22.5 MPa (2200 to 3260 psi); those of k_0 from 1.1×10^{-14} to $2.2 \times 10^{-13} \text{ m}^2$ (1.2×10^{-13} to $2.4 \times 10^{-12} \text{ ft}^2$).

At the in situ confining pressure the permeability of the core samples at 200°C is $\leq 5.0 \times 10^{-18} \text{ m}^2$ ($\leq 5 \text{ } \mu\text{d}$).

5.5.1.3. Field Experimental Analyses. Most of the flow experiments began with the wellbores nearly full; that is, with the initial pore pressure at hydrostatic pressure, which will be taken as the zero pressure in the analysis.

Fig. 5-91.

Permeability of the microstructure of GT-2 granite vs confining pressure.

The first phase of the flow analyzed is that occurring at times small enough so that the flow from the planar fractures will be one dimensional. We will later show that this can be true for times $\ll 25$ h. In this case, the differential equation to be solved is

$$\frac{\partial}{\partial z} \left(\frac{k_0}{\mu(1 - c_2 P)^{1.8}} \frac{\partial P}{\partial z} \right) = \frac{\beta_0}{(1 - c_3 P)^{1.6}} \frac{\partial P}{\partial t}, \quad (5-75)$$

where z is the coordinate perpendicular to the plane of the fracture. Also, as in the case of constant coefficients, the pressure at a distance ℓ from the fracture will be determined by

$$\frac{\ell^2 \mu \beta}{k} = b. \quad (5-76)$$

In the nonlinear case, b is determined by fitting the solution of Eq. (5-75) to the data.

Solutions of this nonlinear one-dimensional version of Eq. (5-67) were obtained with the AYER code.³⁸ AYER is an implicit finite-element code that solves the diffusion equation in plane or cylindrically symmetric coordinates for

variable material properties. For the case of constant flow rate and time such that $C_2P \ll 1$ and $C_3P \ll 1$, the solution to Eq. (5-75) is at $z = 0$ (Ref. 39)

$$P = 2 \sqrt{\frac{\mu}{k_o \beta_o \pi}} \left(\frac{\dot{Q}}{2A} \right) \sqrt{t} , \quad (5-77)$$

where $2A$ is the total area (m^2) into which the water is permeating and $\dot{Q}$ is the total flow (m^3/s). The initial slope of P vs $\sqrt{t}$ then gives as a value for

$$A \sqrt{k_o \beta_o} = \frac{\dot{Q}}{P} \sqrt{\frac{\mu t}{\pi}} . \quad (5-78)$$

Experiment 111 (Ref. 2) was designed so that $A\sqrt{k\beta}$ could be determined at several initial pressures in EE-1 and hence give the pressure dependence of $k\beta$. The pressure response in GT-2 also gives b , and hence gives the pressure dependence of β/k . Fits to the solutions of Eq. (5-75) to the data from this experiment confirm that the pressure dependence of k and β in Eqs. (5-71) and (5-73) are approximately correct and give values for C_3 and C_2 . The experiment was conducted as follows. With GT-2 shut-in, EE-1 was pumped into alternately at constant flow and constant pressure. The pressure was raised rapidly by pumping at a high constant rate then maintained at a constant pressure to establish a new pore pressure near the fracture. This cycle was repeated four times. The pressure response in GT-2 is plotted in Fig. 5-92. The calculated fit to the GT-2 pressure is for $C_3 = 0.980 \times 10^{-7} \text{ Pa}^{-1}$ ($6.8 \times 10^{-4} \text{ psi}^{-1}$) and $C_2 = 0.196 \times 10^{-7} \text{ Pa}^{-1}$ ($1.35 \times 10^{-4} \text{ psi}^{-1}$). In Fig. 5-93 the pressure history of EE-1 is replotted for the short constant-flow periods. In each case time is zero at the beginning of the constant-flow phase, and the initial pressure P_o established by the constant pressure phase is subtracted. A good fit is obtained for the previously mentioned values of C_2 and C_3 .

During the initial pumping at a constant flow rate in either wellbore the pressure generally increases approximately linearly with the square root of time. The departure from linearity becomes pronounced when the pressure nears 6.0 MPa (870 psia). This behavior is typified by the data for Experiment 110 in EE-1, plotted in Fig. 5-94. The AYER results for the one-dimensional model are also shown. A good fit is obtained for the same values of C_2 and C_3 that fit Experiment 111.

The relationship of fracture areas and separation to the permeability and compressibility can be determined from some of the experiments at pressures near zero (hydrostatic). In addition to Eqs. (5-76) and (5-78), steady flow ($\dot{Q}$) between the fracture systems at a pressure difference of P gives

$$\frac{P}{\dot{Q}} = \frac{\ell \mu}{\bar{A} k_o} \quad (5-79)$$

or

$$\frac{\bar{A} k_o}{\ell} = \frac{\mu \dot{Q}}{P} = c, \quad (5-80)$$

where $\bar{A}$ is the connecting area, some weighted average of A_1 and A_2 . Here it is assumed that $\bar{A} = (A_1 + A_2)/2$. Equations (5-76), (5-77), and (5-78) are not independent, so A and ℓ must be specified to obtain k_o and β_o . During these experiments the product $A_2 \sqrt{k_o \beta_o}$ of the GT-2 fracture remained constant, so the area probably remained constant. This area and approximate separation of the fractures can be inferred from the microseismic data (Ref. 2) and Sec. 5.1. While GT-2 was being pressurized, the locus of resulting microseismic events was recorded with geophones located at various depths in the EE-1 wellbore. The events lie roughly in a plane, and an envelope drawn around them has an area of $A_2 = 2.0 \times 10^4 \text{ m}^2$. Similar data indicated that the transverse extent of the fracture system was $\ell \gtrsim 30 \text{ m}$. These values will be used in the characterization of the system with A_1 determined from the ratio of the $A \sqrt{k_o \beta_o}$ products. EE-1 has received more high-pressure pumping than GT-2, and the area (or $A_1 \sqrt{k_o \beta_o}$) has increased during some experiments. Figure 5-95 is a plot of k_o vs β_o for $A_2 = 2.0 \times 10^4 \text{ m}^2$ and $\ell = 10$ and 30 m . Curve A is for a constant $k_o \beta_o$ from Eq. (5-78). B and C are from the fits to the data of Experiment 111 that determine a constant k_o/β_o with Eq. (5-76). In Experiment 119 steady-state flow from EE-1 to GT-2 was achieved with a pressure of 4.8 MPa (48 bars). From Eq. (5-72) k was within 20% of k_o in the region between the fractures. The values of k_o determined by Eq. (5-80) for this experiment and the canonical values of A and ℓ are indicated by D and E in Fig. 5-95. Nominal values of the permeability and compressibility at hydrostatic pressure are $k_o = 2.0 \times 10^{-17} \text{ m}^2 \text{ (} 2.2 \times 10^{-16} \text{ ft}^2 \text{)}$ and $\beta_o = 2.0 \times 10^{-6} \text{ MPa}^{-1} \text{ (} 0.0138 \text{ psi}^{-1} \text{)}$.

Equations (5-71) and (5-73) give for the porosity

$$\theta_0 = \frac{\gamma \beta_0}{c_3} \approx 3.0 \times 10^{-5} . \quad (5-81)$$

The effective compressibility of the water in Eq. (5-66) is $\theta_0 \beta_w = 1.5 \times 10^{-8} \text{ MPa}^{-1}$ ($1.0 \times 10^{-4} \text{ psi}^{-1}$), and neglecting this effect was justified.

The Kozeny-Carmen equation,³⁵ which relates porosity and pore geometry to permeability, gives

$$d = \left(\frac{B k_0}{\theta_0} \right)^{1/2} \quad (5-82)$$

for the spacing of the cracks for $\theta_0 \ll 1$. The coefficient $\beta \approx 180$ depends to some degree on the pore geometry. Because all of the porosity need not contribute to k_0 , the porosity determined above should give a lower limit to d ; it is $d \approx 0.63 \text{ m}$.

The time required to establish steady flow between the fractures varies because of the pressure dependence of k and β . However, it will be of the order

$$\tau_\ell = \frac{\ell^2 \mu \beta_0}{k_0} , \quad (5-83)$$

which for $\ell = 30 \text{ m}$ is $\tau_\ell = 3.5 \text{ h}$. This condition occurs in several experiments near the calculated time and permits the determination of the steady-state specific impedance $P/\dot{Q}$ of Eq. (5-79).

A constant-flow condition at constant pressure can be established for the flow from the fractures into the infinite medium. This can be established in a finite time even though the pore pressure in the far field may be changing with time. The time required to establish this steady state depends on β and all three components of k . An estimate can be obtained from the case of a circular fracture of area A in a homogeneous medium.³⁹

$$\tau_\infty = \frac{A \mu \beta_0}{\pi k_0} . \quad (5-84)$$

For the canonical values of the parameters $\tau_{\infty} \approx 25$ h. This condition has also been observed in some experiments near 25 h of pumping time.

5.5.1.4. Discussion. The analysis of these data is consistent with a simple model of the pre-redrilled fracture system – that is, two roughly planar, parallel, and overlapping fractures, each connected by a low-impedance path to one of two wellbores. The use of the dimensions of the fracture system implied by microseismic studies results in permeabilities and pore spacings that are large compared to those of the microstructure. This implies that the permeation in the formation occurs in large, widely spaced and, perhaps, natural fractures (see Sec. 5.4.). The permeability near GT-2 has also been measured by pressurization of short sections of the wellbore.⁴⁰ The values obtained, shown to the left in Fig. 5-95, range downward from the large values obtained from the analysis to much smaller ones close to that of the microstructure at similar confining pressures.

The model for porosity, based on very general principles, provides fits to the data thus far. Further development of this model will be required to determine the significance of the constants involved and to justify independently the assumptions. Measurements of S_3 at depth indicate that S_3 is 8.0 MPa (1160 psi) above hydrostatic or $C_3^{-1} \cdot S \approx 2.1$ MPa (3000 psi). Even with C_2 assumed to be a constant, S_2 cannot be determined. The in situ value of the ratio k/H is not known, and the other stresses can contribute to some extent.

Extensive calculation of long-term flows are in progress and will be compared to field data collected in FY78 during operation of the loop. These calculations examine the transition to multidimensional flow and to steady-state conditions. Early indications are that, with the inclusion of anisotropic permeability, the assumed fracture geometry and porosity model will be consistent with the recent experimental data for the redrilled EE-1/GT-2 system.

5.5.2. Wellbore-to-Fracture-Impedance Modeling

Cases exist where the geometry of the borehole intersection with a hydraulic fracture is restricted so that fluid flow through a fracture near its connection to the borehole (via such a confined geometry) results in high flow velocities, accompanied by very large pressure losses. Examples of such geometries include the intersection of a vertical borehole with a horizontal fracture; the initiation of a vertical fracture from a vertical borehole through a casing perforation of small diameter (as was the case with the GT-2 wellbore before redrilling); and communication of a vertical borehole and a vertical

fracture via a slanting hydraulically activated fracture of small extent and aperture, as is the present situation with the redrilled path GT-2B (see Sec. 5.4.).

In these highly restricted geometries, the flow is distinctly non-Darcian.⁴¹ Some investigators have occasionally termed the flow "turbulent," but only because the pressure drop in these flows eventually tends to vary with the square of the velocity rather than linearly with velocity, as in Darcy-type flow. However, this square of velocity dependence can occur even when the flow is truly laminar.

A reasonable idealization for flow regimes of this type is to assume that flow in the fracture approaches the confined exit radially and axisymmetrically, as shown in Fig. 5-96. Analytical calculations of laminar flow between smooth-wall fractures with these ideal geometric constraints have been completed and confirmative experimental work is in progress. The experimental work is intended to guide the extension of these calculations to consider rough-wall fractures with truly turbulent flow.

Analysis of this flow requires the consideration of viscous and dynamic acceleration effects. The appropriate equations are the equation of flow continuity (mass conservation) and the boundary-layer momentum equation

$$\frac{1}{r} \frac{\partial(ru)}{\partial r} + \frac{\partial w}{\partial z} = 0 \quad (5-85)$$

$$u \frac{\partial u}{\partial r} + w \frac{\partial u}{\partial z} = -\frac{1}{\rho} \frac{\partial P}{\partial r} + \nu \frac{\partial^2 u}{\partial z^2} \quad (5-86)$$

Velocities u and w are in the radial, r , and axial, z , directions, respectively (Fig. 5-96); P is pressure and ρ and ν are the fluid density and kinematic viscosity, respectively. The terms on the left-hand side of Eq. (5-86) represent fluid accelerations; the terms on the right side are the pressure gradient and the viscous or frictional terms, respectively. A dimensional analysis revealed that there is a dimensionless radius,

$$r_D = \frac{r/t^*}{\sqrt{\frac{Q}{4\pi\nu t^*}}} \quad (5-87)$$

that characterizes the importance of the various terms in Eq. (5-86). The fracture half-width is denoted as t^* and the total volumetric flow rate is $\dot{Q}$. The dimensionless grouping $Q/4\pi vt^*$ is an overall Reynolds number. When r_D is much greater than 1, the acceleration terms are negligible, the pressure drop is controlled by viscous friction, and the flow is Darcy-like. When r_D is much less than 1, the acceleration terms dominate and a Bernoulli equation governs the pressure,

$$P + \rho u^2/2 = \text{constant.} \quad (5-88)$$

At intermediate values of r_D , between 0.1 and 10 [for a 5-MW (thermal) extraction experiment, this corresponds to actual radii of 0.1 - 10 m (0.3 - 30 ft)] complete solutions to Eqs. (5-85) and (5-86) are required. This was accomplished numerically,⁴¹ and results for the dimensionless pressure drop r_D are shown in Fig. 5-97 for various initial or inlet values of the dimensionless radius r_i . The dimensionless pressure drop is normalized by the characteristic value of the pressure drop when only viscous effects are operative.

For $r_D < 1$ acceleration effects cause substantial pressure drop increases. This type of accelerating flow is also being modeled experimentally. Figures 5-98 and -99 show the flow system and the apparatus. The valves on the table top shown in Fig. 5-99 permit independent measurement at all the pressure taps with the pressure tubes shown. In this experiment the use of air, rather than water, as the modeling fluid greatly simplified the piping and pumping problems. Because of kinematic similitude, the numerical analysis represents the phenomenon equally well for either air or water. Figure 5-100 shows a typical radial pressure-drop distribution. The agreement between the numerically calculated and experimental results is sufficiently good to verify that the model for the base-line case of laminar flow between smooth walls is correct.

The next task is to explore the effects of turbulence, that is, when the viscosity of the fluid is controlled by random, eddy-like mixing of the fluid rather than its molecular, laminar value. As unlikely as it may seem, flow acceleration tends to stabilize a laminar flow and thus prevent the transition to turbulent flow even at very high Reynolds numbers. In some cases acceleration will actually relaminarize an initially turbulent flow. For fully developed flow in pipes, the critical Reynolds number for transition is about 2000, but in our experiment we found that the flow was laminar even for Reynolds numbers as

Fig. 5-96.
Idealized geometry for flow in a fracture near its outlet.

Fig. 5-97.
Dimensionless pressure variation.

Fig. 5-98.
System apparatus (side view).

Fig. 5-99.
Experimental apparatus to simulate flow in a fracture near its outlet.

Fig. 5-100.
Comparison of theoretical and experimental pressure variation with radius.

high as 77 000. Moretti and Kays⁴² found that an accelerated flow, if initially turbulent, would tend to become laminar again if the acceleration parameter $K = \frac{-v}{u^2} \frac{du}{dr}$ exceeded 3×10^{-6} . In the experimental work described here K was about 10^{-5} , so it is not surprising that the flow was laminar. To obtain turbulent flows we are modifying the experimental apparatus to yield values of K less than 10^{-6} .

5.5.3. Heat-Extraction/Fluid-Flow Models

The development of a numerical model for calculating the fluid and heat transport in a three-dimensional hot dry rock geothermal reservoir was described previously.^{2,43} During FY77 the model was used to determine ideal fracture widths and flow capacities from measured flow impedances, and subsequently, to predict the rate of heat extraction from the present EE-1/GT-2 system.

During Experiments 172 A and C we found that of a total circulatory impedance of 11 bar-s/liter (10 psi/gpm) about 8 bar-s/liter (7 psi/gpm) is associated with local impedances, perhaps communicating fractures close to GT-2B. Thus, the impedance of the main hydraulic fracture is about 3 bar-s/liter (3 psi/gpm) (see Sec. 5.4.).

The numerical model was run for several assumed fracture widths until the calculated impedances matched the hydraulic fracture value. We found that the fracture width must be of the order of 0.2 mm (8 mils), which in fact, is the value to be expected from self-propping mechanisms based upon laboratory measurements of fracture roughness on core specimens. With this width (w) the fracture permeability for Darcy-type flow would be $w^2/12$ or 4×10^3 d, and the fracture transmissivity (flow capacity) would be 1 d-m (3 d-ft), about 50% greater than a fracture propped with 4.15 kg/m^2 (0.85 lb/ft^2) of 10- to 20-mesh sand at the same closure stress.

Using this fracture width, but still assuming that the fracture was penny-shaped with no thermal-stress cracking allowed, and that the maximum circulation flow was controlled by an overall impedance of 11 bar-s/liter (10 psi/gpm), we then used the model to predict the rate of heat extraction with time. The following conditions, consistent with the present EE-1/GT-2 system, were specified.

Fracture radius	= 140 m (450 ft)
Inlet position	at center
EE-1 inlet pressure	= 90 bars (1300 psi)
GT-2 outlet pressure	= 14 bars (210 psi)

Reinjection temperature	= 40°C
Maximum impedance	= 11 bar-s/liter (10 psi/gpm)
Flow rate	= 6.4 kg/s (110 gpm)

The results of these calculations are shown in Fig. 5-101. The maximum thermal power, occurring at zero operating time, will be diminished somewhat because, at early times, a significant fraction of the up-flowing heat is lost by conduction from the water to the rock surrounding the outlet wellbore (see Sec. 5.5.4.). The dashed line schematically indicates the expected effects of thermal stress cracking on the cooled rock. Estimates of the time required to develop thermal stress augmentation of heat transfer are provided in Sec. 5.5.5.

The effects of total system impedance on the maximum thermal power and the power required for pumping are shown in Fig. 5-102. The power required for pumping represents the thermal power required as input to a heat engine that converts thermal energy to pumping power at a net conversion efficiency of 10% (Ref. 44). This could be accomplished, for example, with conversion of geothermal power to electrical power at a conversion efficiency of 15%, which in turn drives a geothermal fluid circulation pump at a hydraulic efficiency of 75%. The parasitic pumping power load could be reduced somewhat if direct geothermal turbine-driven pumps were used. The calculation of pumping power includes wellbore friction losses as well as the beneficial effects of buoyancy caused by the density differences between the cold and hot water columns. In these calculations

Fig. 5-101.
Thermal power output for an idealized 140-m-radius fracture.

Fig. 5-102.
Maximum thermal and pumping power (no drawdown) as a function of fracture impedance.

we presumed that the inlet pressure would always be held just below the fracture extension pressure (~ 90 bars) so that the effect of increasing impedance is to decrease the circulating flow rate and, thus, the thermal and pumping power accordingly. For these cases where the impedance exceeds the effects of buoyancy, the power required for pumping is about one-eighth of the maximum thermal power so that the reservoir can be drawn down by a factor of 8 before the power required for pumping exceeds that provided by the reservoir. Calculations, without thermal-stress cracking, indicate that this will not occur for 15 - 20 yr.

If the system impedance could be reduced from 11 to 3 bar-s/liter (10 to 3 psi/gpm) by eliminating the local GT-2B impedance, as discussed earlier, the maximum thermal power could be increased by a factor of 3 with a corresponding increase in pumping power.

