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Hot Dry Rock Geothermal Energy Development Program

Semiannual Report

October 1, 1978—March 31, 1979

MASTER

University of California

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ABSTRACT

The Department of Energy, Division of Geothermal Energy, established a national Hot Dry Rock Geothermal Energy Development Program at the Los Alamos Scientific Laboratory in the Geosciences Division on October 1, 1978. This Program continues to investigate the potential of energy extracted from hot dry rock (HDR) as a commercially feasible alternate energy source.

Run Segments 3 and 4 were completed in the prototype reservoir of the Phase I energy-extraction system at Fenton Hill, New Mexico. Results of these tests yielded significant data on the existing system and this information will be applicable to future HDR systems. Plans and operations initiating a Phase II system are underway at the Fenton Hill site. This system, a deeper, hotter commercial-size reservoir, is intended to demonstrate the longevity and economics of an HDR system.

Major activity occurred in evaluation of the national resource potential and in characterizing possible future HDR geothermal sites. Work has begun in the institutional and industrial support area to assess the economics and promote commercial interest in HDR systems as an alternate energy source.

1. EXECUTIVE SUMMARY

This report describes work on the development of hot dry rock (HDR) as a geothermal energy source conducted by the Los Alamos Scientific Laboratory (LASL) during the first half of FY79 (October 1, 1978 through March 31, 1979). The successful demonstration in FY78 of the technical feasibility of recovering energy from the HDR geothermal energy extraction system at the Fenton Hill, New Mexico, site led to the establishment of new, and continuation of ongoing, programmatic activities for FY79. October 1, 1978 marked the expansion of the Fenton Hill Project into an HDR Geothermal Energy Development Program of national scope. The HDR Program Management Office was established at LASL in the Geosciences Division by the Department of Energy (DOE), Division of Geothermal Energy (DGE).

Experimentation at the Fenton Hill site continued. Run Segment 3 of Phase I was conducted as a second long-term closed-loop reservoir experiment to determine whether continued flow under high mean reservoir pressure (via imposed high back pressure) would increase the effective heat transfer area and decrease the system flow impedance. The experiment was terminated prematurely, due to a serious leak that developed behind the casing in EE-1, but it was observed that the reservoir flow impedance declined significantly in the high back-pressure mode of operation.

A series of workover and testing operations was undertaken. Specific operations included recementing of EE-1, testing of fracture initiation methods (Kine-Frac), flow testing using radioactive tracers, and massive hydraulic fracturing. Analysis of the data obtained from these experiments continues, together with planning for a fourth run segment to evaluate the overall effect upon the existing system of those operations. Data from these tests will aid in producing more efficient systems in the future.

The detailed planning and preparations for Phase II at Fenton Hill site are now also underway. Phase II (a larger, hotter reservoir) is intended to demonstrate the longevity and investigate the economics of an HDR system approaching a commercially useful size. The specifications for the drilling rig were completed and submitted for bid, and a contract was subsequently let to Brinkerhoff-Signal Company. A technical manager has been appointed, the rig has been inspected, accepted, and mobilized at the site.

Environmental monitoring has continued around the Fenton Hill site. Extensive seismological, hydrological, biological, and climatological monitoring has shown no adverse environmental impact. An interim Environmental Analysis, covering Fenton Hill operations through Phase II, was completed and published. A formal Environmental Assessment is being prepared by Oak Ridge National Laboratory and should be published by the end of the fiscal year.

Other analytical and experimental support included collection and analysis of acoustic emission data and further studies on rock mechanics and rock-fracturing processes. A computer program (GEO) has been written and successfully applied to certain water-flow and heat-exchange problems. Six experiments were conducted using radioactive tracers to measure water movement through the existing wellbores and fracture system. The results from these experiments have provided valuable information about the downhole reservoir and can be applied to more advanced systems.

Continuing efforts, both at LASL and through industrial contractors, have resulted in significant advances in several areas of downhole instrumentation and equipment development. The three-independent-arm caliper tool was designed to define the profile of geothermal boreholes such as those at Fenton Hill. Sensitive enough to detect accurately 1-mm variations along the borehole wall, it was used to determine where a hydraulic fracture intersected the boreholes and to assess the integrity of the borehole casing. A Worth Well spinner tool, modified by LASL to apply to Fenton Hill needs, was used to investigate the flow of the geothermal fluid throughout the system. The LASL adaption of this high-temperature downhole flowmeter improved the sensitivity, repeatibility, and resolution of the tool.

A controlled environment enclosure, the Dewar, a primary heat transfer barrier, was designed to protect instruments from the hostile downhole environment of the geothermal wellbore. An injector sonde was developed by LASL to inject radioactive tracers into the boreholes to study water circulation. A high-temperature downhole detonator, using an acoustic geophone, was designed to map the hydraulic fracture and determine borehole locations.

Major activity occurred in evaluating the resource potential and in selecting prospects for new HDR geothermal sites during the first half of FY79. The geologic activities were designed to define areas of the US where HDR geothermal extraction techniques might be used, obtain an estimate of the potential utilization in these areas, calculate the amount of thermal energy that might be ultimately available, and locate specific sites for testing the HDR method under various geologic conditions. In evaluating resource potential, HDR program activities have concentrated on stimulating the production of high-quality heat-flow measurements. A meeting at LASL in December 1978 was attended by heat-flow experts from the US Geological Survey (USGS) and many universities. Various geophysical methods, such as magnetotellurics, gravity, and aeromagnetics are used to define areas of high heat flow. Approximately ten areas in the US were examined for site prospects during FY78 and the first quarter of FY79. An HDR Site Selection Advisory Panel met (February 1 and 2, 1979) and ranked the prospects presented based on evaluation of data obtained from these areas. Two areas -- one near Boise, ID and the other on the Delmarva peninsula -- were selected for detailed geological and geophysical investigation during the rest of FY79 and early FY80. Reconnaissance work continues on the remaining eight and several additional areas.

Work in the institutional and industrial support area has grown extensively. Bechtel National, Inc. was selected as the subcontractor to conduct a nationwide 2-yr study on "an Industrial Assessment of the Economic Feasibility of Hot Dry Rock Geothermal Systems." A professional legal study is planned relating to the litigatory question of ownership of HDR resource, to suggest appropriate definitions for states now comtemplating geothermal legislation. A study is planned on environmental acceptability; the results will have widespread distribution and serve as a basis for obtaining industry and public acceptance of HDR industrialization.

The HDR Program issued $675 000 in subcontracts during the first half of FY79, most of which were ancillaries related to the Phase II drilling at the Fenton Hill site.

The HDR Program Management Office was established October 1, 1978 and assumed the responsibility for planning, management, fiscal control, and reporting of HDR activities both at LASL and elsewhere. Gregory J. Nunz was appointed as the Program Manager. W. Porter Grace, DOE/ALO Special Programs Division, was named Associate Program Manager to provide a direct involvement by DOE/ALO. A national HDR Program Development Council representing industry, academia, and government was organized to advise the Management Office. The management plan was approved by DOE/ALO, DOE/DGE, and LASL/G-Division on March 5, 1979.

Formal quarterly reviews of program progress, planning, and budgets were held on December 20, 1978 and March 14, 1979. The HDR annual report was published and distributed. The HDR Program Plan, which will detail operational tasks and objectives for the technical and economic evaluation of HDR Geothermal Energy systems, is in preparation.

2. INTRODUCTION

Progress of the Hot Dry Rock Geothermal Energy Development Program during the first six months of FY79 is briefly reported here. Greater detail and perspective will be presented in the next annual report covering the entire year.

During FY78, the technical feasibility of recovering energy from a manmade HDR geothermal energy system was successfully demonstrated for the first time in the Fenton Hill Phase I system. This result and the experience gained and questions raised in achieving it led to establishment or continuation in FY79 of programmatic activities in the following major areas:

- Expansion of the project into an HDR Geothermal Energy Development Program of nationwide scope with the Program Office based at LASL, and field-managed jointly by LASL and DOE/ALO under the aegis of the DOE/DGE Program Director. The Program will investigate both the commercial viability of HDR systems and their potential usefulness in the varied geologic, geopolitical, and environmental situations in which they might be produced across the United States.
- Development of a larger, deeper, hotter Phase II system at Fenton Hill to demonstrate the longevity and investigate the economics of an HDR system approaching a commercially useful size.
- Continued experimentation with the existing Phase I system and continuing analysis and evaluation of results from it, with the objectives of achieving better understanding of that system and of learning how to create more efficient systems in the future.
- Further development of the equipment, instrumentation, techniques, and analyses required to produce new systems, understand and predict their behavior, and monitor their operation.

Individual activities contributing to progress in these areas are discussed in the following sections.

3. SITE I DEVELOPMENT

3.1. Run Segment 3 of Phase I

The high back-pressure heat extraction test Expt. 186, was intended as a second long-term, closed-loop, reservoir experiment. It differed from the previous 75-day Phase I Heat Extraction Experiment in that a high back pressure was established and maintained in GT-2B. Furthermore, the flow duration was considerably shorter (28 days) and the initial mean reservoir temperature considerably lower. The experiment was terminated due to an increasing rate of flow behind the EE-1 casing above ~2740 m (9000 ft), which suggested a progressive deterioration of the cement between the casing and the EE-1 wellbore.

The primary objectives of Expt. 186 were to see if continued flow under the imposed high back-pressure in GT-2B would: (a) increase the effective heat transfer area and (b) decrease the system flow impedance. During the experiment the EE-1 surface pressure was kept quite constant at ~91.7 bar (~1330 psi) and the GT-2B surface pressure also kept constant at ~96.9 bar (~1405 psi). The GT-2B reservoir outlet temperature decreased steadily from 136°C to 98°C as shown in Fig. 3-1. An effective heat transfer area of 8000 m^2 for one side of the fracture was found to match the drawdown data. Since this is essentially the same area as was empirically determined for the previous 75-day test, it can be concluded that operation in the high back-pressure mode did not result in any appreciable increase in the heat transfer area of the system.

A comparison of spinner surveys at low and high back-pressure flows, as shown in Fig. 3-2, indicates a definite shift in the entry points into the GT-2B wellbore. The high back-pressure mode of operation favors entry points lower down in the wellbore. The significance of this observation has yet to be determined.

Figure 3-3 shows that the system flow impedance did decrease in the course of the high back-pressure flow experiment. At the end of the previous 75-day flow experiment the impedance had dropped to ~3.28 bar-s/ℓ (~3 psi/gpm) although subsequent measurements showed that the impedance had "recovered" to ~6.54 bar-s/ℓ (~6 psi/gpm). As can be seen from Fig. 3-3, after a transient period of a day or two, the impedance dropped from an initial value of ~2.18 bar-s/ℓ (~2 psi/gpm) to a value ~0.55 bar-s/ℓ (~0.5 psi/gpm). Thus, the high back-pressure mode of operation definitely decreased the system flow impedance.