5.5.4. Wellbore Heat Transmission

5.5.4.1. Outlet Temperature Rise. Figure 5-103 shows that prediction of the rise in outlet water temperature for the GT-2 well at several constant outlet flow rates. We assumed that hot water was continuously provided to the bottom of GT-2 at 185°C ; that is, no reservoir drawdown was provided for. The initial surface temperature was taken to be 20°C . The discrete points were calculated with the finite-element wellbore heat transmission computer program.² The solid curves were obtained from Ramey's⁴⁵ analysis and are approximate because it was assumed that the indigenous earth temperature gradient was constant and that the formation heat transfer varied logarithmically with time. Note that the final temperature 185°C ($165^{\circ}\Delta T$ plus 20°C) is approached asymptotically and that at a flow rate of $6.3 \times 10^{-3} \text{ m}^3/\text{s}$ it will take 100 days for the temperature to exceed 155°C . As shown in Sec. 5.5.3., for a 140-m-radius ideal reservoir with no thermal-stress cracking enhancement and a constant 10 bar-s/liter (10 psi/gpm) impedance, drawdown calculations indicate that the reservoir outlet temperature will decline to 150°C , so it is possible that the maximum temperature obtained from GT-2 at a flow rate of $6.3 \times 10^{-3} \text{ m}^3/\text{s}$ (100 gpm) will never exceed 150°C . If the impedance were lowered to 3 bar-s/liter (3 psi/gpm) the situation is quite different. The flow rate would then be $1.9 \times 10^{-2} \text{ m}^3/\text{s}$ (300 gpm), and an outlet temperature of 175°C would be reached after 20 days.

5.5.4.1. Flow Tracing. As shown in Sec. 5.1.6., shut-in temperature surveys of EE-1 have indicated the presence of major temperature depressions above the casing bottom at 2920 m (9590 ft). Based on this information and radioiodine tracer logs (Sec. 5.1.5.) we concluded that a considerable fraction of the water pumped into EE-1 must be flowing upward behind the casing via the

deteriorated cement in the annulus between the casing and the rock formation. To determine the magnitude of this effect, we used a heat transfer analysis, based on counterflow heat exchanger concepts, to analyze EE-1 surveys taken during flow conditions.

The results of these surveys are shown in Fig. 5-104. Survey A is the background log and shows all the temperature anomalies discussed in Sec. 5.1.6. Surveys B and C were taken after the start of pumping into EE-1. Once again the convection-induced dispersion of the anomalies is apparent. The dramatic temperature rise that starts at 2920 m (9590 ft), very close to the casing bottom, demonstrates that the injected flow, and its cooling effect goes no deeper than the casing. Instead the flow either goes into the rock formation at this point or else flows up behind the casing for several hundred meters before entering the formation. As the following heat-transfer analysis indicates, the latter situation is much more likely.

The heat conservation equations for the flow inside and outside the casing are, respectively,

$$\dot{m}_i c \, dT_i/dz = 2\pi rh(T_o - T_i) \quad (5-89)$$

$$\dot{m}_o c \, dT_o/dz = 2\pi rh(T_o - T_i) - q, \quad (5-90)$$

Fig. 5-103.
Outlet temperature rise for several outflow rates.

Fig. 5-104.
Temperature surveys in EE-1 taken while flowing water.

where

$\dot{m}$ = mass flow rate

c = specific heat capacity

T = temperature

z = depth

r = casing radius

h = overall heat-transfer coefficient

q = heat conduction from the formation per unit time and depth

i, o = subscripts indicating inside and outside the casing.

Manipulation of Eqs. (5-89) and (5-90) to eliminate T_o yields:

$$(\dot{m}_i - \dot{m}_o)c \frac{dT_i}{dz} = q + \frac{\dot{m}_o \dot{m}_i c^2}{2\pi r h} \frac{d^2 T_i}{dz^2} \quad (5-91)$$

If we assume for a moment that there is no flow behind the casing, that is, $\dot{m}_o = 0$, then Eq. (5-91) simplifies to

$$\dot{m}_i c \frac{dT_i}{dz} = q \quad (5-92)$$

Thus if $\dot{m}_o$ is zero and q is a finite positive quantity, then the temperature should continuously increase with depth. When the temperature of the wellbore during flow is less than the background temperature at the same depth, heat will flow from the formation, that is, q is positive. This occurs at depths greater than 2820 m (9250 ft), so we expect $dT_i/dz > 0$ below 2820 m, if $\dot{m}_o = 0$. Instead, near the casing bottom, 2920 m, the B and C surveys become flat, and, in fact, the gradient there is zero. This is precisely the situation predicted by Eq. (5-89) because, if the flow does turn around and flow up the annulus at the casing bottom, T_i must equal T_o at this point.

Although we have established that water does not flow below the casing but flows up behind the casing, we have yet to show that all the water flows up the annulus, that none of it locally penetrates the rock formation at 2920 m. If this is true, $\dot{m}_i = \dot{m}_o$ and Eq. (5-91) becomes

$$\frac{\dot{m}_o^2 c^2}{2\pi r h} \frac{d^2 T_i}{dz^2} = -q \quad (5-93)$$

Because the degree of cooling is roughly the same during survey C, we expect that q , and consequently d^2T_i/dz^2 will also be roughly constant and negative. In other words, the temperature distribution will be parabolic, its slope continuously decreasing so that at the casing bottom it is zero. Survey C from 2750 m (9030 ft) to the casing bottom does indeed show this parabolic temperature distribution. Hence, we conclude that most of the water does flow up behind the casing to a depth of 2750 m or less, where it then begins to enter the formation. This behavior has been verified by radioiodine tracer experiments, as discussed in Sec. 5.1.5.

5.5.5. Thermal-Stress Cracking Estimates

The effects of thermal-stress cracking upon heat extraction were first considered by Harlow and Pracht.⁴⁶ Their treatment was a numerical one, lacking the detail required to resolve individual crack geometries (widths, depths, and spacing). Thus, they considered cracking to result in additional porosity, which they distributed homogeneously. This additional porosity (θ) was calculated by an integration of the volumetric coefficient of thermal expansion of the rock over the temperature decrease incurred by cooling the rock. The new permeability (k) of the thermal-stress crack-altered rock was calculated from the Kozeny-Carmen formula for flow in porous media.⁴⁷

$$k = \frac{4D_c^2}{5} \left[\frac{\theta^3}{(1 - \theta)^2} \right] . \quad (5-94)$$

Thus, in addition to its dependence on θ , the permeability of thermally fractured rock is a very sensitive - even critical - function of D_c , the average distance between cracks. Harlow and Pracht were not able to calculate D_c a priori, but instead simply assumed various values, and in so doing found that if D_c was 0.01 m or less, the power enhancement from thermal-stress cracking became negligible. Thus, the viability of thermal crack enhancement was strongly controlled by an unknown value of D_c .

To remedy this situation we performed a simplified analysis to estimate the geometric aspects of thermal-stress cracking. Where required, simplifying assumptions were made to make the problem tractable. Therefore, some of the results are only qualitatively correct, but even so they indicate that thermal-stress augmentation of heat extraction has a high probability of occurring.

The plane strain solution for the thermal stress induced in a homogeneous, linearly elastic rock contiguous to a large hydraulic fracture is

$$\sigma = E\alpha\Delta T/(1 - \nu) \quad , \quad (5-95)$$

where

σ = tensile stress, Pa

E = elastic modulus, Pa

α = linear thermal expansion coefficient = $\frac{1}{L} \left(\frac{\partial L}{\partial T} \right)$, $^{\circ}\text{C}^{-1}$

ΔT = the cooling of the rock, $^{\circ}\text{C}$

ν = Poisson's ratio.

By assuming that the stress concentration at the base or tip of a propagating crack is very large or that the tensile strength of the rock is negligible, cracking will occur when the induced tension equals the horizontal compressive earth stress, S_2 , parallel to the fracture plane. From Fenton Hill flow experiments it has been estimated that S_2 is 386 bars (5600 psi). Estimates⁴⁸ of E , α , and ν for granite are, respectively, 5×10^5 bars (7×10^6 psi), 8×10^{-6} per $^{\circ}\text{C}$, and 0.22. Thus, according to Eq. (5-95), cracking is expected when the rock is cooled by about 75°C . When the surface (next to the main hydraulic fracture) of the rock is cooled more than 75°C , the crack penetrates (stays open) to the point where the rock temperature is 75°C lower than its original temperature.

An estimate of the rock cooling is

$$\Delta T = \Delta T_s \operatorname{erfc} \left(\frac{z}{\sqrt{4\kappa t}} \right) \quad , \quad (5-96)$$

where

ΔT = the rock cooling at any point, $^{\circ}\text{C}$

ΔT_s = the rock cooling at the surface ($z = 0$), $^{\circ}\text{C}$

z = distance into the rock, measured from the main hydraulic fracture surface, m

κ = thermal diffusivity of the rock, m^2/s

t = time, s

erfc = complementary error function.

At the critical degree of cooling, $\Delta T_c = 75^\circ\text{C}$, the crack penetration distance z_c becomes

$$z_c = \sqrt{4\kappa t} \operatorname{erfc}^{-1} (\Delta T_c / \Delta T_s) . \quad (5-97)$$

Maximum crack penetration occurs at the maximum ΔT_s , which is estimated to be 135°C for a heat-extraction experiment at Fenton Hill. No cracking occurs when:

$$\Delta T_s \leq \Delta T_c = 75^\circ\text{C} . \quad (5-98)$$

Figure 5-105 shows thermal-stress crack penetrations for various values of ΔT_s and time. A value of $1.0 \times 10^{-6} \text{ m}^2/\text{s}$ was used for κ . Note that for the first half year of operation, most cracks penetrate no more than 2 or 3 m.

Having estimated the penetration of these cracks, we must next estimate their spacing. This is a typical end-effects problem for which, as a first approximation, crack spacings and penetrations are roughly equal. This claim is supported by calculations⁴⁹ and observations of thermal-stress cracking experiments performed on concrete slabs. Note that this suggests that at an early time, the cracks in a reservoir will be closely spaced and of very shallow penetration, but as time goes by, fewer but deeper-penetrating cracks will form. This process relieves the stress field around the shallow cracks. The process is shown in Fig. 5-106.

If the width of the small stress-relieved cracks is ignored, then the maximum width of the largest cracks at any time is:

$$\delta_{\max} = \alpha \Delta T_s z_c . \quad (5-99)$$

Furthermore, if the width of these cracks as a function of z is approximated as

$$\delta = \delta_{\max} (1 - z/z_c)^2 , \quad (5-100)$$

which ensures smooth closure of the crack; then the mean width δ is

$$\bar{\delta} = \frac{1}{z_c} \int_0^{z_c} \delta dz = \delta_{\max}/3 \quad (5-101)$$

and if Eqs. (5-97) and (5-99) are substituted in Eq. (5-101), the result is

$$\bar{\delta} = \frac{2}{3} \alpha \Delta T_s \sqrt{kt} \operatorname{erfc}^{-1} (\Delta T_c / \Delta T_s) \quad (5-102)$$

Representative values of $\bar{\delta}$ are plotted in Fig. 5-107. During the first half year of operation, most cracks are less than a millimeter in thickness.

The distinction between whether the fracture is propped open (either natural, self-propping, or artificially propped) or held open in an inflated state by pressurization is important in the continued study of thermal cracking.

5.5.5.1. Fractures Held Open by Pressurization. When the fracture is held open by pressurization, the width w of the main fracture is also growing because of thermal contraction, as given by

$$w = w_0 + 2\alpha \int_0^{\infty} \Delta T dz \quad (5-103)$$

Substituting Eq. (5-97) and integrating gives the result

$$w = w_0 + 4\alpha \Delta T_s \sqrt{kt/\pi} \quad (5-104)$$

The value w_0 is the initial value of the fracture width, obtained from the theory of elasticity. For simplicity we assume that $w_0 = 0$; then the ratio of Eqs. (5-102) and (5-104) becomes,

$$\frac{\bar{\delta}}{w} = \frac{\sqrt{\pi}}{6} \operatorname{erfc}^{-1} (\Delta T_c / \Delta T_s) \quad (5-105)$$

The maximum value of ΔT_s for the present EE-1/GT-2B system is expected to be 135°C, and ΔT_c was previously determined to be 75°C, thus

Fig. 5-105.
Thermal-stress crack penetration depths.

Fig. 5-106.
Thermal-stress crack growth.

Fig. 5-107.
Average widths of thermal-stress cracks.

$$\frac{\bar{\delta}}{w} \leq 0.12 . \quad (5-106)$$

When viscous effects dominate the flow, the flow-rate capacity (flow rate per unit length of crack) of any crack is proportional to the cube of crack width. Thus, the ratio of the flow rate in the thermal-stress crack to that in the main fracture will be $(\bar{\delta}/w)^3 \leq 0.0017$.

When viscous forces dominate the fluid dynamics in a pressurized reservoir, the flow rate, and thus the augmented heat transfer to be expected from thermal-stress cracking, is insignificant. Fortunately, this situation changes considerably when the effects of buoyancy are considered. McFarland and Murphy⁴³ have shown that the buoyancy term becomes greater, in magnitude, than the viscous term in the linear momentum equation when the ratio of Grashof and Reynolds numbers is one or greater, or

$$\frac{\bar{\delta}^3 R g \beta \Delta T_s}{\nu \dot{Q}} \geq 1 , \quad (5-107)$$

where

R = the characteristic radius of the fracture, m

g = gravitational acceleration, m/s^2

β = volumetric thermal expansion coefficient of water, $\frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_p$, $^{\circ}C^{-1}$

ν = kinematic viscosity of water, m^2/s

$\dot{Q}$ = volumetric flow rate, m^3/s .

Ordinarily R is taken as the fracture radius, but when the inlet and outlet are close together (the situation at Fenton Hill) R is taken as the distance between the inlet and outlet, about 100 m. The flow rate for a nominal 5-MW (t) system is about $0.006 m^3/s$ (110 gpm), and β and ν for water are about $2 \times 10^{-4} ^{\circ}C^{-1}$ and $1.8 \times 10^{-7} m^2/s$, respectively. A critical value of $\bar{\delta}$ results by solving Eq. (5-107).

$$\bar{\delta}_c \geq 0.4 \text{ mm} . \quad (5-108)$$

Thus when $\bar{\delta} \geq 0.4$ mm, buoyancy becomes important, allowing a significant fraction of the total flow to enter the thermal-stress cracks.

Figure 5-107 shows that this "critical" width is attained after 25 days of operation for the very small region near the inlet, where ΔT_s is maximum. Unfortunately, the area near the inlet is too small for very many critical-size cracks to develop, and significant augmentation will occur only far from the inlet, where ΔT_s will be less than the maximum. Waiting times for significant thermal-stress cracking effects in a pressurized fracture may therefore be several months to a year (Fig. 5-107). These times are considerably different for a self-propped fracture, as will be shown later.

An interesting observation is that, once thermal-stress cracks start to reach the critical size, their growth rate might be increased by improving the ratio of the thermal crack flow rate and capacity resulting from the inequality of Eq. (5-106). If a low-permeability (conductivity) proppant could be introduced into the main fracture only, the resistance to flow in the main fracture could be greatly increased, forcing more of the flow into the thermal-stress cracks.

5.5.5.2. Self-Propped Fractures. We estimated in Sec. 5.5.3. that the average width of the self-propped fracture between EE-1 and GT-2B was 0.2 mm (8 mils). The flow rate in the thermal cracks would thus be of the same order of magnitude as the flow rate in the main fracture when

$$\bar{\delta}_c = 0.2 \text{ mm} \quad . \quad (5-109)$$

In this case the waiting time for significant thermal crack effects would be 2 wk to 2 months.

5.5.5.3. Estimates of D_c . When significant amounts of water finally do start to flow into the first set of thermal-stress cracks, the conductive heat transfer will become two dimensional, resulting in greater values of z_c and $\bar{\delta}$ and the eventual forming of new orthogonal thermal-stress cracks, now parallel to the original hydraulic fracture. These, in turn, will eventually lead to a third set of fractures, followed by other sets, so that the system is "autocatalytic" in time. Only those cracks with $\delta > \delta_c$ transmit water and thus propagate and form new cracks; therefore, these are the cracks that control the effective permeability of the rock. Substituting Eq. (5-101) in Eq. (5-99) results in

$$D_c = 3\bar{\delta}_c / \alpha \Delta T_s$$

(5-110)

as an estimate of the minimum crack spacing for permeability estimates. Values of D_c , given in Table 5-XV, are of the order of 1 m (3 ft), or 2 orders of magnitude greater than the value that Harlow and Pracht⁴⁶ found necessary for significant thermal-stress augmentation of heat extraction. Substitution of $D_c = 1$ m and $\theta = 0.0001$ in the Kozeny-Carmen formula [Eq. (5-94)] shows that the thermally fractured rock will have an effective permeability of the order of 1 d (10^{-12} m²) or greater, which is an extremely large permeability (typically oil and gas reservoirs have values hundreds to thousands times lower). We therefore expect that thermally fractured reservoirs will have low flow impedance.

TABLE 5-XV
ESTIMATES OF MINIMUM CRACK SPACING

ΔT_s (°C)	Self-Propped Fractures ^a (m)	Pressurized Fractures ^b (m)
95	0.8	1.6
115	0.7	1.3
135	0.6	1.1

^a $\bar{\delta}_c \approx 0.2$ mm.

^b $\bar{\delta}_c \approx 0.4$ mm.

5.6. Economics of HDR Systems (R. L. Bivins, R. G. Cummings, G. E. Morris, J. W. Tester)

5.6.1. Critical Issues for HDR Commercialization

Hot dry rock systems share similar requirements with hydrothermal systems for the attainment of commercial feasibility. Installed electrical generating costs will depend on geothermal well, fluid pumping, and piping costs associated with reservoir development as well as equipment costs associated with the surface conversion plant. Costs associated with well drilling and completion, stimulation, and the circulation of fluid, will be controlled by certain characteristics of the reservoir, namely its

- (1) fluid-flow capacity or productivity, $\dot{m}_w$ (kg/s)
- (2) depth from surface, Z (km)
- (3) pressure losses associated with fluid circulation
- (4) lifetime [energy drawdown, $dP(t)/dt \leq 0$]
- (5) fluid composition.

All of the above have inherent uncertainties because the detailed character of the reservoir is largely unknown. In addition, drilling and stimulation costs for any geothermal (or oil or gas) reservoir are highly variable and subject to many unforeseeable contingencies. Consequently, reservoir cost estimation is difficult and frequently subject to considerable error, which leads to inevitable high-risk factors for investment capital. Surface equipment costs, although easier to estimate, will be controlled by the conversion efficiency and may be strongly dependent on fluid composition; therefore, these costs are also somewhat uncertain, for example, as to whether serious scaling or corrosion problems will exist.

The second law of thermodynamics imposes real limitations to the production of electricity from a low-temperature geothermal heat source. Because the temperature of a hot dry rock geofluid declines as one extracts useful work, the ideal Carnot efficiency decreases from a maximum value at the wellhead condition (T_{gf} , P_{gf}) to zero at the ambient dead state (T_o , P_o). The maximum work can then be expressed by the availability ΔB , which is given by

$$W_{\max} = \Delta B = \Delta H - T_o \Delta S \left[\begin{matrix} T_{gf}, P_{gf} \\ T_o, P_o \end{matrix} \right], \quad (5-111)$$

where

ΔH = enthalpy difference between State (T_{gf}, P_{gf}) and State (T_o, P_o)

ΔS = entropy difference between State (T_{gf}, P_{gf}) and State (T_o, P_o) .

Comparisons of this type are usually achieved by defining a cycle efficiency (η_{cycle}), which represents the net useful work obtained from the system divided by the amount of heat transferred from the geothermal reservoir. As the cycle efficiency decreases, the amount of heat rejected to the environment increases. For an ultimate sink of 25°C with a geothermal heat source at 50°C, cycle efficiencies would be less than 5%. As the temperature increases to 100°C the efficiency would be ~8%, at 150°C ~12.5%, and at 200°C ~17.5%.

An alternative approach to cycle efficiency would be to compare directly the real work to the maximum possible work ΔB by defining a utilization efficiency $\eta_u = W_{net}/\Delta B$, which will then be a measure of the effectiveness of the utilization of the geothermal resource. Ideally, we would like to keep η_u as high as practical, but there are limitations in the efficiency of work-producing machinery (turbines and pumps) as well as in the heat-transfer components of a power-generating cycle.

Because the maximum availability of the geofluid (ΔB) increases as the resource temperature (T_{gf}) increases and as the sink or heat-rejection temperature (T_o) decreases, high T_{gf} 's and low T_o 's should be maintained. Because of the relatively low geothermal gradients (20 - 40°C/km) that prevail in the eastern US, there are some economic limitations to maintaining a high T_{gf} . For instance, because geothermal drilling costs increase exponentially with increasing depth, the difference between drilling costs for a 200°C reservoir with an average formation gradient ∇T of 40°C/km vs 20°C/km will be substantial. At the other extreme, many areas have favorable conditions for heat rejection, particularly where large quantities of water exist. In other locations, such as the southwestern US, water is scarce and dry cooling towers or direct air-cooled condensers will be required. There are further limitations to these minimum and maximum temperatures. For example, any heat-transfer step will require reasonable temperature differences to keep the equipment sizes practical. Temperature differences are very important in the tradeoff between fluid utilization and the economics associated with producing power (see Sec. 5.6.2.).

As discussed in Ref. 2, a tradeoff exists between equipment and drilling costs in establishing an optimum drilling depth for minimum busbar generation costs. The optimum will depend on fluid flow rate requirements, geothermal

temperature gradient, and fluid temperature. In many cases, particularly for low-gradient areas, geothermal fluid production costs may exceed 70% of the total capital investment; consequently, the utilization efficiency η_u of the plant may approach the thermodynamic maximum for optimum economic design. These effects are discussed in detail in Ref. 44.

Another important factor in establishing an optimal reservoir development and management strategy is the anticipated heat-extraction performance of the HDR reservoir. Clearly, at this early stage of development, only preliminary estimates can be made. The predicted lifetime with, and the rate at which energy can be extracted from, a single fracture depend on several major factors,^{2,43,46}

- (1) thermal conductivity of the rock, λ_r
- (2) accessible surface area of the fracture, A
- (3) rate and distribution of fluid flowing across the fracture surface.

A simplified approach to estimating reservoir performance would assume that a certain fraction η of the recoverable power, corresponding to uniform flow across the face of the fracture, could be extracted. By following a procedure suggested by McFarland and Murphy⁴³ and analogous to the approach of Gringarten et al.⁵⁰ for multiple parallel fractures, the recoverable power, $P(t)$ in joules per second, for uniform flow can be expressed as:

$$P(t) = \eta \dot{m}_w C_w (T_i - T_{\min}) \operatorname{erf} \left(\sqrt{\frac{(\lambda \rho C)_r}{t} \frac{\pi R^2}{\dot{m}_w C_w}} \right), \quad (5-112)$$

where

- $A = \pi R^2$ = area of one face of the fracture, m^2
- C_w = heat capacity of water = 4200 J/kg-K
- C_r = heat capacity of granite = 1000 J/kg-K
- $\dot{m}_w$ = water flow rate through the fracture, kg/s
- R = fracture radius, m
- t = time, s
- T_i = mean initial rock temperature, °C
- $T_{\min}$ = fluid reinjection temperature, 60°C
- λ_r = thermal conductivity of granite, ~3.0 W/m-K
- ρ_r = rock density, kg/m^3 .

McFarland and Murphy⁴³ compare $p(t)$ to estimated values that account for non-uniform flow across the accessible fracture area. Fluid buoyancy and convection effects within an ideal fracture as well as transient conduction of heat through the surrounding rock are treated in a numerical solution of the four coupled, two-dimensional, nonlinear, partial differential equations describing continuity, fluid momentum, and rock and fluid energy balances. Depending on the location and separation of fluid injection and recovery points within the fracture and the internal fracture permeability (gap width vs radius), the recovered fraction of power η may vary from about 0.4 to 0.9. When these conditions are fixed, Eq. (5-112) shows that $P(t)$ depends directly on the error function of

$$\left[K \frac{R^2}{\dot{m}_w \sqrt{t}} \right] \quad (5-113)$$

for constant rock and fluid properties, where

$$K = \pi \sqrt{\frac{(\lambda \rho C)_r}{C_w^2}} \quad (5-114)$$

Consequently, reasonably accurate predictions of reservoir lifetime can be made for specified ideal fracture sizes and flow rates. Figure 5-108 presents parametric results for the power ratio $P(t)/P(t=0)$ vs time t , using different values of $\dot{m}_w/R^2$ to generate a family of curves for a granitic HDR reservoir. The quantity $\dot{m}_w/R^2$ reflects the mass flow capacity of the system for a given accessible fracture area. In analogous fashion, Gringarten et al.⁵⁰ present elaborate power and temperature drawdown curves for multiple parallel fracture systems showing the effects of variable fracture number and spacing.

Neither the approach presented here nor the one presented by Gringarten et al.⁵⁰ include any beneficial effects caused by thermal-stress cracking. Harlow and Pracht,⁴⁶ using a simplified model, were able to demonstrate that substantial enhancement of reservoir performance could be anticipated. The mechanisms associated with thermal-stress cracking are extraordinarily complex and not well understood even under well-defined laboratory conditions. Consequently, the Fenton Hill field reservoir will be used to identify in situ thermal-stress effects. It is important to emphasize that economically acceptable rates of energy extraction (>50 kg/s per pair of wells) and reservoir lifetimes (>20 yr)

Fig. 5-108.

Parametric power drawdown curves for a single fracture with no thermal-stress cracking, $\eta = 0.9$.

may be achieved by either growing large fractures ($R \sim 1000$ m), using smaller multiple parallel fractures, or by remedial refracturing to generate new surface area.

To fully explore the ramifications of a finite rate of reservoir power drawdown, we are modifying our cost models to accept a time-dependent reservoir thermal power output for any specified HDR reservoir concept:

$$P(t) = P(t = 0) \left[f(\dot{m}_w/R^2, t) \right] , \quad (5-115)$$

where $f(\dot{m}_w/R^2, t)$ depends not only on transient heat conduction but also on the detailed history of the reservoir in the sense that thermal-stress cracking and refracturing (restimulation) might be used to alter the drawdown rate from that expected for a single fracture of radius R as given in Fig. 5-108.

5.6.2. Cost Models

A flow diagram depicting the major components of all the cost models discussed in this section is shown in Fig. 5-109. A factored estimate method was used for determining the total capital investment required for a completed geothermal power plant. Separate estimates are made for production and reinjection wells and for major pieces of equipment, including pumps, turbines,

Fig. 5-109.
Economic optimization model components.

generators, heat exchangers, and condensers. Direct and indirect cost factors are introduced for calculating total or installed costs from purchased costs, with separate empirical cost descriptions for each of the major components (for details, see Ref. 44).

5.6.2.1. Generalized Cost Model. For preliminary economic assessments, a simplified approach based on detailed analyses of several geothermal reservoir and electric power plant types has been developed. The total installed generating cost, including drilling and equipment-related costs, is expressed as a function of geothermal fluid temperature (T_{gf}), geothermal gradient (∇T), and reservoir capacity given by well flow rate ($\dot{m}_w$). The model assumes a two-hole circulating HDR system. Well costs are represented as an exponential function of depth.⁴⁴ Given the mean geothermal gradient, depth can be specified by T_{gf} . Equipment costs for a cost-optimized binary-fluid conversion cycle in dollars per kilowatt were expressed as a linearly decreasing function of T_{gf} from 100 to 300°C. This is due primarily to increased cycle efficiency as T_{gf}

increases, thereby decreasing heat-exchange requirements. If we assume that an appropriate working fluid can be found for this temperature range to provide a utilization efficiency (η_u) of at least 60%, required total flow rate per unit output power ($\dot{m}/P$, kg/s-kW) can be estimated from

$$\frac{\dot{m}}{P} = \frac{1}{\eta_u \Delta B} = \frac{1000}{\eta_u C_w} \left[T_{gf} - T_o - T_o \ln (T_{gf}/T_o) \right]^{-1}, \quad (5-116)$$

where

T_o = minimum heat-rejection temperature

ΔB = availability, J/kg-K or W-s/kg-K

and all temperatures are expressed in degrees K.

For a given T_o , η_u , ∇T , T_{gf} , and $\dot{m}_w$, total generating cost can be estimated by using the set of generalized equations if a uniform reservoir productivity is assumed for 20 yr under self-pumped (buoyant-circulation) conditions. As mentioned earlier, uniform productivity could be obtained by large fractures, multiple smaller fractures, thermal-stress cracking enhancement, and/or remedial refracturing. To express the total generating cost in cents per kilowatt-hour, we must make additional assumptions, which include an 85% (7446-h/yr) capacity or load factor, a 17% annual fixed-charge rate, and 0.13¢/kWh annual operating and maintenance cost. Furthermore, equipment costs are assumed not to decrease beyond 300°C because anticipated difficulties with scaling in the primary heat exchanger (caused by a higher concentration of dissolved silica and other elements) will offset the benefits of higher cycle efficiency.

Figure 5-110 shows the optimal or minimum cost as a function of geothermal temperature gradient for well-pair flow rates of 10 - 200 kg/s. These optima represent a tradeoff between well and equipment costs. At a fixed gradient, increasing temperature by drilling deeper increases cycle efficiency and ΔB in Eq. (5-114); therefore, $\dot{m}/P$ decreases and fewer wells are required. In addition, equipment costs would decrease up to 300°C. However, increasing temperature by drilling deeper also increases the cost per well. The optimum or minimum generating cost will then occur where there is a balance among fewer, more expensive wells and less expensive power conversion equipment.

As seen in Fig. 5-110 for gradients below 30°C/km and flow rates of 10 - 200 kg/s, total costs are controlled by well costs. At higher gradients and flow rates above 20 kg/s, equipment costs dominate. For gradients above 50°C/km,

Fig. 5-110.

Busbar cost minima as a function of average geothermal gradient for a series of well flow rates with $\eta = 0.60$ and $T_0 = 26.7^\circ\text{C}$ (1976 dollars).

costs below 4¢/kWh are achieved for well flow rates equal to or greater than 50 kg/s. With proper design of an HDR reservoir, well flow rates of 100 kg/s or greater should be possible. For these cases, generating costs would be 3¢/kWh or less for gradients of 40°C/km or more. If nonelectric uses are introduced, economic feasibility of HDR systems, even with gradients of 20 - 30°C/km, is possible for well flow rates less than 50 kg/s.

5.6.2.2. Multiparameter Optimization Model - HDRCOST. A combined thermodynamic and economic computer code has been developed that incorporates a previously developed Rankine cycle evaluation scheme for nonaqueous working fluids and a factored estimate approach to HDR economics.⁴⁴ The total installed cost of an HDR power plant is calculated for a fixed set of cost correlations and a specified set of input parameters:

- P = output power level, MW(t or e)
- $\dot{m}_w$ = flow rate per pair of wells
- $\overline{\nabla T}$ = mean geothermal temperature gradient
- T_{gf} = geofluid temperature at wellhead
- T_0 = heat-rejection temperature (air or water)
- T_c = condensing temperature

ΔT_o	= condenser pinch-point temperature difference
ΔT_{HE}^{out}	= heat-exchanger outlet temperature difference, $T_{gf} - T_{wf}$
ΔT_{HE}	= heat-exchanger pinch-point temperature difference
P	= maximum cycle (turbine inlet) pressure
η_t	= turbine dry-stage efficiency
η_p	= feed pump efficiency
$\bar{U}_{HE}$	= overall mean heat-transfer coefficient in the heat exchanger
$\bar{U}_c$	= overall mean heat-transfer coefficient in the condenser/desuperheater
d_w	= well spacing
N_ℓ	= load or capacity factor.

The effects that one, several, or all of the above parameters have on the total installed cost for wells and equipment (\$/kW) or on busbar generation cost (¢/kWh) can be investigated following an exhaustive grid procedure or an adaptive function evaluation algorithm. Multiparameter optimizations can easily be made for a specified set of input arguments. The sensitivity of installed cost to variations in component costs can easily be examined also. Preliminary results of the model are described in Ref. 44. Adaptations to permit cost estimation for process heat and combined electric/nonelectric applications are under way (see also Sec. 5.6.3.).

5.6.2.3. Intertemporal Reservoir Management Optimization Model (IRMOM). A dynamic programming approach developed by Cummings et al.⁵¹ is used for estimating the "net benefits" attributable to the sale of HDR-produced electricity over a specified planning horizon of n years. The benefits G , exclusive of transmission and distribution costs, can be expressed in present value functional form as

$$G = \sum_{t=1}^n \frac{1}{(1+r)^t} \left[R_t(T_t) - C_{OM} - C_w(d_t, D_t) - C_s(T_d, P_d) \right] ,$$

with

$$T_{t+1} = T_t(\bar{\nabla} T_d)_t \ f \left[R, \dot{m}_w, t \right] \quad (5-117)$$

$$D_{t+1} = D_t + d_t ,$$

where

- r = discount rate
- R_t = $8.8 \times 10^4 p_t N_\ell \xi P$ = revenues from sale of electricity in period t , \$
- $f[R, \dot{m}_w, t]$ = specifies the drawdown of reservoir temperature
- p_t = busbar price of electricity received in period t , ¢/kWh
- T_t = wellhead fluid temperature during period t
- N_ℓ = load or capacity factor during period t
- P_d = rated plant capacity at design condition, MW(e)
- R = fracture radius
- $\dot{m}_w$ = well-pair flow rate
- ξ = P/P_d = ratio of actual plant capacity at T_t to design capacity at T_d
- T_d = surface plant design temperature
- d_t = drilling depths achieved during period t
- D_t = depth of drilling at the beginning of period t ,

with operating and maintenance costs C_{OM} usually assumed constant during period t . Capital costs for the electric generating plant are proportional to P_d and would be expected to decrease with increasing T_d . In the preliminary cases examined, C_S was assumed to follow the empirical equation given by Milora and Tester.⁴⁴

$$C_S = (\$) = (888.110 - 1951 T_d) P_d \quad (5-118)$$

with

$$P_d \geq 50 \text{ MW(e)}$$

$$100 \leq T_d \leq 300^\circ\text{C}.$$

Total well cost C_w has four components:

- (1) costs of drilling and completing one pair of wells, denoted $c_w(D)$, which are an exponentially increasing function of depth (D) as given in Fig. 5-111.
- (2) the number of (pairs of) wells required (N), which is determined by the well flow rate $\dot{m}_w$, plant flow rate $\dot{M}_d$, and installed capacity

Figure 5-112 shows the required geothermal fluid flow rate per megawatt (electric) of capacity as a function of plant design temperature for a reference case of an R-32 (CH_2F_2) binary-fluid Rankine cycle with heat rejection to a sink at 26.7°C (80°F)

- (3) drill rig mobilization and demobilization costs C_m , which are an increasing function of depth
- (4) reservoir establishment costs, expressed as a factor, $(1 + s)$, where s reflects the percent by which well costs must be inflated to account for wellhead-to-plant piping, exploration costs, etc.

Thus, a generalized expression for total well costs is given by

$$C_w = [c_w(D)N + C_m(D)] (1 + s). \quad (5-119)$$

By combining Eqs. (5-117), (5-118), and (5-119), G can be expressed as a function of two variables, D_t and T_t , for a fixed discount rate r , selling price p_t , gradient $\bar{\nabla T}$, design temperature T_d , fracture size R , and power output design capacity P_d . The general objective of the optimization is to maximize the value of G subject to the constraints specified in Eq. (5-117) for D_t and T_t . Thus, the optimal strategy for drilling and redrilling along with management of well flow rates ($\dot{m}_w$) as they affect T_t will be determined for maximum benefits. An alternative way of viewing the optimization problem is to set G to a fixed value and select the busbar electricity price p_t parametrically until that condition is reached in Eq. (5-117). For example, the HDR operation becomes economically feasible when $G = 0$ with a capital recovery factor corresponding to a specified discount rate r ; p_t^* for that condition then corresponds to the minimum busbar price p^* necessary for a specified design temperature T_d and power output design capacity P_d . A dynamic programming (DP) algorithm is used to solve the optimization problem in the two "state" variables, D_t and T_t . Effects of other variables, such as T_d , $\bar{\nabla T}$, P_d , R , p_t , and r , have to be explored parametrically. The methodology used in the DP algorithm is outlined below.

Let a state of the system (reservoir and power plant), denoted by $S(D, T)$, be characterized by the two quantities, D well depth, and T temperature. The state of the system will vary over time as power generation occurs and may be influenced by altering the flow rate and/or drilling/redrilling activities. Given a state of the system at time t , the net benefits derived from such a

Fig. 5-111.

Estimated HDR total drilling and completion costs (1976 dollars) for a pair of 23.5-cm-diam wells in hard crystalline rock. Includes direct (1.17) and indirect (1.56) costs to account for wellhead-to-plant piping and land acquisition, surface exploration, and contingency.

Fig. 5-112.

Geothermal fluid flow rate as a function of design temperature for an R-32 Rankine cycle with heat rejection to a sink at 26.7°C.

system over a period of time Δt can be calculated. The average temperature over the period may also be calculated, and the effects of any voluntary activities may be used to determine the state of the system at time $t + \Delta t$. Of course, a different set of activities will lead to a different state at time $t + \Delta t$.

Thus, over n time periods the system will proceed over a path

$$S(D_1, T_1) \rightarrow S(D_2, T_2) \rightarrow \dots \rightarrow S(D_n, T_n) \quad (5-120)$$

We wish to determine the path that maximizes the present value of net benefits, G , summed over n periods [see Eq. (5-117)]. We assume that all voluntary activities (that is, varying the flow rate and/or undertaking drilling/redrilling) occur at the beginning of a period and all parameters then remain constant throughout the period. The procedure is as follows:

1. For every possible state of the system at time t_{n-1} , determine the activities that maximize benefits over the time period $t_{n-1} \rightarrow t_n = t_{n-1} + \Delta t$. At the end of this calculation we know how to proceed from every possible state at time t_{n-1} to later times in an optimal fashion.
2. For every possible state of the system at time t_{n-2} , determine the activities that maximize the benefits over the time period $t_{n-2} \rightarrow t_{n-1}$ plus the discounted benefits over the period $t_{n-1} \rightarrow t_n$.
3. Continue stepping backward in time until time zero is reached.

The modeling work done so far has concentrated on conceptual HDR reservoir systems that have sufficient heat-transfer surface area to maintain a constant thermal power extraction rate for the lifetime of the plant (20 - 40 yr) at a specified flow rate $\dot{m}_w$. This assumption is discussed in Sec. 5.6.1. [Eq. (5-116)] and is equivalent to assuming that the ratio of fracture surface area to well flow rate ($\sim R^2/\dot{m}_w$) is large, $\geq 1.3 \times 10^5 \text{ m}^2\text{-s/kg}$. We are modifying the DPHDR model to permit study of the impacts of various rates of reservoir drawdown on drilling strategy, busbar generating costs for feasibility, and net benefits.

Preliminary parametric analyses have been made for several physical parameters of interest in this study: $\dot{m}_w$ (50 - 200 kg/s), $\overline{\nabla T}$ (20 - 35°C/km), and T_d . As Milora and Tester⁴⁴ showed, the power plant optimum design temperatures are a strong function of the mean gradient $\overline{\nabla T}$. The values of T_d used and their $\overline{\nabla T}$'s are 120°C, 20°C/km; 150°C, 25°C/km; 162°C, 28°C/km; 168°C, 30°C/km; and 178°C, 35°C/km.

Generally speaking, in regions with low geothermal gradients (less than $\sim 30^\circ\text{C/km}$) HDR geothermal power is feasible ($G = 0$) with busbar prices between 2.5 and 7.7¢/kWh as well flow rates from 200 to 50 kg/s are considered for a discount rate of 6% and a 40-yr lifetime. For well flow rates in the range 75 - 100 kg/s, p^* lies between 42.3 - 53.8 mills/kWh. In the western three-fourths of the US, with average geothermal gradients of at least 28°C/km, maximum values of p^* range from 14 to 35.7 mills/kWh as well flow rates vary from 200 to 50 kg/s. Again, for $\dot{m}_w$ in the range 75 - 100 kg/s, p^* would be 21 - 25.8 mills/kWh.