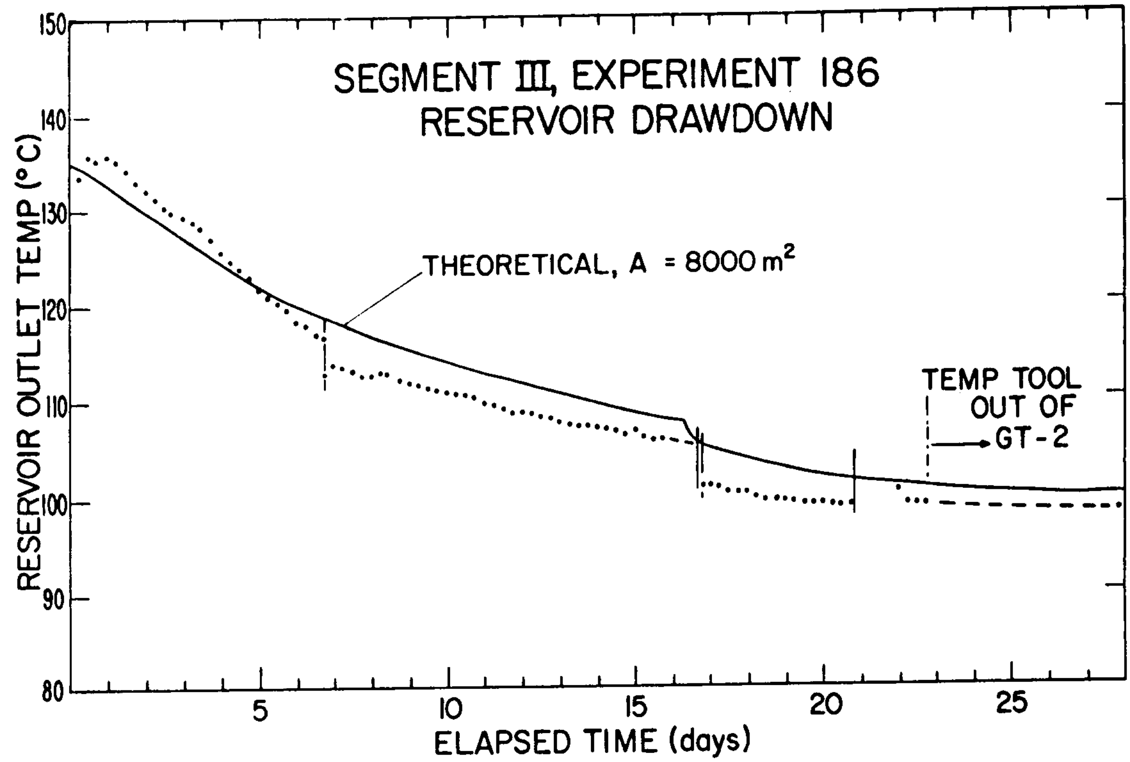


Fig. 3-1. Measured downhole temperatures at 8500 ft cable depth in GT-2B during the high back-pressure heat extraction test.

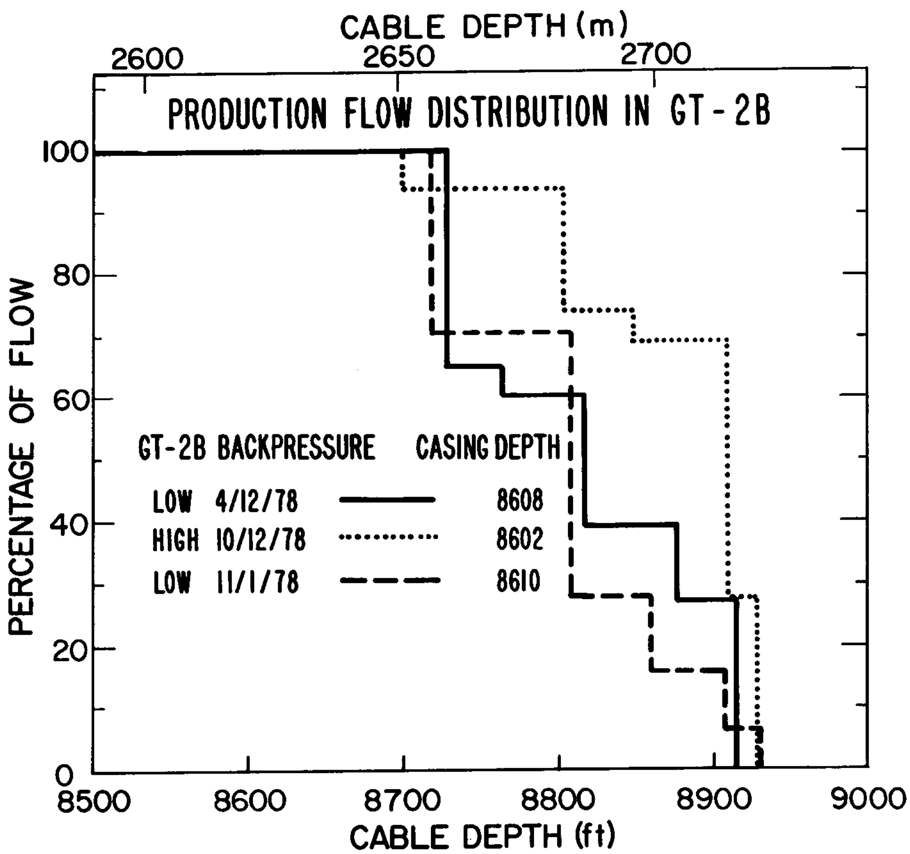


Fig. 3-2. Distribution of produced flow in GT-2B as determined by three separate spinner surveys conducted during high and low back-pressure operation.