The generalized cost approach in its present form would estimate busbar prices for HDR-produced electricity which are considerably higher than those cited above (see Fig. 5-110). For example, with a well flow rate of about 50 kg/s and a gradient of 30°C/km, a busbar price of 8.0¢/kWh results compared with 3.1¢/kWh for the IRMOM mode. The generalized cost model results are derived by applying a 17% annual fixed-charge rate to total capital costs of the plant and wells with an 85% capacity factor, and adding operation and maintenance costs of 1.3¢/kWh. The use of a 17% fixed charge rate implies that all capital costs must be recovered within a period of about 6 - 7 yr, which would correspond to about 17%, rather than 6%, discount rate. But, analogous to a hydroelectric generating facility, fuel costs for the HDR facility are essentially included in initial capital costs; "future" costs are simply operating and maintenance costs, which can be expected to be quite low, and the HDR facility is not subject to the vagaries of fuel prices as might be the case with coal- and nuclear-fired plants. The imposition of a 6- to 7-yr period for the recovery of capital investments thus obscures the "fuel-free" character of HDR production and can substantially understate potential profits. Of course, in this particular case, revenues from the sale of electricity are valued over the assumed 40-yr life of the plant, and the busbar price p^* , assumed constant over this 40-yr horizon, results in the present value of revenues equaling the present value of costs. Busbar prices generated in the IRMOM model would roughly equal those for the generalized cost model if a time horizon of 6 - 7 yr rather than 40 yr were used to find p^* for $G = 0$.

The impact of the choice of a time horizon on busbar prices for HDR-produced electricity is shown by the data in Table 5-XVI. For example, with a gradient of 35°C/km and a well flow rate of 75 kg/s, the busbar price increases by 4%, from 17.3 to 18 mills/kWh, as the time horizon falls from 40 to 30 yr; p^* rises by 28% (from 17.3 to 22.2 mills/kWh) as the time horizon falls from 40 to 20 yr.

We will continue economic modeling work with IRMOM in FY78 to explore the parametric effects of varying well costs, reservoir energy drawdown, discount rate, front-end capital investment before revenues, taxes, and flow rates on power plant performance.

5.6.3. HDR Cogeneration Cycles

Because geothermal fluid temperatures can be specified by design in a normal HDR reservoir situation, that is, drilling to depth Z with $\bar{\nabla}T$ defined, user needs for electricity and/or process heat may be met in an optimal manner.

TABLE 5-XVI

BUSBAR PRICES FOR HDR-PRODUCED ELECTRICITY WITH ALTERNATIVE
WELL FLOW RATES, GEOTHERMAL GRADIENTS, AND TIME HORIZONS
(DISCOUNT RATE 6%)

Time Horizon (yr)	Well Flow Rate (kg/s)	Busbar Price (¢/kWh 1976 Dollars) With Mean Geothermal Gradient			
		20°C/km	25°C/km	30°C/km	35°C/km
20	50	10.0	6.4	4.1	3.0
20	75	7.0	4.2	2.9	2.2
20	100	5.3	3.4	2.4	1.9
30	50	8.3	3.1	3.4	2.4
30	75	5.7	3.7	2.5	1.8
30	100	4.6	2.9	2.0	1.6
40	50	7.7	4.6	3.1	2.3
40	75	5.4	3.0	2.3	1.7
40	100	4.2	2.6	1.9	1.5

For example, if the user requires 5 MW of electric power and 40 MW of 4.8-bars process steam at 150°C, a combined cycle could be used to provide that mix of electrical and thermal energy with high efficiencies realized (see Fig. 5-113). The electric generation cycle might be a supercritical Rankine cycle with a halogenated hydrocarbon, such as R-32 (CH_2F_2), as a working fluid selected because of its high η_u and small turbine-size requirements. The process heat section would require a steam generator heated by the residual enthalpy of the geofluid as it leaves the electric cycle.

Optimization of a combined cycle, such as shown in Fig. 5-113, is more complex than either a pure electric or nonelectric system. The interface between electric and process heat sections is subject to constraints imposed by the relative power load, wellhead temperature T_{gf} , and heat-rejection temperature T_o . The HDRCOST and IRMOM cost models are being modified so that parametric studies can be made of effects of electric-to-thermal load $\left(0 \leq \frac{\text{MW}(e)}{\text{MW}(e + t)} \leq 1\right)$, $\bar{\nabla}T$, drilling costs, and reservoir lifetime and capacity on the selection of optimal cycle design and reservoir management strategies.

Fig. 5-113.
Process flow schematic for a conceptual HDR cogeneration cycle.

REFERENCES

1. J. N. Albright and R. J. Hanold, "Seismic Mapping of Hydraulic Fractures Made in Basement Rocks," Proc. ERDA Symp. on Enhanced Oil and Gas Recovery, Tulsa, 1976 (ERDA, Washington, DC, 1976) Vol. 2 - Gas, pp. C-8/1-13.
2. A. G. Blair, J. W. Tester, and J. J. Mortensen, "LASL Hot Dry Rock Geothermal Project, July 1, 1975-June 30, 1976," Los Alamos Scientific Laboratory report LA-6525-PR (October 1976).
3. K. Aki, M. Fehler, and S. Das, "Source Mechanism of Volcanic Tremor: Fluid-Driven Crack Models and Their Application to the 1963 Kilauea Eruption," J. Volcanol. Geotherm. Res. 2, 259-287 (1977).
4. D. Lockner and J. D. Byerlee, "Hydrofracture in Weber Sandstone at High Confining Pressure and Differential Stress," J. Geophys. Res. 82, 2018-2026 (1977).
5. D. P. Hill, "A Model for Earthquake Swarms," J. Geophys. Res. 82, 1347-1352 (1977).
6. R. P. Mott, Jr., "The Relationship of Microearthquake Activity to Structural Geology for the Region Around Socorro, New Mexico," M. S. Thesis, New Mexico Inst. of Mining and Technology (1976).
7. D. J. Cash, "The Dulce, New Mexico, Earthquake of January 23, 1966," Ph.D. Thesis, New Mexico Inst. of Mining and Technology (1971).

8. J. Albright, L. Aamodt, and R. Potter, "Definition of Fluid-Filled Fractures in Basement Rocks," Proc. ERDA Symp. on Enhanced Oil and Gas Recovery and Improved Drilling Procedures, Tulsa, 1977 (ERDA, Washington, DC, 1977), Vol. 2 - Gas and Drilling, pp. E-2/1-8.
9. H. D. Murphy, "Fluid Injection Profiles-A Modern Analysis of Wellbore Temperature Surveys," Soc. Pet. Eng., Paper 6783, presented at 52nd Annual Meeting, Denver, Colorado, October 9-12, 1977.
10. F. G. West and A. W. Laughlin, "Spectral Gamma Logging in Crystalline Basement Rocks," Geol. 4, 617-618 (October 1976).
11. J. Zemanek; R. L. Caldwell; E. E. Glenn, Jr.; S. V. Holcomb; L. J. Norton; and A. J. O. Strauss, "The Borehole Televue--A New Logging Concept for Fracture Location and Other Types of Borehole Inspection," J. Pet. Technol. 21, 762-774 (1969).
12. I. N. Sneddon, Fourier Transforms (McGraw-Hill Book Company, Inc., New York, 1951), p. 499.
13. J. H. Moran and K. S. Kuntz, "Basic Theory of Induction Logging," Geophys. 27, No. 6, 829 (1962).
14. A. W. Laughlin and A. C. Eddy, "Petrography and Geochemistry of Precambrian Rocks from GT-2 and EE-1," Los Alamos Scientific Laboratory report LA-6930-MS (August 1977).
15. F. G. West, P. R. Kintzinger, and A. W. Laughlin, "Geophysical Logging in Los Alamos Scientific Laboratory Geothermal Test Hole No. 2," Los Alamos Scientific Laboratory report LA-6112-MS (November 1975).
16. D. G. Brookins and A. W. Laughlin, "Rubidium-Strontium Geochronologic Study of GT-1 and GT-2 Whole Rocks," EOS Trans. AGU 57, 352 (1976).
17. C. W. Naeser and R. B. Forbes, "Variation of Fission Track Ages with Depth in Two Deep Drill Holes," EOS Trans. AGU 57, 352 (1976).
18. D. L. Turner and R. B. Forbes, "K-Ar Studies in Two Deep Basement Drill Holes: A New Geologic Estimate of Argon Blocking Temperature for Biotite," EOS Trans. AGU 57, 352 (1976).
19. D. G. Brookins, R. B. Forbes, D. L. Turner, A. W. Laughlin, and C. W. Naeser, "Rb-Sr, K-Ar, and Fission-Track Geochronological Studies of Samples from LASL Drill Holes GT-1, GT-2, and EE-1," Los Alamos Scientific Laboratory report LA-6829-MS (June 1977).
20. W. L. Sibbitt, J. G. Dodson, and J. W. Tester, "Thermal Conductivity of Rocks Associated with Energy Extraction from Hot Dry Rock Geothermal Systems," paper presented at the 15th Intern. Conference on Thermal Conductivity, Ottawa, Canada (August 1972).
21. H. D. Murphy and R. G. Lawton, "Downhole Measurements of Thermal Conductivity in Geothermal Reservoirs," 1977 Energy Technology Conference, Houston, Texas (September 1977).

22. F. Birch and H. Clark, "The Thermal Conductivity of Rocks and Its Dependence on Temperature and Composition," *Am. J. Sci.* 8, Part I, 529-558 (August 1940) and Part II, 613-635 (September 1940).
23. E. L. Ohle, "The Influence of Permeability on Ore Distribution in Limestone and Dolomite," *Econ. Geol.* 46, 667-706 (1951).
24. W. F. Brace, J. B. Walsh, and W. T. Frangos, "Permeability of Granite Under High Pressure," *J. Geophys. Res.* 73, 2225-2236 (1968).
25. R. K. Iler, The Colloid Chemistry of Silica and Silicates (Cornell Univ. Press, Ithaca, New York, 1955).
26. A. R. March III, G. Klein, and T. Vermeulen, "Polymerization Kinetics and Equilibria of Silicic Acid in Aqueous Systems," Lawrence Berkeley Laboratory report LBL-4415 (October 1975).
27. W. F. Brace, "Pore Pressure in Geophysics," in Flow and Fracture of Rocks, H. Herd, Ed. (American Geophysical Union, Washington, DC, 1972), pp. 265-273.
28. H. J. Ramey, Jr., and A. C. Gringarten, "Effect of High Volume Vertical Fractures on Geothermal Steam Well Behavior," 2nd UN Symp. on the Use and Development of Geothermal Energy, San Francisco, California, May 20-29, 1975.
29. D. T. Secor, Jr., and D. D. Pollard, "On the Stability of Open Hydraulic Fractures in the Earth's Crust," *Geophys. Res. Lett.* 2, 510-512 (1975).
30. P. C. Paris and G. C. Sih, "Stress Analysis of Cracks," in Fracture Toughness Testing and Its Applications (STP No. 381, ASTM, Philadelphia, 1965), pp. 30-81.
31. J. Weertman, "Theory of Water-Filled Crevasses in Glaciers Applied to Vertical Magma Transport Beneath Oceanic Ridges," *J. Geophys. Res.* 76, 1171-1183 (1971).
32. Y. C. Hsu and F. Santossa, "The Stability of a Large Open Hydraulic Penny-Shaped Fracture (Crack) Near the Earth's Surface," Preliminary Progress Report ME-80(77) LASL-494-1 (July 1977).
33. R. A. Sack, "Extension of Griffith's Theory of Rupture to Three Dimensions," *Proc. Phys. Soc., London* 58, 729-736 (1946).
34. G. Simmons and H. Cooper, "DSA of the Microcrack in GT-2 Core: Interpretations and Implications," Final Tech. report to LASL, unpublished, Contract X67-69648-1 (November 1977).
35. J. Bear, Dynamics of Fluids in Porous Media (American Elsevier Publishing Company, Inc., New York, 1972).
36. J. C. Jaeger and N. G. W. Cook, Fundamentals of Rock Mechanics (Chapman and Hall Ltd., London, 1969).

37. F. H. Harlow and A. A. Amsden, "Fluid Dynamics: An Introductory Text," Los Alamos Scientific Laboratory report LA-4100 (May 1970).
38. R. G. Lawton, "The AYER Heat Conduction Computer Program," Los Alamos Scientific Laboratory report LA-5613-MS (May 1974).
39. H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids (Oxford, London, 1959).
40. F. G. West, P. R. Kintzinger, and W. D. Purtymun, "Hydrologic Testing Geothermal Test Hole No. 2," Los Alamos Scientific Laboratory report LA-6017-MS (July 1975).
41. H. D. Murphy, D. M. McElligot, and M. Coxon, "Radial Converging Flow Between Stationary Disks," submitted for publication (1977).
42. P. M. Moretti and W. M. Kays, "Heat Transfer to a Turbulent Boundary Layer with Varying Free Stream Velocity and Varying Surface Temperatures," Intl. J. Heat and Mass Transfer 8, 1187 (1965).
43. R. D. McFarland and H. D. Murphy, "Extracting Energy from Hydraulically Fractured Geothermal Reservoirs," 11th Intersociety Energy Conversion Engineering Conference, State Line, Nevada, September 12-17, 1976.
44. S. L. Milora and J. W. Tester, Geothermal Energy as a Source of Electric Power (MIT Press, Cambridge, Massachusetts, 1976).
45. H. J. Ramey, "Wellbore Heat Transmission," J. Pet. Technol. 14, 427-435 (1962).
46. F. H. Harlow and W. E. Pracht, "A Theoretical Study of Geothermal Energy Extraction," J. Geophys. Res. 77, 7038-7048 (1972).
47. D. E. Gray (Ed.), American Institute of Physics Handbook (McGraw-Hill New York, 1963).
48. S. P. Clark, Jr., Handbook of Physical Constants (Geological Society of America, New York, 1966).
49. L. M. Keer, S. Nemat-Nasser, and K. S. Parihar, "Growth and Stability of Thermally Induced Cracks in Brittle Solids," The Technological Institute, Northwestern University (1976).
50. A. C. Gringarten, P. A. Witherspoon, and Yuzo Ohnishi, "Theory of Heat Extraction From Fractured Hot Dry Rock," J. Geophys. Res. 80, No. 8, 1120-1124 (1975).
51. R. G. Cummings, J. W. McFarland, and S. C. Nunn, "An Economic Analysis of the Hot Dry Rock Geothermal Energy Resource," (to be published).

6. ENERGY EXTRACTION SYSTEM (P. J. Chavez, Jr.; B. R. Dennis; R. H. Hendron; J. H. Hill, Task Mgr.; E. D. Holmes; E. H. Horton; J. C. Skalski, Jr.)

6.1. Description

The energy extraction facility for LASL's Hot Dry Rock Geothermal Energy Demonstration comprises a closed-loop, pressurized circulating water system in which cold water is pumped into the EE-1 borehole, through the geothermal reservoir, out of the GT-2 borehole, through the heat exchanger, and back to the pumps. The surface portion of this loop and ancillary equipment are shown in Fig. 6-1. The geofluid, under pressure, remains liquid throughout the cycle. Water losses, incurred primarily by permeability and leakage in the reservoir are made up from the water well at Fenton Hill, with the EE-1 reserve pond used for interim water storage.

The surface piping, made of schedule 160 carbon steel, was designed for a pressure rating of 17.2 MPa (2500 psi). Much of the surface piping was prefabricated at the Zia Company in Los Alamos (DOE contractor). Field construction of the piping system included thermal-expansion sections in the long piping run from

Fig. 6-1.
Surface facilities and equipment for the circulating loop.

the GT-2 wellhead to the heat exchanger (hot leg). Kaylo calcium silicate insulation was installed on all surface piping to reduce heat loss. Upon completion of the field installation, the entire surface piping system (with the borehole and fracture system by-passed) was tested to a hydrostatic pressure of 13.8 MPa (2000 psi).

The heat exchangers (Fig. 6-2) are finned-tube, water-to-air units. Each bay consists of two-tube bundles connected in parallel; each bundle is a 12-pass arrangement of straight tubes in plugged headers. The heat exchangers were designed to the following specifications:

Heat transfer - 12.1 MW(t)

Inlet temperature - 250°C

Outlet temperature - 65°C

Pressure - 17.2 MPa (2500 psi)

Flow rate - 19 liters/s (300 gpm) water

Air circulation - 133 m³/s (282 600 cfm) with inlet temperature of 21°C.

Pumping requirements were set, based on experiments and predicted conditions, at 19 liters/s (300 gpm) with 8.3-MPa (1200-psi) differential head and 10-MPa (1450-psi) maximum pressure. The water temperature was specified at 80°C with a possible total dissolved solids content up to 400 ppm. Various types of pumps were compared to determine best performance. One restrictive requirement was inherent in the local (rural) electric power supply, which limits the pump motor starting current to that of a 150-kW (200-hp) rated motor.

The circulation pumps that will be permanently installed are canned vertical-turbine units. Two such pumps will be connected in series to produce the required head pressure within the motor starting limitation. These seven-stage units will operate at about 72% efficiency and 125 kW (168 hp) at full load. Two standby units will be installed in parallel and may be operated to increase flow, if required.

A pressure-lock section, consisting of valves and a pressure chamber, will be installed at the GT-2 wellhead to allow for deployment of certain downhole instrumentation equipment while the loop is operating. Critical downhole temperature and pressure measurements will be made with the system fully pressurized.

6.2. Operation in FY77

A 10 000-h minimum cumulative operation of the circulation loop is planned. A nominal 100-h flow experiment to obtain preliminary information of the loop's operating characteristics, before the final installation of pumping, control, and

instrumentation facilities, was conducted starting September 26, 1977. This continuous-flow experiment, operated at a nominal 9.5 liters/s (150 gpm), provided a functional check-out of the complete closed-loop system (except for use of temporary rented pumping equipment). The experiment also provided preliminary information on extracted power, make-up water requirements, and geochemistry and, in addition, allowed final check-out of instrumentation, controls, and on-line computational algorithms. The experimental operating parameters included a steady-state injection flow rate of about 9.5 liters/s (150 gpm) with the injection pressure to be maintained below 9.7 MPa (1400 psi), corresponding to a system impedance of 1.09 MPa-s/liter (10 psi/gpm). Extensive fluid sampling of the inlet water, make-up water, outlet cooled liquid, and outlet condensate enhanced the geochemistry studies.

The first 35 h of the flow test were run with the GT-2 effluent diverted to a catch pond, by-passing the heat exchangers. The total throughput of about 1.1×10^6 liters (300 000 gal) during this period was intended to flush the well-bores and reservoir and to provide base-line water chemistry data. The outlet temperature increased from the static ambient to above boiling, producing the steam plume shown in Fig. 6-3. The loop was then closed through the heat exchangers for nonflashing circulating operation during the remainder of the test.

Fig. 6-2.
Circulation system heat exchangers.

Fig. 6-3.
Experiment 176, GT-2 effluent during open-loop operation.

Flow stabilized at about 9.5 liters/s (150 gpm); impedance was about 1.3 MPa-s/liter (12 psi/gpm). The maximum thermal power was measured at 3.2 MW(t) at a temperature of 132°C. The injection pressure was nominally 6.9 MPa (1000 psi) for the first 50 h and was maintained at 9.1 MPa (1325 psi) for the following 46 h.

Several shutdowns and restarts were accomplished during the run. A sodium-fluorescein dye injection experiment was performed to detect any dramatic changes in fluid residence time in the fracture system caused by the redrilling operation. Some minor problems occurred when pulsations from the rented piston-driven pumps caused a drain valve in the loop plumbing to vibrate open. On one occasion the circuit breaker controlling a large fan in one heat-exchanger unit tripped off, caused primarily by a misalignment during installation. There was also some discrepancy in the total fluid inventory among system flow meters, indicating the need for in situ calibration of all flow-metering instrumentation.

The numerical results of the 100-h experiment were consistent with predictions, and the test was extremely useful in wringing out the various subsystems under operating conditions.