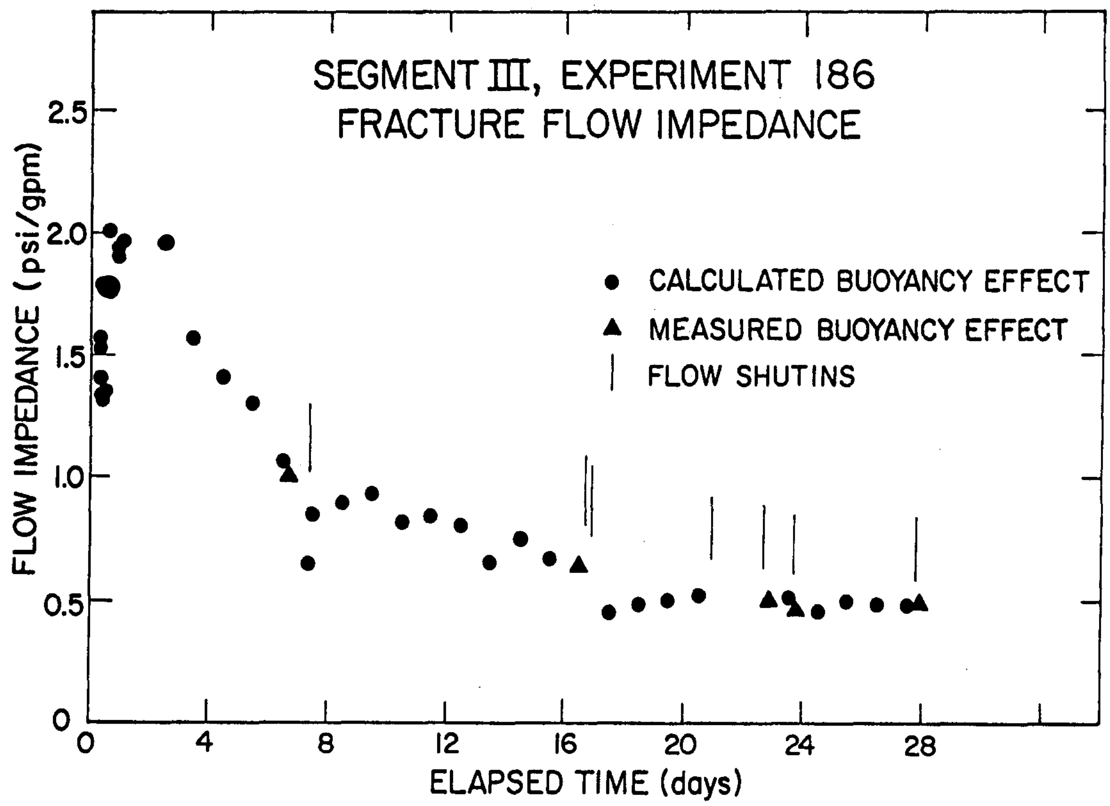


Fig. 3-3. Flow impedance between EE-1 and GT-2B during the 28-day high back-pressure heat extraction test.

There could be at least two contributing causes for the observed steady decrease in flow impedance. First, during the course of the experiment the GT-2B water temperature steadily dropped; as a result of the temperature decrease, the effective downhole pressure in GT-2B increased. Such a pressure increase, particularly at pressures approaching S_3, might very well open up fracture regions which were closed under lower pressure conditions. Second, the gradual decrease in rock temperature during the course of the experiment could result in the widening of fracture widths. For example, the decrease in the reservoir flow impedance during the 75-day test can be directly correlated with the decrease in the reservoir outlet temperature during that test.

Some days after the termination of Expt. 186, the impedance of the system with GT-2B at low pressure ~15.8 bar (~230 psi) was measured in Expt. 190. The measured impedance was ~6.54 bar-s/ℓ (~6 psi/gpm), very similar to that measured some weeks after the 75-day flow experiment.

The water loss in Expt. 186 was substantially greater than in the previous 75-day test. This additional water loss probably arises from an increased flow behind the EE-1 casing to a near-surface sink as subsequently observed in Expt. 193.

3.2. Run Segment 4 of Phase I

3.2.1. Scope. Preparations for Run Segment 4 have so far consisted of a series of workover and testing operations on the GT-2B/EE-1 system. During this period several activities were undertaken. Southwest Research Institute (SWRI) tested a hydrothermal silica polymer cement. We tested new fracture initiation concepts (for example, Kine-Frac) in an attempt to enlarge the effective heat transfer area of the GT-2B/EE-1 system with an acceptably low flow impedance. We are developing techniques for understanding the creation and operation of multiple fracture systems including activation, propagation, and flow control. We evaluated further the passive microseismic methods for fracture mapping.

During the first half of FY 1979, several specific workover and experimental operations were conducted. We successfully recemented behind the open annulus of EE-1 from 2926 to 2743 m (9600 to 9000 ft). By flow testing with a Br^{82} tracer and a low injection rate, we evaluated the recemented and Kine-Fraced regions in EE-1. The Kine-Frac concept for pneumatically initiating fractures by chemical deflagration was tested on four regions of the open-hole section of EE-1.

Further massive hydraulic fracturing (MHF) and associated flow testing with passive microseismic measurements will be used to attempt to provide the Phase I reservoir with an enlarged heat transfer and obtain information of value to the development of the 20-50 MW(t) Phase II system.

3.2.2. Recementing of EE-1. A workover rig was mobilized for the recementing operation. After several months of independent testing of various SWRI cement formulations for use in EE-1 by SWRI and the National Bureau of Standards (NBS), in cooperation with the DGE Geothermal Cement Development Program, significant uncertainties and inconsistencies remained as to the potential quality of the SWRI polymer cement. Consequently, it was decided to substitute a silica-stabilized Portand Type G cement designed and tested by Halliburton. The cementing operation was successful and after extensive pressurization and thermal cycling over the past two months, it appears to have completely isolated the 2760-m (9050-ft) injection region of EE-1, as well as sealed the region from

2626 to 2743 m. A comprehensive cement-bond log was run by Schlumberger and shows an adequate seal behind the casing. This is shown, for example, by the before and after cement bond logs given in Fig. 3-4 for the region 2623-2926 m (8606-9600 ft) in EE-1.

Operations in the open-hole region of EE-1 subsequently began. During the removal of the cement plug and reverse circulation of the sand pad that was used to keep cement out of the open-hole section, the appearance of numerous large (2-5 cm) fragments of granite were noted apparently resulting from the mechanical action of an undersized drill bit. This method of providing rock samples of the reservoir is currently being evaluated.

3.2.3. Br^{82} Tracer and Flow Test (Expt. 194). This experiment followed the completion of the EE-1 recementing operation to seal the approaches to the extensive fracture system at ~2760 m (9050 ft) behind the casing in EE-1. The $A\sqrt{k\beta/\beta_o}$ product determined from the initial EE-1 pumping during Expt. 194 was 9.2 cm^3, within 5% of the value obtained on December 3, 1975 during Expt. 105. Initial evidence of the activation of the 2760-m (9050-ft) fracture system in EE-1 or any other fractures above the bottom of the casing at 2926 m (9600 ft) did not appear until Expt. 114, February 14, 1976. Consequently, the present behavior suggests that the injected flow now enters only the original EE-1 fracture located below the casing. The measured circulating impedance was 149 bar-s/ℓ (137 psi/gpm) within 5% of the impedance reported for the fracture system before activation of fractures above 2926 m. Analysis of the GT-2B pressure rise after shut-in suggests that cross flow enters the same GT-2B fracture system that existed prior to recementing of the EE-1.

The Br^{82} tracer studies indicate that injected water flows to a depth of at least 2960 m (9710 ft), LASL cable depth, before entering the formation. This depth is 21 m (70 ft) below the casing and is nearly coincident with the bottom of the recently emplaced cement, therefore verifying its integrity. Although this depth is somewhat below the position of an acceptable maximum inflow for the original EE-1 fracture (~1948 m), it may be near the bottom of this fracture's communication with EE-1. Furthermore, some of the flow injected during the current experiment may have entered as high as 9680 ft. In the other well, GT-2B, the tracer appears at the same depths previously identified by temperature and spinner surveys, approximately 2621, 2652, and 2713 m (8600, 8700,