6.3. Modifications/Additions for FY78 Operation

The prototype energy extraction system will be heavily instrumented for the balance of the 10 000-h operation. System performance will be determined from measurements of reservoir behavior in terms of system impedance, extracted power, fracture diffusivity and transmissibility, and fluid inventory. Geothermal fluid chemistry will be studied in detail throughout the loop operation. The heat exchangers will be monitored for scaling effects as well as heat transfer.

The heart of the data acquisition and control equipment is a programmable-calculator-based, low-level multiplex system (Hewlett Packard 3050B). This system will scan 60 data channels at a sampling rate of 60 channels/min. These data will be stored in magnetic tape cassettes throughout the operation and will also be printed out every 10 min for on-line quick-look analysis. A block diagram of the system is shown in Fig. 6-4. The data channels are listed in Table 6-I. The programmed calculator will also output numerous control channels (Table 6-II) critical to loop operations. Critical channels (Table 6-III) will also be continuously monitored on numeric displays. Figure 6-5 shows the 3050B equipment as installed.

In addition to the 3050B equipment, a circulation system indicator panel (Fig. 6-6) will monitor the operating condition of all components including

Fig. 6-4.

Block diagram, data acquisition and control system for energy extraction loop.

Fig. 6-5.

Hewlett Packard 3050B system installed.

Fig. 6-6.

Circulation system status indicator panel.

TABLE 6-I
CIRCULATION LOOP DATA INPUTS, 3050B SYSTEM

1. GT-2 wellhead pressure	13.8 MPa	(0-2000 psi)
2. GT-2 wellhead pressure (backup)	13.8 MPa	
3. Heat-exchanger input pressure	13.8 MPa	
4. Heat-exchanger output pressure	13.8 MPa	
5. Circulating pumps 1,2 pressure	13.8 MPa	
6. Circulating pumps 3,4 pressure	13.8 MPa	
7. EE-1 wellhead pressure	13.8 MPa	
8. EE-1 wellhead pressure (backup)	13.8 MPa	
9. Supercharger pressure	1.38 MPa	(0-200 psi)
10. Make-up pump pressure	13.8 MPa	(0-2000 psi)
11. GT-2 filter ΔP	0.035 MPa	0-5 psid
12. Heat-exchanger ΔP	0.69 MPa	0-100 psid
13. GT-2 flow venturi ΔP	1.93 MPa	0-280 psid
14. Heat-exchanger bundle 1, flow ΔP	0.035 MPa	0-5 psid
15. Heat-exchanger bundle 2, flow ΔP	0.035 MPa	5 psid
16. Heat-exchanger bundle 3, flow ΔP	0.035 MPa	5 psid
17. Heat-exchanger bundle 4, flow ΔP	0.035 MPa	5 psid
18. EE-1 wellhead inlet temperature		50°C
19. EE-1 wellhead inlet temperature (backup)		50°C
20. GT-2 wellhead outlet temperature		200°C
21. GT-2 wellhead outlet temperature (backup)		200°C
22. Heat-exchanger input temperature		200°C
23. Heat-exchanger output temperature		50°C
24. Heat-exchanger fan 1, exit air temperature		
25. Heat-exchanger fan 2, exit air temperature		
26. Heat-exchanger fan 3, exit air temperature		
27. Heat-exchanger fan 4, exit air temperature		
28. Heat-exchanger flow, turbine meter	17.66 liter/s	(280 gpm)
29. Make-up water flow, turbine meter	5.05 liter/s	(80 gpm)
30. Supercharger		proximity
31. Make-up pump		proximity
32. GT-2 motorized control valve		proximity
33. Circulating main pump 1		proximity
34. Circulating main pump 2		proximity
35. Circulating main pump 3		proximity
36. Circulating main pump 4		proximity
37. Heat-exchanger fan 1		proximity
38. Heat-exchanger fan 2		proximity
39. Heat-exchanger fan 3		proximity
40. Heat-exchanger fan 4		proximity
41. Heat-exchanger motorized control valve		proximity
42-60. Transducer excitation (pressure, ΔP transducers)		

TABLE 6-II
CIRCULATION LOOP CONTROL FUNCTIONS, 3050B SYSTEM

1. Circulating pump 1	power on-off
2. Circulating pump 2	power on-off
3. Circulating pump 3	power on-off
4. Circulating pump 4	power on-off
5. Supercharger pump 5	power on-off
6. Make-up water pump 6	power on-off
7. Heat-exchanger fan 1	power on-off
8. Heat-exchanger fan 2	power on-off
9. Heat-exchanger fan 3	power on-off
10. Heat-exchanger fan 4	power on-off
11. GT-2 wellhead pneumatic safety valve	close
12. EE-1 wellhead pneumatic safety valve	close
13. GT-2 motor control valve	open-close
14. EE-1 motor control valve	open-close
15. CDA system calculator malfunction	alarm
16. CDA system malfunction	alarm

TABLE 6-III
CRITICAL DATA DISPLAY, 3050B NUMERIC

1. GT-2 wellhead pressure
2. EE-1 wellhead pressure
3. Heat-exchanger Δ pressure
4. GT-2 flow (outlet)
5. EE-1 flow (inlet)
6. GT-2 temperature (outlet)
7. Filter, Δ pressure
8. Heat-exchanger temperature input
9. Heat-exchanger temperature output
10. Thermal power (calculated)

manual valves, control valves, pumps, and heat-exchanger fans. The continuous operation of the energy extraction system demands that critical channels be alarmed if dangerous limits are exceeded. Visual and audio alarms to alert the operators will be provided for those critical channels.

The heat-exchanger units will be instrumented with an additional 80 chromel/alumel thermocouples. These temperature sensors will have a sensitivity of 0.1°C and will measure scaling effects during the long-term loop operations. The thermocouple outputs will be scanned (Autodata 8 Data Logger) twice each day.

The 3050B data and control system will employ a power-fail-safe supply. A battery-operated back-up system (Uninterruptible Power Source) will provide 60-Hz power for 30 min should a line power failure occur. The 30 min will be more than enough time to bring standby auxiliary power (diesel motor generator unit) on-line until main power is restored.

The 3050B Data Acquisition System was temporarily installed at the Fenton Hill test site and operated for over 600 h during numerous flow experiments conducted in FY77. The system was programmed to simulate circulation loop conditions and was evaluated for system performance and software requirements. The system performed all data logging and control functions as required.

7. ENVIRONMENTAL STUDIES (J. N. Albright, Task Mgr.; D. D. Douglas; K. D. Elsberry; C. O. Grigsby; W. S. Midkiff; C. A. Newton; R. A. Pettitt; R. M. Potter; K. H. Rea, Co-Task Mgr.; K. D. Rowlinson; J. W. Tester)

This section provides an overview of the environmental monitoring responsibilities and activities related to the HDR Project. Included are descriptions of the work that has been done in four major environment-related areas: seismology, hydrology, geothermal fluid treatment, and related environmental studies, which includes work in climatology and biology. The purpose of these programs is to obtain base-line data, define potential effects from Project activities, and determine and record any impacts that may occur.

7.1. Induced Seismicity Studies

Historically, New Mexico is an area of low-to-moderate seismic risk. Records of shocks felt by people or causing structural damage date back to the mid-1800s. These records coupled with recent seismograms show the region of greatest earthquake activity to be centered along the Rio Grande Valley between the cities of Socorro and Santa Fe, in the central portion of the state, more than 80 km from the LASL HDR site, which is situated on the Jemez Plateau.

Although historical records did not show much earthquake activity in or around the Jemez Plateau, a geological survey to locate faults and seismological monitoring to record shocks were deemed necessary^{1,2} to determine the likelihood of large seismic events within the region, and to monitor for possible induced seismicity at the LASL HDR site resulting from the pressurization of a subterranean reservoir. A geological survey was conducted in 1971 to determine the proximity and probable activity of faults near the Fenton Hill HDR site.³ The survey showed that the Jemez fault zone is the nearest major fault system to the site. Two northeast-trending faults within this zone, the Virgin Canyon fault and the Jemez Springs fault, pass within about 4 and 7 km, respectively, of the site (see Fig. 2-4). Field checks of these faults have indicated that their movement rates are far below those of major active faults in the western US. Because of the distance of these faults from the site, the fact that they trend away from the site, and their relatively low movement rates, it is improbable that they would be activated by experimentation at Fenton Hill.

A seismic reconnaissance of the HDR Project area located several hidden faults in the sedimentary rocks above the Precambrian granite where strong, continuous, and near-horizontal reflectors predominated.⁴ These faults originate

in the granite and some may have been intersected by the boreholes. There is no evidence that they penetrate the Bandelier Tuff, so they probably are old enough to be completely cemented. Therefore any contemporary faulting may require stresses that exceed the effective breaking strength of granite containing sealed, natural fractures under in situ conditions.

Two sets of seismic networks were established (close-in and on-site) to measure seismic activity around Fenton Hill, and to supplement measurements of an existing regional network (see Fig. 7-1). The regional network was established to measure seismic events important to other LASL programs. It is composed of 15 high-gain, continuously telemetered stations located in northern New Mexico and includes 3 of the HDR Project's close-in stations. The regional network was started in 1972 with the establishment of the first station at LASL, and by 1976 enough stations were functional so that epicenters of microearthquakes [Richter's local magnitude (M) greater than 0.5] can be located up to 100 km from Los Alamos.⁵

The three close-in stations that are still operational and are included in the regional network are the La Cueva, Barley Canyon, and Lake Fork Canyon stations. The La Cueva station (LCV), located about 450 m north of the HDR site, contains a three-axis low-gain system of seismometers. The Barley Canyon and Lake Fork Canyon systems are special borehole stations (125 m deep), established in 1975 to augment the detection and location capability for $M_L < 0$ seismic events within 5 km of the site.

The close-in and on-site seismic networks were established in 1974 in an attempt to detect signals from hydraulic fracturing experiments carried out at depths from 850 to 1900 m, and later to 2900 m. The close-in seismic network, which was operational during injection experiments in 1974 and 1975, was composed of nine surface stations located about 1500 - 2000 m from the site. The on-site network, which has operated since September 1975, has six stations; one is located about 200 m from the site, the rest are in a circular configuration, each about 750 m from the site. The on-site network, recording on slow-speed paper charts, has operated about 95% of the time.

A typical on-site surface station contains three short-period seismometers coupled to battery-powered line-driving amplifiers. Two of the seismometers are vertical; the other is horizontal, oriented parallel to an imaginary radial line intersecting the HDR site. Signals from these stations are transmitted by cable to a recording trailer at the site.

Fig. 7-1.
Close-in and regional seismic networks.

Microseismic events have been recorded by the regional network of seismic stations in northern New Mexico; however, no events greater than $M_L = 0.5$ have occurred at the HDR site since 1973. Although no events related to project activities have been detected by any of the surface networks, some nearby microseismic activity has been recorded as outlined below.

The first natural event recorded whose epicenter was near the facility occurred May 28, 1975. This was a single shock ($M_L = 0.7$) about 17 km southeast of the HDR site, and its significance remains unclear.

A larger natural event took place later the same year, on September 29. This activity was preceded by two shocks, on September 25 and 27, and was followed by a series of aftershocks. The main shock ($M_L = 3.2$) was located about 22 km northwest of the site, and had sufficient magnitude to enable sensitive instruments throughout the state to measure it. This shock, one of several events associated with the Nacimiento Mountains fault zone, demonstrates that this is still an active fault system. No other significant shocks have been monitored by the Project's seismic network.

An $M_L \approx 0$ earthquake occurred November 11, 1976, about 23 km south of the HDR site. Although this event had gone unnoticed during readings of the regional network seismograms, data from six of those stations were able to locate it after it was read on the on-site seismograms. Location of such small events at present requires a fortuitous low-level of background noise at four properly located stations. The on-site array and the nearest station (LCV) of the close-in network have detected infrasonic signals originating near the two wells, EE-1 and GT-2. The source of these signals, which travel faster than acoustic waves but are possibly Rayleigh waves, has not yet been identified. If this type of signal continues to be recorded, additional instrumentation to identify the source(s) will be added to the network.

Although the local seismicity over the last 3 yr has not exceeded expectations, based on geological studies of the local faults and the historical earthquake record, there have been unexpected earthquakes in the Colorado Plateau west of the Nacimientos. If the existing network of regional stations had been in operation for a decade or more, it is possible that what now appear as anomalous epicenters would be understood in relation to a regional tectonic model. Tectonic models for this region do not have a sufficient base of seismic evidence to properly evaluate the earthquake risk to the HDR Project. A recent review of our seismic monitoring by Woodward-Clyde Consultants supports our analysis that we need increased seismic station coverage and additional geological studies.⁶

During 1974 and 1975 attempts were made to measure the noise generated by hydraulic fracturing experiments at depths from 850 to 2900 m within boreholes penetrating the Precambrian granitic rocks. The surface stations of the close-in and on-site seismic networks (placed on the Bandelier ash-flow deposits about 700 m above the granite rocks) were unable to separate these events from background noise. Therefore, special downhole geophones were required to monitor these activities. These special high-temperature borehole geophone packages are still the only instrumentation available for recording the low-energy seismic-acoustic signals generated within the reservoir. Because they require internal cooling from ice-filled Dewars, they are limited to about 6 h at 200°C in the borehole. These geophones were used almost exclusively (but for less than 20 h total) during experiments in which water was pumped into the HDR reservoir. The most energetic signals originating within the recorded reservoir had peak particle velocities below 25 $\mu\text{m/s}$. Work is continuing on developing a borehole geophone package that will have a minimum operating time of 12 h at 250°C.

The original concern to seismologists studying the Project was that the fluid injection could reduce the effective normal stress across existing fractures enough that pre-existing shear stresses would be released, causing earthquakes. This has been the interpretation of the causes of earthquakes occurring in Colorado, near Denver and in the Rangely oil field. In both cases, however, the earthquakes occurred along natural faults - fluid injection in portions of the Rangely oil field where there were no natural faults did not cause earthquakes. One study of the Denver earthquakes⁷ concluded that no single triggering mechanism was dominant throughout the disposal reservoir.

To provide assurances that we would be able to locate and determine causes of earthquakes, should they occur, that could threaten the continuation of the HDR Project, a contract for analysis of the present seismic monitoring program was let to a recognized expert in seismic risk analysis, Woodward-Clyde Consultants. Their completed report⁶ contained several recommendations for altering that program. In brief, Woodward-Clyde recommended additional stations, sharing of data from the separate networks to have increased coverage at the Los Alamos and Fenton Hill recording centers, and continuous subsurface monitoring. Based partly on this recommendation, LASL has submitted to DOE a proposal consisting of:

- (1) relocating the on-site seismometer array of five stations into ~30-m (100-ft) boreholes spaced on a radius of about 1.5 km (5000 ft) from the site,
- (2) telemetering the signals from the on-site seismometer array to the LASL recording center,
- (3) forming a close-in seismic network by installing and telemetering seven additional seismic stations within 25 km of the HDR site,
- (4) installing and telemetering six additional seismic stations (see Fig. 7-1) as part of the existing regional network in northern New Mexico at locations greater than 25 km from the site, and
- (5) expanding data analysis to increase our contribution to basic seismology and to understanding of the relationship between induced seismicity and HDR experimentation.

Implementing these recommendations would guarantee that changes in background seismicity are observed, and that the accuracy of calculated hypocenters and focal

mechanisms is sufficient to establish the relationship between seismic events (should they occur) and changes to the local stress-field induced by Project activities.

7.2. Hydrology Studies

The HDR site is located near major drainages that support natural fisheries and contribute water supplies to several small towns and villages. Any degradation of these surface waters, should it occur, must be documented and related to the HDR facility, or to other geothermal, logging, construction, or other activities in the area. In addition to the possibility that the surface-water quality may be altered, the potential exists for pollution of aquifers because of the nature of the HDR experiment. Therefore, base-line data were established to document the water quality of the region before and after setting up the HDR facility.

Water-quality data continued to be collected, as in past years since 1973, from 9 surface stations along the Jemez River, the Rio Guadalupe, and their tributaries; from 11 ground-water stations on the Jemez River drainage; and from 3 ponds at Fenton Hill. Surface- and ground-water samples were collected in August and November of 1976, and in June and November of 1977. In addition, samples of water and waterborne sediments were collected along the Jemez River in October 1976. Samples from all 23 stations were also collected in November 1977 for analysis for 22 trace elements.

Chemical analyses were made to determine levels of silica, calcium, magnesium, sodium, carbonate, bicarbonate, sulfate, chloride, fluoride, nitrate, and total hardness. Measurements were also made for total dissolved solids, conductance, and pH. All analyses were conducted according to the procedures outlined in U.S. Geological Survey Water-Supply Paper 1454.⁸

Slight changes in chemical quality at individual stations were observed during the year. Predominant ions and total dissolved solids remained essentially stable. Variations in quality were within the expected normal seasonal fluctuations and were not considered significant. There were no detectable effects from the LASL HDR activities or from other geothermal explorations in the area.

The data show that there is little difference between the ground water (potable supply) and surface water adjacent to the site. The ground water is slightly higher in silica (SiO_2), whereas the surface water is higher in calcium.

This difference is expected because of the soil and rock material in contact with these waters.

7.3. Geothermal Fluid Treatment

During closed-loop operation of the system, geothermal fluid will be recycled, but until now - with the exception of 61 h of closed-loop operation in Experiment 176 (see Sec. 6.2.) - almost all flow through the system has been once-through only. This once-through operation has presented a fluid storage and disposal problem. Fluid stored in the EE-1 and GT-2 ponds has been analyzed periodically for content, particularly of environmentally hazardous substances. Typical analyses are presented in Table 7-I.

The presence of fluoride ion (F^-) at concentrations of 10 - 20 mg/liter (10 - 20 ppm) in water that has been circulated through the geothermal reservoir has been of concern regarding the possible environmental impact of discharging the geothermal fluid (see Sec. 5.2.4.).

A technique to reduce the fluoride concentration before the water is discharged into Lake Fork Canyon was examined in laboratory and field tests. The technique involves selective absorption of fluoride on a packed bed of activated alumina (Al_2O_3). The apparatus used in laboratory studies is shown in Fig. 7-2. It consists of a 25-mm (1-in.) -i.d. Plexiglas tube with brass ends. Glass beads are used as bed support and for distribution of the feed to insure uniform flow through the bed. The bed itself is F-1 grade, 28- by 48-mesh alumina, available in bulk from Alcoa. The field treatment facility used during Experiment 137 is shown in Fig. 7-3. Each bed has a capacity of about 1 m^3 (28 ft^3).

As received, the alumina is laced with solid Na_2CO_3 , which must be removed to reduce the bed pH to 7 or less before the alumina will effectively absorb F^- . In addition, very fine particles of alumina and Na_2CO_3 are present in the as-received material, which result in high bed pressure drops at operational flow rates.

These problems are largely corrected by back flushing and fluidizing or expanding the bed ~100% with warm water. Bed pH pretreatment was accomplished with a pH 5 solution of H_2SO_4 to remove the Na_2CO_3 that did not dissolve in the warm water. When the effluent has a pH of 7 or less, the bed is ready for fluoride treatment.

7.3.1. Laboratory Tests

Laboratory tests were conducted that used about 100 cm^3 of activated alumina per bed. Large volumes (~190 liters) of solution with a

TABLE 7-I
LIQUID ANALYSIS

	Upper Pond (7/21/76) EE-1 (ppm)	Lower Pond (7/21/76) GT-2 (ppm)	Injected Water ^a (7/21/76) (ppm)
SiO ₂ ^b	203	206	46
SiO ₂ ^c	164	158	42
Na ⁺	470	460	63
K ⁺	45	44	8
Ca ²⁺	32	35	23
Al ³⁺	<1 ^d	<1	<1
Mg ²⁺	0.02	0.03	5
Fe ²⁺ & Fe ³⁺	7	6	0.3
Cl ⁻	501	501	10
F ⁻	11	10	1
SO ₄ ²⁻	145	185	<20
HCO ₃ ⁻	360	260	240
CO ₃ ²⁻	<1	<1	<1
S ⁻	21	39	-
PO ₄ ²⁻	0.3	0.4	0.5
TDS	1730	1690	-

EMISSION SPECTRA
(SPECTRO QUANT)

	Upper Pond (ppb)	Lower Pond (ppb)		Upper Pond (ppb)	Lower Pond (ppb)
Li	10000	10000	Ge	<30	<30
Be	<3	<3	As	<500	<500
B	8000	9000	Se	<1000	<1000
Ti	10	15	Sr	400	400
V	<5	<5	Zr	<3	<3
Cr	<3	<3	Nb	<30	<30
Mn	50	60	Mo	40	40
Fe	5000	5000	Ag	<10	<10
Co	<3	<3	Cd	<100	<100
Ni	5	5	Sn	<30	<30
Cu	20	20	Sb	<200	<200
Zn	150	150	Pb	60	20
Ga	<10	<10	Bi	<10	<10
			Ba	200	200
TDS	1670 (ppm)	1640 (ppm)			
(dried solids)					

^aUnfiltered San Antonio River water.