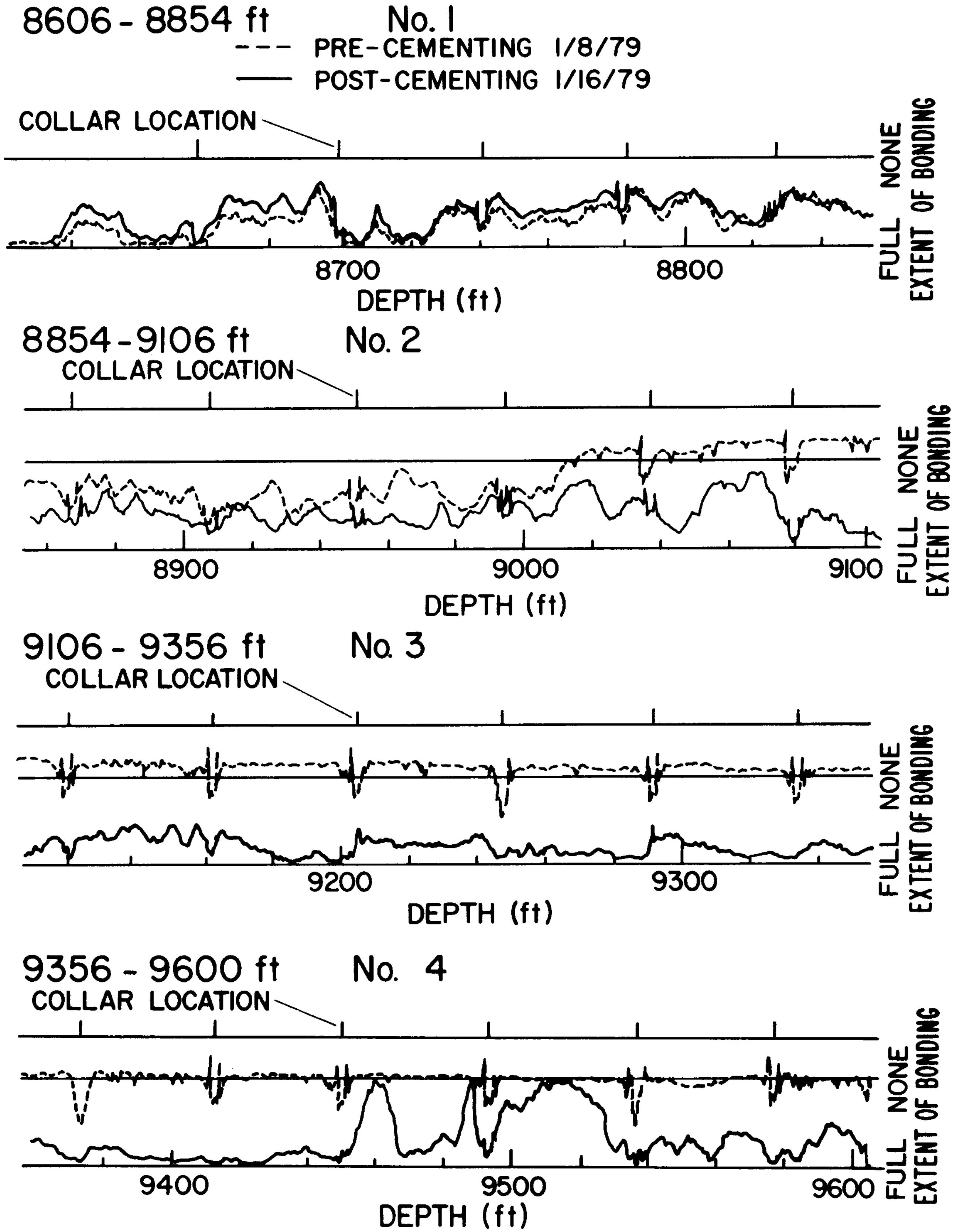


Fig. 3-4. Pre- and post-cementing cement bond logs in EE-1.

and 8900 ft), further confirming that communication with the existing GT-2B/EE-1 fracture system has been achieved.

3.2.4. Kine-Frac Operation. This sequence of operations was designed to evaluate the Kine-Frac technique of fracture initiation with gas pressurization by rapid combustion in restricted regions of the open-hole section of EE-1. This method, developed by the Kine-Tech Corporation for initiating fractures and stimulating production in oil and gas wells, was modified for use in our reservoir. The Kine-Frac method uses a relatively slow deflagration process, which should more closely meet optimal conditions for fracture initiation. Since pressurization is restricted to a very localized region around the tool, it may be an effective way of isolating certain wellbore regions and eliminating the need for "straddle" packers.

The zones were selected on the basis of a correlation between several anomalies observed on geophysical logs and the drilling rate as shown in Fig. 3-5. Different regions were selected to provide information on formation conditions varying from competent, unfractured rock to previously fractured zones.

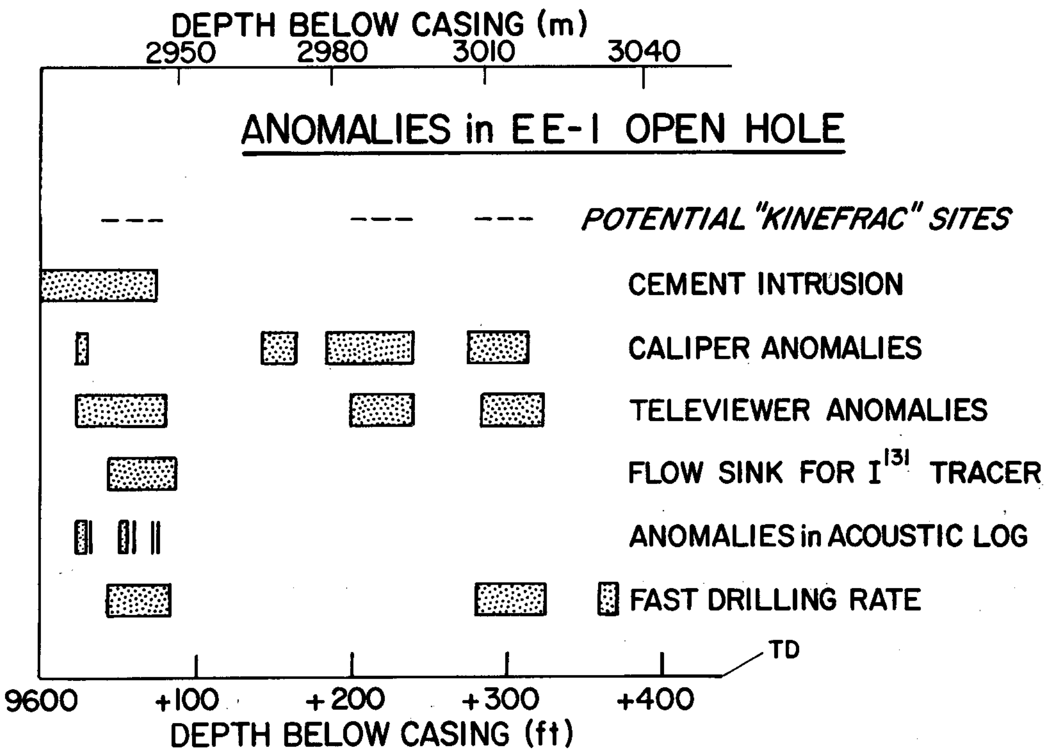


Fig. 3-5. Correlation between geophysical logging and drilling rate anomalies in the open-hole section of EE-1 from 2743-2926 m (9000-9600 ft).

The Kine-Frac technique was tested in the EE-1 borehole at six different depths. Successful ignition of the gas-generating material was achieved in 9 out of 10 firings. The system was designed to reach 1170 bar (17 000 psi) in 3 ms with sustained pressurization for 500 ms. Leakage of water into the region between the igniter and the active material prevented deflagration in the one unsuccessful test. Because no downhole pressure transducer was used, only indirect methods of verifying ignition could be used.

One test for successful ignition consisted of "feeling" the cable during firing. A sharp tug downwards occurred a few seconds after the fire signal in the majority of the tests. The first two shots gave evidence of preignition (cable tug). The apparent preignition occurred at the bottom station where the maximum temperature was attained.

A second method of verifying ignition was to examine the tool itself after firing. The support structure for the gas-generator tubing suffered measurable damage in each of the successful firings. The first two shots employed 7/32-in. airplane cable, which after ignition was completely severed a few inches below the igniter, leaving the sinker bar in the hole. Subsequent shots were supported on a heavy-walled black iron tube, 1 1/4-in. o.d. This tube, on returning to the surface after firing, was bent in a direction away from the gas generator, so that straightening was required after each shot. The presence of mechanical action on the support structure was used as a measure of successful firing.

The third method employed in determining whether successful firing had occurred was through the use of a downhole geophone array in GT-2B and a vertical geophone strapped to the EE-1 casing at the surface. The results from these measurements were mixed; however, strong signals were received by both sets of instruments during the last few shots. The direct travel path for acoustic waves was over 305 m (1000 ft). It was also possible that the signals observed in GT-2B were guided borehole surface waves in EE-1 radiating to the GT-2B array. All signals were recorded on high-speed magnetic tape and will be analyzed in the near future.

Flow tests consisting of a programmed pumping sequence after each set of firings at a given depth were conducted to see if changes in the pressure-volume pumped characteristics of the borehole had occurred. None were noted.

Table 3-I is a listing of data from each shot. Considerable variation is noticeable in the various listings, which might indicate uneven performance by the gas-generating system. The diagnostics available at this writing are not good enough to judge the effectiveness of the method. To do so will require that we process the present acoustic data and then repeat the use of the Kine-Frac tool with two pressure transducers located near the tool. In EE-1 and GT-2B this would characterize the pressure pulse and, along with accurate timing, could differentiate the dominant mode of acoustic transmission to the GT-2B geophone array. The shape of the pressure pulse with time after a second firing at the same station might indicate the nature of the rock failure from the first firing.

Although the Kine-Frac tests had some obvious shortcomings, it was the first time they were tested at ~200°C and 300 bar hydrostatic pressure. It appears that in addition to improved downhole diagnostics, some development of the tool hardware for our borehole environment will be required.

3.2.5. Massive Hydraulic Fracturing (MHF) and Associated Flow Testing (Expt. 195, 203, and 204). The objectives for pre-MHF Flow Test Exp. 203 (March 14, 1979) were the following: (1) To determine pressurization and breakdown behavior at a 27-ℓ/s (10-bbl/min) injection rate for ~4 hr and to estimate the maximum flow rate allowable with the 207-bar (3000-psi) casing pressure limit for the MHF operation. (2) Downhole seismic measurements during pressurization,with Sperry-Sun magnetic compass multishot orientation.

For MHF Expt. 195 (March 21, 1979), the objectives were the following: (1) Extend and/or enlarge fractures originating from the open-hole region of EE-1, 2920-3050 m (9600-10 000 ft), to provide an improved connection with GT-2B. A maximum pumping rate of 40-53 ℓ/s (15-20 bbl/min) for a total injection of 757 000 ℓ (200 000 gal) was anticipated. (2) Downhole seismic measurements with lead-azide detonator orientation for passive microseismic event mapping. (3) $A\sqrt{k\beta/\beta_o}$ measurement at an 8-ℓ/s (3-bbl/min) injection rate. (4) Formation breakdown possible with extended pressurization to 207 bar (3000 psi).

The post-MHF Flow Test Expt. 204 (March 22, 1979) was designed to measure the high back-pressure flow impedance in the present reworked EE-1/GT-2B system using 27-ℓ/s (10-bbl/min) injection rate.