^bDetermined by atomic absorption.

^cDetermined by spectrophotometric molybdate method.

^dAll values reported with the less than (<) sign are below the limit of detection for the technique used.

Fig. 7-2.
Laboratory absorption bed.

Fig. 7-3.
Prototype water treatment facility.

concentration of 10 ppm F^- were prepared by using deionized or tap water ($[F^-] < 0.1$ ppm, $[SiO_2] \approx 80$ ppm) and reagent-grade NaF. This feed solution ($[F^-]_0$) was gravity-fed to the column, and flow rates through the bed were adjusted to a constant level (1/2 - 4 bed volumes/min). Feed flow rates were measured with rotameters and adjusted with needle valves. Samples of the effluent were taken at regular intervals and analyzed for F^- with an ORION select-ion electrode. Graphs of $[F^-]/[F^-]_0$ vs volume throughput (V/V_{bed}) are presented in Fig. 7-4 for A (tap water) and B (deionized water). The difference between the onset of the breakthrough as well as total F^- removed for these curves is probably due to competition between SiO_2 and F^- for the active absorption sites on the alumina. At this time no data are available for the silica concentration vs volume throughput for these beds. At high pH, OH^- also competes with F^- , affecting bed performance; in fact, it is because of this behavior that bed regeneration with NaOH is possible. In practice, almost complete removal of F^- is achieved by

back flushing with a 1 - 2% solution of NaOH. The final step of regeneration is to neutralize the bed with a pH 5 acid wash. Figure 7-5 shows a breakthrough curve for a regenerated bed.

Numerous preliminary experiments at various flow rates have been run in an attempt to determine how the breakthrough curve is affected by flow rate and to identify the regimes in which liquid-phase diffusional mass transfer and surface absorption kinetics are controlling. The data follow expected trends, but additional work is necessary to complete characterization of bed performance over the anticipated range of operating conditions.

7.3.2. Field Studies

During Experiment 137, in November 1976, geothermal fluid from the reservoir left the GT-2 wellhead and entered the prototype water treatment facility as shown in Fig. 7-3. These beds were not regenerated because the two beds had enough capacity to process all the geothermal fluid generated during the experiment. A graph of $[F^-]/[F^-]_0$ vs V/V_{bed} for one bed is presented in Fig. 7-5. Silica removed by the alumina is plotted against normalized volume (V/V_{bed}) in Fig. 7-6. Silica was removed in large quantities by the alumina, and in comparing Figs. 7-5 and -6 we see that removal of silica had an appreciable effect on the bed's performance in absorbing F^- .

Although the field and laboratory data are preliminary, the results will lead to further experiments and then to the design of a 10-liters/s (150-gpm) capacity water treatment facility for Fenton Hill.

7.4. Related Environmental Studies⁹

7.4.1. Climatology

The Jemez Mountain range is typical of most southwestern mountains in its general weather patterns. The climate is characterized by localized convective shower activity during the summer and more regional major storms during the winter. Total precipitation received generally increases at higher elevations; however, the irregular terrain causes irregularities in the storm patterns.

Although some generalizations about the weather patterns can be made, specific events in these mountains tend to be localized. This localization makes it impossible to extrapolate weather events from one area to another. Because of the lack of climatological information at or near the site, we set up a weather station to measure a few basic weather parameters to determine the climatic regime of the area and to characterize prevailing wind patterns. These data will be used to determine where potential environmental contaminants

Fig. 7-4.
Breakthrough curve for laboratory bed; 10 ppm F^- in (A) tap water and (B) de-ionized water at a flow rate of $1 V_{bed}/min$.

Fig. 7-5.
Breakthrough curve for bed during field Experiment 137; flow rate about $0.055 V_{bed}/min$.

Fig. 7-6.
Silica absorbed by alumina bed during Experiment 137, concurrent with fluoride breakthrough shown in Fig. 7-5.

released from the site will go on to explain variations in biological measurements that may be linked directly to climatological phenomena.

The weather station was established about 150 m west of the site. Its location, as close to the site as possible, minimized the effects of surrounding terrain and structures upon air flow patterns. The station consists of a Meteorology Research Incorporated (MRI) mechanical weather station and a weighing bucket rain gauge. The MRI station is mounted on top of a collapsible 9-m-high tower and records wind speed, wind direction, and temperature on a pressure-sensitive strip chart. The weighing bucket rain gauge, located 10 m west of the tower, records precipitation on a strip chart attached to a revolving drum.

Another weighing bucket rain gauge is located on the mesa top about 1500 m west of the site. This gauge, on the periphery of the area set aside for ecological studies, will be used to compare precipitation at the two locations. Some localized convection showers dump large quantities of moisture in nonuniform patterns in this mountainous terrain.

Data recorded by these instruments are reduced into hourly averages and put into a form that can be read by a computer. Computer programs check the data for key punch errors, missing cards, and suspicious-looking numbers. Once checked, the data are summarized monthly in graphic and tabular forms.

The weather station at the site has been recording data continuously since it became operational in January 1976. Although no conclusions can be made about weather patterns from such a small data base, several interesting, but expected, phenomena are evident.

Air flow patterns have a distinct seasonal shift. During January the air flow is primarily from the northwest. Air flow patterns shift as the seasons progress into summer, and by the end of August are almost completely reversed. Figure 7-7 shows the monthly wind summary for September 1977.

Precipitation at the site also followed the pattern expected for semiarid southwestern mountain ranges. During the winter months, precipitation is a more-or-less random event and does not follow a predictable pattern. However, during the summer, regional storms are replaced by localized convective activity, which generally builds over the mountains during the morning and results in showers during the afternoon (Fig. 7-8).

Temperatures at the site were relatively mild with the extremes being between -23 and 27°C for winter and summer, respectively. These temperature ranges probably are typical in that Los Alamos seldom exceeds 32°C in the summer and seldom

Fig. 7-7.

Wind summary for September 1977.

Fig. 7-8.

Precipitation summary for September 1977.

drops below -18°C in the winter. Large diurnal variations in temperature, however, can occur. For example, on August 2, 1976, the ambient air temperature changed from 4°C at 5:00 a.m. to 19°C at 4 p.m., for a change of 15°C in 11 h. Figure 7-9 shows the temperature summary for September 1977.

March is the windiest month of the year with an average wind power of 38.4 W/m^2 . The transition between winter and summer air flow patterns also begins in March. The summer months are relatively calm, indicating that the southeast air flows associated with summer convective activity are not as strong as the northwest flows during the winter.

7.4.2. Biology

During 1976, studies were initiated to obtain information on the amount of vegetation and wildlife (small mammals, elk, and birds) near the site. The results of these studies now establish the base-line data to which future

measurements can be compared. Funding for this work has come from the Division of Biomedical Research (DBR).

7.4.2.1. Vegetation. Three major vegetative complexes or community types are found at the site. Typical climax vegetation found at 2600-m elevation in northern New Mexico is a mixed coniferous forest or broad ecotone between upper elevation spruce-fir communities and lower elevation ponderosa pine communities. A wildfire in 1971 destroyed parts of this climax vegetation at the site, resulting in the formation of two additional community types. Shortly after the fire, the fire scar was aerially seeded with a mixture of higher elevation pasture grasses and legumes. One year later, ponderosa pine tree seedlings were planted 3 - 5 m apart. The resultant secondary succession has developed into a grass-forb community interspersed with small stands of aspen suckers.

Transects placed in each community type to measure cover and density of the species were read in the spring, summer, and fall during the 1976 and 1977 field seasons. Five transects were located in the coniferous forest, 3 in the new-growth aspen, and 16 in the grass-forb community.

Dual sets of transects in the grass-forb community were used to protect against unavoidable loss of the transects nearest the site. These transects were placed in an area previously used as a temporary USFS heliport. A wildfire on the mesa to the southwest of the site in late June of 1976 made it necessary to use this heliport area again. Excessive trampling in the area resulted in these transects being discarded.

After summarizing the plant population field data by community type, we selected 15 dominant species from which to characterize all community types. Only those species that contributed at least 0.1% cover in any community type were selected. The cut-off point of 0.1% cover eliminated those species that did not contribute significantly to the total vegetative biomass, yet it left enough species so that a good cross section of the dominants was found within all three community types.

The grass-forb community is dominated by members of the Gramineae family, especially timothy and orchard grass. These two species, which were part of the seed mixture spread over the area following the burn, are somewhat intolerant of shade. Although they are found in the understory of the aspen community, few are found in the mixed coniferous community.

As expected, the mixed coniferous community is dominated by tree species with a rich understory of shrubs. Douglas fir and white fir make up about three-fourths

of the aerial tree cover within this community type, with the rest being predominantly ponderosa pine.

The third community is dominated by aspen. However, there is an understory of shrubs and grasses that represents species from the mixed coniferous and grass-forb communities.

7.4.2.2. Small Mammals. Herbivores are one of the most abundant forms of wildlife in any ecosystem. Because small mammals feed on a large cross section of plant material, they are easily affected by toxic elements released into the environment. Studies made to determine small-mammal populations surrounding the site give base-line data for one of the potential bioindicators of environmental impacts from the LASL HDR Project.

Small mammals were live-trapped within each community to determine the trap susceptibility of various species and their relative abundance among the vegetation communities. One trap line was set per community, and all three trap lines were run simultaneously during each trapping session.

Two trapping sessions were held during the 1976 field season and one in the 1977 field season. The first session was held in midsummer 1976 before the rodent populations reached maximum numbers. The follow-up trapping session was held in late-summer/early-fall 1976 and 1977 to measure peak populations.

Each trapping session consisted of two nights of prebaiting to familiarize the rodents with the traps, followed by three consecutive nights of trapping. Traps baited with a mixture of rolled oats and peanut butter were set up in the late afternoon and examined the following morning. This schedule prevented animals from being trapped during the hot part of the day and drastically reduced the chances of mortality as a result of heat exhaustion. A large square of cotton in each trap gave the rodent something to burrow in and reduced the death rate from excessive traumatization.

The rodents were classified by species, sex, and age. They were weighed, then marked by a standard technique. Dead specimens were tagged, frozen, and stored. We will use these specimens to compare elemental body burdens with specimens caught in the future if we encounter significant changes in rodent populations or if any environmentally hazardous releases should occur at the HDR site.

In addition to trapping by community type, traps were set in six areas (three downwind and three down the principal drainage from the site) to establish a data base from which to compare future trapping results. These

comparisons will be used to determine if a gradient is established within these rodent populations as a result of the LASL HDR Project, and if the Project is adversely affecting the local environs.

Within the three vegetative complexes, the species trapped most often is the deer mouse. Trapping results show that the grass-forb community contains the highest numbers of small mammals, yet it has the lowest species diversity. The high percentage of trappings indicates that all of the vegetative communities support a substantial population of small mammals.

7.4.2.3. Elk. With establishment of the grass-forb community following the wildfire in 1971, this area has become an important winter range for the Rocky Mountain elk. These large animals, one of the major big-game species of New Mexico, tend to be disturbed by human activity. Therefore, establishment of the HDR site might eventually result in elk leaving the area immediately adjacent to the site.

A stratified random set of permanently marked counting plots for pellet groups (fecal material) was established and read during mid-1976 to document elk usage of this burn area and to create a data base from which to compare future measurements.

The burned area was arbitrarily divided; about 50% of the plots were adjacent to and 50% of the plots were away from the site. Each pellet group counting plot was 4 m wide by 22 m long. Plots were examined by two persons who physically removed all pellet groups from the plots and checked each other's work. It was therefore assumed that few, if any, pellet groups were overlooked. Physically removing the pellet groups, rather than marking them, ensures that future examinations will be made on new pellet groups and that the data collected are related to elk usage of the area after establishment of the HDR Project.

The pellet group counting plots cannot be fully interpreted from the initial set of readings. However, statistical tests between the two areas are nonsignificant, indicating that elk usage within the grass-forb community has been distributed uniformly in the past.

7.4.2.4. Birds. The avian community is perhaps the most mobile component of wildlife found in any ecosystem. Typically, the avian component will change constantly throughout the year because of the seasonal migrations of the various species.

Two extensive plots were established (see Fig. 7-10), one adjacent to and one away from the site, to describe the avian community dynamics and to quantify

Fig. 7-9.

Temperature summary for September 1977.

Fig.7-10.

Location of bird counting transects at the LASL HDR site.

the impacts from the facility on these populations. The study plot adjacent to the drilling site is about 250 m wide by 500 m long. This plot falls mostly within the mixed coniferous community. Parts of this plot have been encroached upon by expansion of the site. The other study plot (open mesa site) is ~1000 m west of the site, is ~150 m wide by 1000 m long, and predominantly falls within the grass-forb community.

Both plots were examined seasonally during 1976. The number and species of birds were recorded, along with personal observations about their suspected activities. These data were reduced into nesting pairs by species per unit area, densities of resident and transient species, and an overall categorization of the avian component of this ecosystem.

Of the many transient bird species recorded during the census period, 41 species were identified. The high elevation and cold weather, however, prevented most birds from nesting and becoming residents.

Table 7-II gives the estimated nesting populations from data collected from both study plots. The greater number of nesting pairs recorded at the HDR

TABLE 7-II

ESTIMATED NESTING POPULATIONS AT THE WELL SITE AND OPEN MESA SITE
(PAIRS PER 40.5 HECTARE)

<u>Species</u>	<u>Well Site</u>	<u>Open Mesa Site</u>
Black-chinned hummingbird	5	4
Common flicker	5	7
Yellow-bellied sapsucker	2	4
Hairy woodpecker	5	2
Traill's flycatcher	2	-
Western wood pewee	5	-
Violet-green swallow	7	-
White-breasted nuthatch	2	-
Pygmy nuthatch	5	-
House wren	5	2
American robin	2	-
Western bluebird	7	2
Warbling vireo	2	-
Yellow-rumped warbler	5	-
Western tanager	12	-
Cassin's finch	2	-
Green-tailed towhee	-	11
Gray-headed junco	<u>7</u>	<u>4</u>
Total	80	36

site can be explained by the community type that dominates the area. The plot adjacent to the site falls within a predominantly mixed coniferous community, whereas the plot away from the site falls within a grass-forb community. The mixed coniferous community should allow more nesting sites and subsequently more nesting pairs of birds.

7.4.3. Conclusion

To date, studies show that the only adverse environmental impact that has resulted from the HDR Project has been the necessary destruction of about 2 hectares (5 acres) of vegetative cover during site construction and associated engineering activities. Upon completion of the 10-MW(t) facility,

studies will be made on two other potential environmental problems (air pollution from gaseous and/or particulate emissions and excessive noise), both potentially of concern in geothermal resource developments.

REFERENCES

1. C. A. Newton, D. J. Cash, K. H. Olsen, and E. F. Homuth, "LASL Seismic Programs in the Vicinity of Los Alamos, New Mexico," Los Alamos Scientific Laboratory report LA-6406-MS (November 1976).
2. W. D. Purtymun and H. S. Jordan, "Seismic Program of the Los Alamos Scientific Laboratory," Los Alamos Scientific Laboratory report LA-5386-MS (September 1973).
3. D. B. Slemmons, "Fault Activity and Seismicity Near the Los Alamos Scientific Laboratory Geothermal Test Site, Jemez Mountains, New Mexico," Los Alamos Scientific Laboratory report LA-5911-MS (April 1975).
4. P. R. Kintzinger and F. G. West, "Seismic Reconnaissance of the Los Alamos Scientific Laboratory's Dry Hot Rock Geothermal Project Area," Los Alamos Scientific Laboratory report LA-6435-MS (July 1976).
5. R. A. Pettitt, "Environmental Monitoring for the Hot Dry Rock Geothermal Energy Development Project, Annual Report for the Period July 1975-June 1976," Los Alamos Scientific Laboratory report LA-6504-SR (September 1976).
6. W. U. Savage, R. W. Ely, and D. Tocher, "Review of the Los Alamos Seismic Monitoring Program in Relation to the Hot Dry Rock Geothermal Project," Woodward-Clyde Consultants (August 30, 1977).
7. H. K. Van Poolen and D. B. Hoover, "Waste Disposal and Earthquakes at the Rocky Mountain Arsenal, Derby, Colorado," J. Pet. Technol. 22, 983-993 (August 1970).
8. F. H. Rainwater and L. L. Thatcher, "Methods for Collection and Analyses of Water Samples," U.S. Geological Survey Water-Supply paper 1454 (1960).
9. K. H. Rea, "Environmental Investigations Associated with the LASL Hot Dry Rock Geothermal Energy Development Project," Los Alamos Scientific Laboratory report LA-6972 (December 1977).

8. PROJECT MANAGEMENT AND LIAISON (G. J. Nunz, Alternate Project Mgr.; J. C. Rowley)

8.1. Introduction

A new technical division, the Geosciences Division, was formed within LASL on February 1, 1977, providing a stronger focus within the Laboratory on earth-sciences-related activities. The HDR Project is a major component of the G-Division program, and also contributes to and augments the Division's research and applied activities in Geochemical Applications, Seismology, and the Geological Sciences.

Technical support for the Project from within LASL is coordinated and directed by Project management, under the direct cognizance of G-Division management, and involves many LASL technical divisions. Major assistance has been provided by the Electronics, Health, Nuclear Chemistry, Materials Science, Computer Sciences, Dynamic Testing, and Field Testing Divisions. Coordination with DOE, and especially with the Division of Geothermal Energy, concerning the HDR Project, is maintained by the G-Division management and Project staff personnel.

Liaison and contacts with geothermal and geothermal-related industries is an explicit and important part of the Project management task. The major thrust of this continuing effort is to identify and locate expertise and hardware within industry, universities, and institutions that can be called upon to solve HDR-specific technical problems, advise in general technological areas, and consult on scientific matters of concern to the HDR Project. In addition, Project management interacts with industry, the federal government, and the academic community regarding the progress and problems of the HDR Project and other geothermal developments. Liaison activities are further described in Sec. 8.3.

8.2. Project Management

Along with changes brought about by the creation of the Geosciences Division, several internal structural and administrative changes were made to the Project itself. It was functionally divided into seven generic tasks, with the management structure altered accordingly. (Project organization is shown in Fig. 8-1.)

Externally, the Project is directed by, and reports to, DOE Headquarters, Division of Geothermal Energy, through the DGE Program Manager. Detailed fiscal and contractual DOE support is provided through its local offices--the

Fig. 8-1.
HDR Project organization (second tier).

Albuquerque Operations Office and the Los Alamos Area Office. Within LASL, the Project reports directly to the LASL Geosciences-Division Office. G-Division, in turn, is under the cognizance of the Associate Director for Research.

Internally, the Project is controlled through the "Project Management and Liaison" Task, under the direction of the Project Manager and his alternate. The Project's remaining six operational tasks (and the "Liaison" subtask), each the responsibility of a task manager, are organized under the Project management, as indicated in Fig. 8-1.

The Project's accounting system has also been modified to correspond with the task levels. Each task is divided into several subtasks, which are more-or-less invariant. The current Project work breakdown structure (WBS) to the sub-task level is given in Table 8-I. Each subtask, in turn, comprises a varying number of specific task elements, which may be initiated and/or completed in a given fiscal year.

TABLE 8-I

HOT DRY ROCK GEOTHERMAL ENERGY DEVELOPMENT PROJECT

WORK BREAKDOWN STRUCTURE (WBS)
(SUBTASK LEVEL)

TASK	SUBTASK	TITLE
1		PROJECT MANAGEMENT AND LIAISON
	10	Management
	11	DOE/DGE Coordination and Reporting
	12	Technology Transfer Activities
2		INSTRUMENTATION AND EQUIPMENT DEVELOPMENT
	20	Ranging Tools
	21	Mapping and Orientation Tools
	22	Reservoir Assessment Tools and Equipment
	23	Vertical Induction Fracture Survey Tool
	24	Cabling and Downhole Signal Conditioning
	25	Instrumentation Calibration and Test Facilities
	26	Environmental Package Development
	27	High-Temperature Directional Drilling Technology
	28	High-Temperature Wellbore Sealing Technology
	29	Engineering Support Services
3		DRILLING AND FRACTURING
	30	(Re)Drilling
	31	Casing and Cementing
	32	Routine Logging and Surveys
	33	Hydraulic Fracturing
	34	Workover Activities
4		RESERVOIR ENGINEERING
	40	Wellbore Ranging Technique Development
	41	Fracture Configuration Technique Development
	42	Reservoir Assessment, Field Measurements
	43	Reservoir Characterization
5		ENERGY EXTRACTION
	50	Facility Preparation
	51	Loop Module Procurements and Prefabrication
	52	System Installation and Checkout
	53	System Operation
	54	Loop Data Reduction
6		HDR RESOURCE ASSESSMENT
	60	Long Valley Resource
	61	Synthesis and Modeling
	62	Alternate Site Selection (FY78 <u>et seq.</u>)
7		ENVIRONMENTAL SURVEILLANCE
	70	Seismic Monitoring
	71	Water Quality/Hydrological Monitoring
	72	Climatological Monitoring

Figure 8-2 shows the FY77 schedule and milestone chart. The successive steps in the execution of task elements, such as fabrication completions, deliveries, tests, and facilities activation, appear as milestones along the time lines related to their respective subtasks. The symbols used in this chart are explained in Table 8-II. Monthly reporting of the achievement of these milestones serves as a measure of progress in the subtask areas.

It should be noted that DGE funds the "Induced Seismicity and Hydrologic Monitoring" task separately from Hot Dry Rock Geothermal Energy Source Development proper. However, it is functionally an integral part of the HDR Project and is therefore administered and reported as a task area.

8.3. Liaison Activities

The large resource potential (see Sec. 2), unique nature of HDR geothermal exploration and extraction technology R&D, and needed industrial participation requires that the HDR Project's concepts, developments, problems, and results be widely disseminated within the geothermal and geothermal-related industries. For effective and expeditious transfer to the private sector, the HDR technology must be made broadly available--both for evaluation of the technical issues and Project results, and for assessment of ultimate economic viability. As in previous years, Project information is disseminated by distribution of technical reports and presentation of technical papers and displays at appropriate technical society and trade association meetings. Briefings and tours of the site and facilities were conducted for visitors, and HDR staff visited industrial research laboratories and installations. In addition, technical personnel of appropriate firms were consulted on problems encountered during the R&D efforts.

Industry was involved with and participated in the Fenton Hill field operations through numerous subcontracts, the largest of which was for the workover redrilling operations in GT-2. This major subcontract required close day-to-day liaison with the firms involved, including those which contributed supporting services and supplied hardware, such as packers, directional drilling, cementing, and casing.

The ongoing goals of the industrial liaison activities for the HDR Project are to:

HOT DRY ROCK GEOTHERMAL ENERGY DEVELOPMENT PROJECT FY 77 SCHEDULE

Fig. 8-2.
Hot Dry Rock Geothermal Energy Development Project FY77 schedule.

TABLE 8-II

MILESTONE SYMBOLS AND CODES FOR HOT DRY ROCK PROJECT SCHEDULES

- = DELIVERY (Procured Item) or FAB. COMPLETED (LASL Fabrication)
= LAB. TEST/CALIBRATION/MEASUREMENT PERFORMED
= MAJOR INSTALLATION COMPLETED
= FIELD TEST, or OPERATIONAL EXPERIMENT, PERFORMED
= KEY ANALYSIS, or MODELING EFFORT, COMPLETED
 * = INFORMAL MONTHLY STATUS LETTER
= MINOR REPORT
= MAJOR REPORT
= REVIEW OR SEMINAR
 (where "n" is a code symbol from the following lists)

- Effort Scheduled
Effort Accomplished
Milestone Scheduled
Milestone Accomplished

Instrument Codes

a - Accelerometers	t - D/H Thermocoup. Ref. Junct.
b - Dump Bailer	v - Fluid Velocity Sensor
c - Vert. Ind. Fract. Log Tool (Crack Detector)	w - Mech. Acoustic Source (Wallbanger)
d - Dewar (LASL)	x - Echo Ranging Sonic Xceiver. (p2)
e - Induced Potential Tool	α - Sonde Orientation Device
f - Detonator D/H Firing Unit	β - D/H Hi-Speed Switching Device (p2)
g - Gyro Survey Tools	γ - Geophones
h - Water Sampler	δ - Dewar (commercial)
i - Inclinator	ε - EM Field Gradient Sensor (p2)
j - Electromagnet Ranging Source	θ - Thermopile Sensor
m - D/H Multiplex Unit	λ - Casing/Tubing Locator (p2)
o - Borehole Optical Monitor (p2)	μ - D/H Amplifiers (p2)
p - Pressure Sonde	σ - High-Energy Spark Source (p2)
q - Heat Sink	φ - Flux Gate Magnetometer
r - D/H Recorder (p2)	6 - Six-Arm Caliper
s - Detonator Surface Firing Unit	

Equipment Codes

- C - Hi. Temp. Cement
 D - Dyna Drill
 E - Heat Exchangers
 G - Directl. Drill Guidance
 H - Hi. Temp. Cable Heads
 K - Hi. Temp. Multicond. Cables
 L - Cemented-In Liner (p2)
 M - Measuring Heads & Readouts
 P - Pumps
 R - Drilling/Pulling/Workover Rig
 T - Trailers (bare)
 II - Open-Hole Packers
 ⊗ - Turbodrill (p2)

Facility/System Codes

- A - Shallow-Hole Acoust. Test Facil.
 I - Instrumentation Trailer
 Q - Living Quarters
 S - Sanitary Facilities
 V - Hi. Temp. Vib. Test Facility
 W - Water Supply/Treatmt. Syst.
 X - Energy-Extraction Surface Syst.
 R - Reservoir/Fracture System
 Σ - Instrument Sonde Test Stand
 Y - Chem. Engrg. Lab. Trailer

Technical Area Codes

- F - Fluid Flow
 J - Heat Transfer
 Y - Complete HDR Extraction Syst.
 Z - HDR Resource
 n - Reservoir Enhancement
 ρ - Rock Properties & Chemistry
 ⊙ - Borehole map
 ψ - Fracture map
 ξ - Fracture modeling

Report Codes

- 1 - Annual Report
 2 - Bimonthly Tech. Summaries
 9 - Schedule 189
 Λ - LPAD
 π - Project Plan (p2)
 Ω - Final Report
 (Inst. or Equip. Devt. Report Code)

Review & Seminar Codes

- E - DGE Quarterly Review
 L - LASL Sr. Management Review
 M - Colloquium/Seminar/Soc. Meeting

- Maintain a broad general awareness of the HDR Project plans, progress, results, and problems, on a national scale.
- Locate or develop sources of specialized expertise, instrumentation, hardware, and services.
- Keep the HDR Project informed concerning progress, problems, and business attitudes in private-sector geothermal development.

In addition, four new liaison elements were initiated:

- An Industrial Staff Member program is being established for the Geosciences Division, including the HDR Project.
- A proposal for support of Maurer Engineering's turbodrill development was submitted to DOE, Division of Oil, Gas and Shale, as a result of continuing efforts to promote a wider industrial interest in cooperative and collaborative HDR projects.
- As a result of growing recognition of the enormous energy potential and broad distribution of HDR resources, DOE-DGE has initiated a federal plan for an HDR program of national scope whose success will require extensive active industrial participation and interaction.
- LASL personnel will serve on the steering committees of the DOE-DGE Geothermal Well Drilling and Completion Technology, the Geothermal Log Interpretation, and Logging Instrumentation Development Programs.

8.3.1. Drilling Technology and Equipment.

The redrilling program for GT-2 presented some unique problems in sidetracking and directional drilling in granite. Rather than a review of problems by a panel of experts, a drilling consultant was hired and worked on-site. His advice, together with our experience, helped in preventing the reoccurrence of many previous drilling problems.

Extended liaison efforts resulted in a much-improved open-hole inflatable packer system (Lynes, Inc.) for 200°C service. Lynes, Inc., feels that it may be possible to upgrade this packer system to 250-300°C. Because this is a difficult development, alternative approaches are being considered. One such approach (Baker Oil Tool) focuses on the development of an advanced, easily cemented and removable, cemented-in (scab) liner. Compression-type formation packers for 250°C and higher are also being explored (for example, Guiberson-Dresser and Brown Oil Tool).

The need for improved directional drilling tools has generated two approaches. An R&D subcontract is in progress (Maurer Engineering, Inc.) to design, fabricate, and test an advanced high-temperature (350°C static, 275°C rotating) directional turbodrill especially matched to hard-rock drilling with roller cone bits. Another company (Smith Tool Co.) has indicated interest in developing a hard-rock bit that will have side-wall cutting capability. Such a bit can potentially be used for sidetracking or deviating a hole in conjunction with use of a whipstock. There is also a need for an improved high-temperature directional drilling steering tool service. Discussions to assure such service for the next HDR drilling campaign have been initiated.

8.3.2. Downhole Instrumentation and Logging

The excellent commercial logging service by Dresser Atlas continued in FY77. Even higher temperature (250-275°C) well-logging requirements are anticipated in the near future (FY79). These may be met by the commercial (Dresser Atlas) development of special hot-hole tools and a truck dedicated for geothermal well-logging services, and by the results of the DGE-Sandia Laboratories Logging Instrumentation Technology R&D Projects.

The FY76 requirements for high-temperature borehole gyroscope (nonmagnetic) surveys in EE-1 and GT-2 (as well as future hotter HDR wells) generated interest in enhancing available hot-hole survey services. Two firms (Sperry-Sun and Eastman-Whipstock) upgraded their equipment (larger heat sinks and improved thermal insulation) and produced 200 and 275°C prototype packages. These upgraded prototype tools were used to determine the absolute and relative trajectories of the EE-1 and GT-2 boreholes. Both survey tools are under active development by their respective firms.

A subcontract [Mechanics Research, Inc. (MRI)] was let for the development and fabrication of a special environmental housing (dewar) for general usage in protecting downhole instrument packages at higher temperatures ($\sim 275^\circ\text{C}$). This unit has been successfully designed and fabricated, and passed acceptance tests at the vendor's facility and in situ tests at the HDR site (see Sec. 3). This multipurpose enclosure should serve as a very useful basic component for other geothermal R&D projects and commercial developers.

8.4. Extent of Industrial Participation

Figure 8-3 is a summary of the extent and type of commercial subcontracting performed for the HDR Project. It serves as one measure of the significant contribution made by the private sector to the LASL HDR efforts. Not represented,

Fig. 8-3.
Project funds expended in commercial subcontracts.

of course, are the many contributions provided gratis, in the form of advice and consultation to the Project, by numerous individuals and firms.

9. LOOKING BACK AND AHEAD (G. J. Nunz, Alternate Project Mgr.)

9.1. FY76TQ and FY77 in Retrospect

The period spanning FY76TQ and FY77 was, from several standpoints, the most successful in the Project's history to date. Despite some comparatively minor setbacks and disappointments, the main aspects of the technical objectives were achieved, and all major schedule milestones were met. From the management standpoint, LASL effected the transition to a more responsive and controllable work breakdown structure and, concurrently, a smoother mechanism of communication between DOE-DGE and the Project was established. Certainly not least significant to all of the parties of interest was the psychological success of seeing the HDR concept actualized in a small working system, vindicating both the faith of LASL's HDR staff and its supporting DGE sponsors and, through national publicity, the trust of the taxpayer.

It is appropriate here to look back - with an overview perspective of the year's results, as described in detail in the foregoing sections - at the progress made against the stated objectives for the year. Those objectives, cited in Sec. 1.3 and repeated here for convenience, were

- (a) to study, by a variety of approaches, the reservoir geometry at the Fenton Hill site;
- (b) given the attainment of an adequate understanding from the results of (a), to take necessary remedial steps to improve the downhole connection; and
- (c) assuming reasonable success in (b), to complete the installations of surface equipment and proceed with the activation of an energy extraction loop.

The difficult problem of accurately defining the geometry of a deep, hot subterranean reservoir yielded significantly to experimental attack during this year. The first part of the problem - that of the geometry of the wellbores themselves - has been reduced to tractable proportions through a combination of LASL-internal developments and work coordinated with industry. The extraordinarily severe downhole environment associated with the Project's boreholes first pointed out the limitations of the originally available commercial wellbore survey equipment. Working with LASL, industry responded by developing and making available

an environmentally upgraded gyroscopic survey service. Meanwhile, during the course of that development, schedule constraints made it necessary for LASL to develop alternative (magnetic and acoustic) ranging techniques. The successful application of these techniques, in combination with subsequent commercial surveys using the upgraded equipment, provided an adequate description of the wellbore geometries and the means for accurately determining the course of any future modifications. In addition, an equally significant benefit of the LASL-developed ranging techniques is that they pointed the way to several approaches for subsequent fracture mapping. The acoustic approach in particular was extremely fruitful. With the use of a relatively unsophisticated implementation - a few discrete detonators as acoustic sources and a triaxial geophone package as a receiver - it was possible to demonstrate the feasibility of sensing a fluid-filled fracture by its propensity to severely attenuate the shear component of a transmitted acoustic wave. This technique, along with other measurements, permitted us to adequately delimit the bounds of the fracture system to formulate a workover strategy. Thus, objective (a) was well satisfied. Later experiments with a more repeatable acoustic source further substantiated the effectiveness of acoustic transmittance and reflectance measurements in this application. As a result an improved acoustic transceiver tool is being developed.

With the downhole geometry reasonably well established, it was clear that some remedial action was required because the two wellbores did not intersect the same fracture. First, chemical leaching was tried in an attempt to etch a channel through the granodiorite by selectively dissolving silica with sodium carbonate solution. Although about 1000 kg (1 ton) of silica were extracted, this approach failed to provide the required connection. Consequently, a workover redrilling program was executed. By the end of June, a usable connection was obtained, meeting objective (b). In addition, the drilling program provided invaluable experience with sidetracking and directional drilling in hot granite, which will prove useful in creating and modifying subsequent reservoirs.

Once the reservoir workover was completed, installation and checkout of the surface equipment needed to form the closed energy-extraction loop proceeded apace. With the exception of the primary circulation pumps and the permanent Controls and Data Acquisition (CDA) trailer, which were delayed, the loop was ready for activation in September. We therefore decided to activate the loop and to run the initial (nominal 100-h) segment of the planned 10 000-h cumulative experimental demonstration with rented pumping equipment and a jury-rigged CDA

trailer. This was accomplished just before the close of the fiscal year, satisfying objective (c) and meeting the single most significant milestone of the year.

In addition to progress made in the technical fronts of initial feasibility demonstration and instrument development, FY77 was a halcyon year with respect to technology transfer and public imaging of the Hot Dry Rock Project. Many companies, previously uninterested or only casually interested in HDR, came forth for serious discussions of ways to participate. The first spectacular production of steam (in purging the newly formed reservoir of residual debris) and the initial operation of the loop were well covered by the news media. This coverage precipitated a continuing series of enquiries and visitors from industry, academia, and government.

9.2. Future Plans

Successful activation of the Fenton Hill energy-extraction loop at the close of FY77 clearly demonstrated the initial technical feasibility of LASL's concept for extracting the geothermal energy of hot dry rock. One major thrust of the Project through FY78, and part of FY79, will be to answer the many questions dealing with the long-term operation and thermochemical stability of such a system, which ultimately bear on the economics of a commercial-scale HDR system. The relatively small reservoir now established at Fenton Hill should demonstrate all the significant effects in a practically short time period. The Project plan, as indicated in Fig. 9-1, is to continue to operate the loop in months-long segments for a cumulative period of up to 10 000 h (and possibly longer, if useful information is still being acquired at that time). It is anticipated that the planned rate of energy extraction from this small system will accelerate both the rate of drawdown and the onset of any thermal-stress cracking in the reservoir. The hiatuses between operating segments will provide time for data synthesis and modeling, empirical data on reservoir recovery, opportunities for *in situ* tests of new or modified instruments, and experience with system stop and restart procedures. The major issues to be addressed by the long-term operation of the loop are:

- rate of drawdown
- rate of recovery from shutdown
- water loss rate vs time
- occurrence of thermal-stress cracking augmentation
- long-term geochemistry and incidence of scaling

Fig. 9-1.

Hot Dry Rock Geothermal Energy Development Project FY78-79 activities.

- stop/restart phenomena
- problems of interfacing with thermal-electric energy conversion systems.

With regard to the latter, provisions will be incorporated in the system during one of the inactive periods for diverting a part of the heat-exchanger flow to a small experimental electric generating unit. The power produced will be used to offset part of the demand from the local utility. One type of converter (a binary fluid-cycle unit) is being procured for the Project; other types will be tested on an as-available loan basis. Appropriate seismic, hydrologic, and climatologic monitoring will, of course, accompany the operational program.

Another major thrust of the Project in FY78 will be toward development of reservoir mapping tools and techniques, with emphasis directed toward those effective with only a single wellbore. A multiple-independent-arm tactile sensor and a borehole optical survey system are being pursued for at-wellbore mapping, while a polymodal acoustic transceiver tool is being developed for far-field mapping. Preliminary investigation of the technical feasibility of still

more sophisticated techniques is also planned. Another part of the overall instrument development program is the eventual establishment of the Deep-Wellbore Equipment Test Site (DWETS) - a dedicated downhole test laboratory - at Fenton Hill. DWETS planning and possible initiation of any long-lead procurements will be begun in FY78. Workover of the GT-2 wellbore to final laboratory configuration will be deferred until the latter part of FY79.

Planning of the larger Phase 2 energy-extraction system will also begin in FY78 and continue into FY79. Drilling of the first wellbore (EE-2) for this Phase 2 system is planned for mid-FY79 (workover of GT-2 for the DWETS will piggyback on this drilling operation), with mapping and fracturing operations following.

A program of formal economic system studies will begin in FY78 with a small-scale preliminary study to bound the problem, indicate gaps and weaknesses in the data base, and delineate areas for subsequent emphasis. Using the results of this preliminary study for guidance, we plan to conduct a structured and comprehensive systems study in FY79-80 with a high degree of industrial involvement.

Subsequent HDR site selection will continue to move ahead in FY78. DGE and LASL will jointly evaluate and select several candidate sites for more intensive geologic and geophysical investigation. LASL will then contract for the required measurements at these sites, beginning in the second quarter of FY78.

A new activity to be undertaken in FY78 is the planning of a Federal HDR Program of national scope, which will include the LASL HDR Project as its first major element. DOE/DGE has asked the LASL HDR staff to assist in structuring and time-scaling the program, and in preparing the detailed planning documentation. This effort was initiated just before the close of FY77, and the first detailed plan is expected to be completed by the end of FY78.

APPENDIXES

APPENDIX A

PUBLICATIONS

June 1976 to September 1977

R. A. Heimlich, "Morphology of Zircons from Precambrian Rocks Penetrated by Geothermal Test Hole GT-2," Los Alamos Scientific Laboratory report LA-6433-MS (July 1976).

P. R. Kintzinger and F. G. West, "Seismic Reconnaissance of the Los Alamos Scientific Laboratory's Dry Hot Rock Geothermal Project Area," Los Alamos Scientific Laboratory report LA-6435-MS (July 1976).

R. A. Pettitt, "Environmental Monitoring for the Hot Dry Rock Geothermal Energy Development Project, Annual Report for the Period July 1975-June 1976," Los Alamos Scientific Laboratory report LA-6504-SR (September 1976).

W. D. Purtymun, W. H. Adams, A. K. Stoker, and F. G. West, "Water Quality in Vicinity of Fenton Hill Site, 1975," Los Alamos Scientific Laboratory report LA-6511-MS (September 1976).

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

J. Balagna, R. Charles, and R. Vidale, "Geothermal Chemistry Activities at LASL, January-December 1975," Los Alamos Scientific Laboratory report LA-6448-PR (October 1976).

Carl A. Newton, Dan J. Cash, Kenneth H. Olsen, and E. Fred Homuth, "LASL Seismic Programs in the Vicinity of Los Alamos, New Mexico," Los Alamos Scientific Laboratory report LA-6406-MS (November 1976).

W. C. Overton, Jr., "Feasibility of Detecting Artificial Magnetic Anomalies in Hydrofractured Rock by Superconducting Gradiometer-SQUID Systems," Los Alamos Scientific Laboratory report LA-6626-MS (December 1976).

J. N. Albright and R. J. Hanold, "Seismic Mapping of Hydraulic Fractures Made in Basement Rocks," Proc. ERDA Symp. on Enhanced Oil & Gas Recovery, Tulsa, 1976 (ERDA, Washington, DC, 1976) Vol. 2 - Gas, pp. C-8/1-13.

R. D. McFarland and H. D. Murphy, "Extracting Energy from Hydraulically Fractured Geothermal Reservoirs," Proc. 11th Intersociety Energy Conversion Engineering Conf., State Line, Nevada, September 12-17, 1976, Vol. 1, pp. 828-835.

U. Nitsan and T. J. Shankland, "Optical Properties and Electronic Structure of Mantle Silicates," Geophys. J. R. Astron. Soc. 45, 59-87 (1976).

R. J. O'Connell, T. J. Shankland, and R. C. Lieberman, "Physical Properties of the Materials of the Earth's Interior," in Geodynamics Progress and Prospects, Charles L. Drake, Ed. (American Geophysical Union, Washington, DC, 1976), pp. 94-99.

John C. Rowley, "Geothermal Energy Development," Phys. Today 30, 37-45 (January 1977).

S. N. Ehrenberg and P. C. Perkins, "Electron Microprobe Analyses of Minerals in Precambrian Rocks at the Los Alamos Scientific Laboratory Geothermal Test Site, Jemez Mountains, New Mexico," Los Alamos Scientific Laboratory report LA-6695-MS (February 1977).

S. N. Ehrenberg, P. C. Perkins, and J. Balagna, "Preliminary Studies of the Alteration of a Granite by an Artificial Hydrothermal System," Los Alamos Scientific Laboratory report LA-6696-MS (February 1977).

R. Lee Aamodt, "Hydraulic Fracturing in GT-1 and GT-2," Los Alamos Scientific Laboratory report LA-6712 (February 1977).

Paul R. Kintzinger, George A. Jiracek, Francis West, Geoffrey Dorn, and H. Truman Holcomb, "Electrical Measurements at Los Alamos Scientific Laboratory's Geothermal Project," presented at the 46th Annual International SEG Meeting, Oct. 24-28, 1976, Houston, TX, published in Geophys. 42 (February 1977).

Carlos L. V. Aiken, A. William Laughlin, and Francis G. West, "Residual Bouguer Gravity Anomaly Map of Northern New Mexico," Los Alamos Scientific Laboratory map LA-6737-MAP (March 1977).

F. G. West and T. J. Shankland, "Exploration Methods for Hot Dry Rock: Report of the Panel Held June 22, 1976," Los Alamos Scientific Laboratory report LA-6659-MS (March 1977).

J. W. Tester; C. E. Holley, Jr.; and L. A. Blatz, "Solution Chemistry and Scaling in Hot Dry Rock Geothermal Systems," Proc. 83rd National Meeting AIChE, Houston, March 21-25, 1977.

C. E. Holley, Jr., L. A. Blatz, J. W. Tester, and C. O. Grigsby, "The Interaction of Granite with Aqueous Sodium Carbonate," Geothermal Resources Council, TRANSACTIONS 1, (May 1977).

Roland A. Pettitt, "Los Alamos Hot Dry Rock Geothermal Energy Project," Geothermal Resources Council, TRANSACTIONS 1, 241-242 (May 1977).

"Hot Dry Rock Geothermal Energy: Status of Exploration and Assessment: Report No. 1 of the Hot Dry Rock Assessment Panel," Energy Research and Development Administration Division of Geothermal Energy report ERDA 77-74 (June 1977).

D. G. Brookins, R. B. Forbes, D. L. Turner, A. W. Laughlin, and C. W. Naeser, "Rb-Sr, K-Ar, and Fission-Track Geochronological Studies of Samples from LASL Drill Holes GT-1, GT-2, and EE-1," Los Alamos Scientific Laboratory report LA-6829-MS (June 1977).

H. N. Fisher, "An Interpretation of the Pressure and Flow Data for the Two Fractures of the Los Alamos Hot Dry Rock (HDR) Geothermal System," Proc. of the 18th US Symposium on Rock Mechanics, Keystone, Colorado, June 22, 1977.

R. Trice and N. Warren, "Preliminary Study on the Correlation of Acoustic Velocity and Permeability in Two Granodiorites from the LASL Fenton Hill Deep Borehole, GT-2, Near the Valles Caldera, New Mexico," Los Alamos Scientific Laboratory report LA-6851-MS (July 1977).

Harold L. Overton and Robert J. Hanold, "Geothermal Reservoir Categorization and Stimulation Study," Los Alamos Scientific Laboratory report LA-6889-MS (July 1977).

P. R. Kintzinger, F. G. West, and R. L. Aamodt, "Downhole Electrical Detection of Hydraulic Fractures in GT-2 and EE-1," Los Alamos Scientific Laboratory report LA-6890-MS (July 1977).

Jeannette J. Mortensen, "The LASL Hot Dry Rock Geothermal Energy Development Project," Los Alamos Scientific Laboratory mini-review 77-8 (July 1977).

Roland A. Pettitt, "Planning, Drilling, Logging, and Testing of Energy Extraction Hole EE-1, Phases I and II," Los Alamos Scientific Laboratory report LA-6906-MS (August 1977).

A. W. Laughlin and A. Eddy, "Petrography and Geochemistry of Precambrian Rocks from GT-2 and EE-1," Los Alamos Scientific Laboratory report LA-6930-MS (August 1977).

H. D. Murphy, R. G. Lawton, J. W. Tester, R. M. Potter, D. W. Brown, and R. L. Aamodt, "Preliminary Assessment of a Geothermal Energy Reservoir Formed by Hydraulic Fracturing," Soc. Pet. Eng. 17, 317-326 (August 1977).

J. W. Tester and M. C. Smith, "Energy Extraction Characteristics of Hot Dry Rock Geothermal Systems," Proc. 12th Intersociety Energy Conversion Engineering Conference, Washington, DC, August 28 - September 2, 1977 (American Nuclear Society, La Grange Park, Illinois, 1977), Vol. 1, pp. 816-823.

W. C. Maurer, J. D. Nixon, L. W. Matson, and J. C. Rowley, "New Turbodrill for Geothermal Drilling," Proc. 12th Intersociety Energy Conversion Engineering Conference, Washington, DC, August 28 - September 2, 1977 (American Nuclear Society, La Grange Park, Illinois, 1977), Vol. 1, pp. 904-911.

J. Albright, L. Aamodt, and R. Potter, "Definition of Fluid-Filled Fractures in Basement Rocks," Proc. 3rd ERDA Symp. on Enhanced Oil and Gas Recovery and Improved Drilling Procedures, Tulsa, 1977 (ERDA, Washington, DC 1977), Vol. 2 - Gas and Drilling, pp. E-2/1-2/8.

A. W. Laughlin, R. A. Pettitt, F. G. West, A. C. Eddy, J. P. Balagna, and R. W. Charles, "Status of the Los Alamos Experiment to Extract Geothermal Energy from Hot Dry Rock," Geol. 5, 237-240 (1977).

Uzi Nitsan, "Electromagnetic Emission Accompanying Fracture of Quartz-Bearing Rocks," Geophys. Res. Lett. 4, No. 8, 333-336 (1977).

Roland A. Pettitt, "Los Alamos Hot Dry Rock Geothermal Energy Project," Tex. Civil Eng. 47, No. 7, 8 (1977).

T. J. Shankland, "Elastic Properties, Chemical Composition, and Crystal Structure of Minerals," *Geophys. Surv.* 3, 69-100 (1977).

F. G. West and T. J. Shankland, " Hot Dry Rock: Widespread but Invisible," *EOS Trans. AGU* 58, 299-302 (1977).

APPENDIX B

FIELD EXPERIMENTS CONDUCTED DURING FY76T AND FY77

Experiment No.	Date Executed	Description	Results
Reservoir Characterization and Development			
137	11/1-11/76	To provide a background flow for the Na ₂ CO ₃ leaching equipment. Secondary objectives were to obtain time variations of the GT-2 effluent water chemistry, to obtain long-term flow impedance values to test the water treatment equipment, and to determine fracture volume and residence time using a sodium-fluorescein dye tracer.	All equipment functioned properly, and test parameters were established. Preparations were made to proceed with the Na ₂ CO ₃ leaching.
138	11/11-18/76	To leach quartz in fracture with Na ₂ CO ₃ solution. EE-1 was shut in on 11/17 at 8.3 MPa (1200 psi). Venting through GT-2 was monitored, and sampling of the effluent continued for several days.	All equipment functioned properly and preliminary test results are now being summarized.
144	10/7/76	To log temperature of GT-2 from ground level to bottom hole with thermopile sensor.	Complete temperature log was obtained.
145	10/14/76	Ranging experiment. To obtain more precise measurements of acoustic velocity in the granite rock at depths of previous experiments. Detonators were fired at 2750, 2770, 2863, and 2770 m (9019, 9089, 9392, and 9089 ft).	Good signals were recorded with the geophone package in GT-2. Computer analysis in progress.
144B	10/21/76	To log temperature of EE-1, again with thermopile sensor.	Complete temperature log was obtained.
146	10/27/76	Ranging experiment. To confirm P-wave travel time of previous experiments. Detonators were fired in EE-1 at 2768, 2732, 2696, 2658, 2621, and 2585 m (9083, 8964, 8845, 8719, 8600, and 8481 ft).	Good signals were recorded with the geophone package in GT-2. The locking arm in the geophone package would not retract, preventing the package from being lowered in the borehole. Readings could be obtained by moving the package up the hole only.
149	12/2/76	Magnetic ranging test. To detect the relative positions of the GT-2/EE-1 boreholes between 2943 and 2967 m (9655 and 9735 ft) in EE-1. Bar magnet was lowered in EE-1 and Sperry-Sun survey compass was lowered in GT-2 to 2938 m (9640 ft).	Magnet position determined from compass response. Bottom region of EE-1 was found by this method to be east of GT-2.
151	12/10/76	Magnetic ranging experiment. Used Scientific Drilling Control surface readout flux-gate magnetometer.	Leak in cable head of magnetometer. Experiment terminated.
152	1/4/77	To mark logging cable (magnetically) and tag casing in EE-1 with casing locator.	Cable on EE-1 logging rig calibrated and depth to bottom of casing measured.
	1/7/77	To mark logging cable and tag casing in GT-2.	Cable on GT-2 logging rig calibrated and depth to bottom of casing measured.
150	1/12-13/77	Ranging experiment. Used large (Mark Products) geophone package (modified for better acoustic coupling). Geophone sonde positioned in EE-1 and detonators fired in GT-2.	Ranging data improved significantly with large modified geophone package. Relative hole position determined.

Experiment No.	Date Executed	Description	Results
153	1/19/77	Electromagnetic ranging. To confirm relative direction of boreholes. Electromagnet source inserted in EE-1 with compass in GT-2.	Electromagnet damage during assembly in EE-1 tower. Test postponed.
154	1/27/77	To log temperature of EE-1 from 2285 to 3050 m (7500 to 10 000 ft) during flow test. To investigate fluid entry paths in EE-1.	Dewar in downhole sonde ruptured. Test terminated. Repeated attempts to run experiment but Dewar ruptured each time. Lab investigation under way.
157	1/28/77	To survey boreholes. Used Eastman gyro survey with heat-hardened gyroscopic survey tool.	Surveyed GT-2 and EE-1 with the Eastman gyro using LASL wire line.
154E	3/1/77	To survey temperature of EE-1. Used thermopile temperature sonde with stainless steel Dewar for ice-bath reference junction.	Temperature profile obtained for EE-1.
159	3/8/77	Shear-shadowing experiment. To help determine extent of fracture upward from EE-1 originating at 2941 m (9650 ft) to aid re-drilling plans. Large LASL geophone package lowered down GT-2 and positioned at 2757 m (9045 ft). Three detonators fired in EE-1 at 2755 m (9038 ft) to obtain background readings. Series repeated with fracture pressurized.	Shear phase of detonator signals measured in GT-2 at this depth during pressurization; showed moderate attenuation relative to the unpressurized case.
159B	3/9/77	Experiment repeated with the geophone package in GT-2 at 2604 m (8544 ft) and detonators fired in EE-1 at 2587 m (8487 ft).	Significant attenuation of the shear phase was observed at this position, but less than that of Exp. 159C. Chosen as the target area for the re-drilling of GT-2.
160	3/16/77	IP measurement experiment. To determine the upward extent of the fracture at 2743 m (9000 ft) in EE-1. The current electrode was lowered in EE-1 to 2957 m (9700 ft) and voltage probe surveyed GT-2 between 2255 and 2775 (7400 and 9100 ft). Measurements made with the fracture deflated and pressurized.	The potential measured in GT-2 decreased markedly in interval 2590 - 2745 m (8500 - 9000 ft) when the fracture was pressurized.
159C	3/21/77	Continuation of Exp. 159. The large geophone package in GT-2 at 2680 m (8794 ft) and the detonators fired in EE-1 at 2670 m (8762 ft). Background test was repeated with fracture inflated at 11.3 MPa (1640 psi).	This position showed the maximum attenuation of the shear phase.
159D	3/22/77	Continuation of Exp. 159 with geophone package in GT-2 at 2476 m (8123 ft) and detonator package in EE-1 at 2438 m (8000 ft).	Insignificant attenuation of the shear phase was observed. Considered to be the background experiment.
161	5/11/77	Low pumping rate flow test. To attempt to improve impedance at GT-2A fracture intersection. GT-2 (with Lynes packer set) and EE-1 were pumped.	Successful setting of high-temperature Lynes packer in the GT-2A open hole. Communication established through fracture system.
162	5/13/77	Fracture dilation and extension flow test. To improve communication and reduce impedance to flow. Repeat of Exp. 161 at higher pumping rate. Temperature log was run to find fluid entry locations in the newly drilled section of GT-2A.	Packer again operated successfully in GT-2A. Apparent impedance of ~ 20 bar.s/L measured under venting conditions.

Experiment No.	Date Executed	Description	Results
163	5/17/77	Loop simulation experiment. To measure steady-state system impedance. Pumped into EE-1 at ~ 800 L/min (5 bbl/min).	Measured steady-state impedance of ~ 40 bar·s/L. (Decision made to redrill for intercept at lower elevation.)
164	5/23/77	To monitor pressure in EE-1 while drilling to observe possible fracture intersection.	Pressure monitor will continue throughout drilling to intersection.
165	5/31/77	System flow-impedance measurement, EE-1/GT-2B. To test the GT-2B to EE-1 connection. Low-pressure and high-pressure impedance value to be obtained.	An impedance of 15 - 18 bar·s/L was measured.
166	6/1-3/77	Pressurization and fracture dilation at 2667 m (8750 ft) in GT-2B. To improve impedance. Lynes packer was run in GT-2 and set at 2654 m (8706 ft). Pumped into GT-2 at an initial flow rate of 160 L/min (1 bbl/min) and gradually increased to 800 L/min (5 bbl/min). EE-1 then shut in and plumbed for inflow at 378 L/min (100 gpm)	With EE-1 pumped, temperature of water discharged from GT-2 reached 130°C with a back pressure of 0.5 MPa (70 psi). Final impedance of ~ 9.5 bar·s/L was measured.
167	6/7-8/77	To monitor pressure in EE-1 while continuing to drill in GT-2. (A sudden pressure change could be used as indicator of when to initiate coring.)	A significant pressure response was noted; coring procedure was initiated.
168	6/9/77	Dynamic temperature logs (under GT-2 and EE-1 fluid injection). To determine the flow rates into the fracture intersections in GT-2B and to determine whether the high-pressure fracture extension (Exp. 166) had affected EE-1 connections.	Four temperature logs were successfully run in GT-2B and intersection parameters measured. Temperature logs were also run in EE-1 under inflow with GT-2 shut-in.
170	6/17/77	Reverse flow test. Pumped into GT-2 at 127 - 160 L/min (0.8 - 1.0 bbl/min).	Typical fracture parameters were obtained, indicating a GT-2B connected fracture distinct from the EE-1 fracture and connected to it.
172A	8/8/77	To measure fracture impedance by pumping EE-1 at successive flow rates of 223, 360, and 537 L/min (59, 95, and 142 gpm) with GT-2 shut-in. Maximum pumping pressure was 9 MPa (1300 psi).	Diffusion parameters were obtained which yielded a pressure dependence similar to that obtained in Exps. 111 and 114.
172C	8/18/77	With EE-1 shut-in, GT-2 was pumped at successive flow rates of 318, 477, 636 L/min (2, 3, and 4 bbl/min) to a maximum pressure of 9 MPa.	Results indicate a fracture size similar to that determined in Exp. 170. A wellbore-to-fracture impedance was obtained.
176	9/26/77	To check out surface circulation loop facility and test the downhole reservoir in preparation for long-term operations.	Estimates of water loss, temperature drawdown, and system impedance were obtained from the 100-h flow test of the reservoir.

Instrumentation Development

101	6/28/77	To determine internal sonde pressure when ice-filled Dewar is used with thermopile sonde. Pressure transducer was installed in thermopile sonde during temperature survey in EE-1 to 3050 m (10 000 ft).	The internal pressure of the sonde increased by 0.14 MPa (20 psi). This pressure was much lower than expected and was generated only by increase in temperature.
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Experiment No.	Date Executed	Description	Results
102	6/29/77	To determine the performance of a high-temperature pressure transducer. Hydrostatic pressure survey of EE-1 to 3050 m (10 000 ft).	The pressure transducer met all specifications and will be used in future experiments to measure buoyancy.
103	7/1/77	To test high-temperature fluid sample tool and fluid injector tool. Red and blue dyes were injected at 2865 and 2715 m (9400 and 8900 ft), respectively, in EE-1. The fluid sampler was developed to obtain a sample of the dye at each depth.	The fluid injector operated satisfactory and ejected dye at prescribed depths. The fluid sampler, however, retrieved the first sample only. A motor shaft coupling that failed will be modified.
104	7/12/77	To obtain a temperature survey of EE-1 with the single-conductor wire line equipment. A thin-walled thermistor probe was used for the temperature measurement.	The temperature measurement was erratic. The thermistor probe will be modified to work on the single-conductor wire line. Experience was gained with the portable Mathey logging rig.
105	7/18/77	To compare the response of a 3.2-mm-diam thermistor probe with the thermopile. EE-1 was surveyed with both probes for temperature profile at 45 m/min (150 ft/min) logging rate.	The small sheathed thermistor probe, using a constant-current source excitation, showed excellent response while surveying the borehole in the downhole direction.
109	8/10/77	To test high-temperature switch (electro-mechanical) to sequentially fire detonators downhole.	The switch solenoid required too much current to activate over the long armored instrumentation cable. A coil "pull in" current < 0.5 A may be required.
111	8/15/77	To determine the electrical characteristics of the multiconductor armored instrument cable (six twisted, shielded pairs plus center coax). The cable was lowered into GT-2 and initial resistance measurements made.	The overall outer PFA teflon jacket was penetrated by moisture, resulting in the twisted-pair shields being shorted to armor. A kink in the cable at the slip ring assembly resulted in insulation breakdown when 500 Vdc was applied. Cable returned to manufacturer.