In the pre-MHF Flow Test, Expt. 203, successful orientation of the package was obtained with the Sperry-Sun system. Because a pressure lock at GT-2 was

TABLE 3-I

KINE-FRAC SHOTS IN EE-1

Shot No.	Cable Depth (ft)	Time of Firing Pulse	Cable Response	Acoustic Response	Tool Support Behavior	Other Remarks
2/26/79						
1	9952	11:35:00	?	?	Cable severed	3 prefiring cable jerks
2	9952	14:13:00	?	none	Cable severed	2 prefiring cable jerks
2/27/79						
3	9911	11:26:00	yes	none	Housing bent	Proper timing on cable response
4	9911	13:56:00	yes (slight)	yes	Housing bent	Proper timing on cable response
5	9782	16:20	yes	none	Housing bent	Slight tug at -8 sec.
2/28/79						
6	9782	11:00:30	no	yes	Housing bent	Slight tug
7	9667	12:59:00	no	none	No change	Igniter burned, gas propellant intact
7a	9667	14:45:00	yes	yes	Housing bent	Double tug, water surge, proper timing on cable and acoustic response
8	9657	16:10:00	yes	yes	Housing bent	" " " " "
9	9647	17:29:00	yes	yes	Housing bent	" " " " "

Shots 6, 7, 7a, 8, and 9 were fired by applying full voltage (300 volts 3 1/2 amperes) to circuit through firing key rather than raising voltage through rheostat.

All depths are for the midpoint of the 20-foot long charges.

not used in Expt. 203, the geophone package could not be removed from the wellhead because of a high (6-ℓ/s or >100-gpm) venting rate and high back pressure at GT-2.

The geophone package was located at a 2695-m (8842-ft) cable depth and remained in place for about 5 hr of the pumping phase at 27 ℓ/s. This time was selected because of the anticipated lifetime of the Sperry-Sun tool. After 5 hr of pumping, the package was returned to the surface and parked. Excellent seismic signals were obtained within 1/2 hr of the start of pumping and continued at a high, steady rate throughout the 5-hr observation period. After 5 hr, approximately 500 000 ℓ (132 000 gal) had been injected.

Apart from the initial transients caused by trouble with the rented pumping equipment, the injection flow into EE-1 was maintained at a 27 ℓ/s nominal rate. After ~30 min, the EE-1 pressure reached 193 bar (2800 psi), rose to 198 bar (2880 psi) after 1 1/2 hr, and declined slightly to a minimum 188 bar (2730 psi) after 5 hr, when the system was shut in to repair a blown-out pressure transducer connection at EE-1. Pumping was resumed in 15 min and continued until a final shut in at 147 bar (2130 psi) after ~ 6 1/2 hr of total pumping. No $A\sqrt{k\beta}$ was obtained due to complex early transients, and no apparent formation breakdown occurred. Impedances were not measured because the GT-2 shut-in pressure responded quadratically for essentially the entire pumping period.

For MHF Expt. 195 and post-MHF Expt. 204, the GT-2 pressure-lock system was installed to allow removal of the geophone package. The initial pump-up with Western was steady at 8 ℓ/s (3 bbl/min) with a good value of ~56 cm for $A\sqrt{k}$ normalized to a $\beta_o = 2.7 \times 10^{-5}$ MPa^{-1}. This represents an increase of 670% over the 9 cm^3 measured in Expt. 194. Somewhat unexpected was the initial decrease in injection rate from 42 ℓ/s (16 bbl/min) to 30 ℓ/s (12 bbl/min) to avoid over-pressurization of the EE-1 casing string. During the first 1 1/2 hr, the net buoyancy effect in EE-1 could account for an additional 14.5 bar (210 psi). This could be enough to require a reduction in flow, but it is difficult to say exactly how much. After an additional 1 1/2 hr of pumping at 30 ℓ/s, increased injection rates up to 42 ℓ/s were required to maintain 207 bar (3000 psi). Although many mechanisms could cause this effect, probably the most plausible causes are: (1) decreased wellbore impedance due to a "washout" of the cement in the 2941-m (9650-ft) zone; (2) fracture extension; (3) development of new injection zones (fractures) in the EE-1 open-hole section; (4) fracture propagation, most likely upward to a region of lower earth stress (S_3); and (5) increasing rate of inflation of the old GT-2 fracture system with a decreasing (pressure-dependent) transient impedance between EE-1 and GT-2B. Without results from flowing temperature, tracer, and/or spinner surveys and knowledge of the in situ stress, it is difficult to tell exactly where and what fraction of flow leaves the wellbore and how fractures are growing if at all. These diagnostic tests will be conducted later.

In all three flow periods (Expts. 203, 195, and 204), no classical formation breakdown occurred with a reduction in pressures to near S_3, which has been estimated to be approximately 103 bar (1500 psi). However, we may be completely wrong in expecting a classical breakdown. Natural, sealed fractures in GT-2, GT-2A, GT-2B, and EE-1 have shown similar sluggish pressurization curves. However, the 207 bar (3000 psi) casing-pressure limit created a serious drawback for the entire MHF operation. Higher pressures (~345 bar) and higher injection rates (~50 bbl/min) may be required to propagate fractures over long distances.

Geophone coverage was formally terminated when 0.2 M gal had been pumped after ~ 6 1/2 hr and the injection flow rate was reduced to 27 ℓ/s. The geophone package was returned to the surface and secured in the GT-2 pressure lock. At 2:00 p.m. on March 22 venting began with the GT-2 wellhead pressure at 96 bar (1400 psi). The GT-2 back pressure was controlled between 96 bar and 103 bar (1500 psi) by regulating the outflow. From 2:00 p.m. to 3:10 p.m., leaks and other minor problems interfered with the venting process. After 3:10 pm, the operation was quite stable with manual flow adjustments to keep the back pressure below 103 bar. The maximum flow rate observed at GT-2 was ~ 6 ℓ/s (~ 100 gpm). Impedances (uncorrected for buoyancy) decreased from 15 to 13 bar-s/ℓ (14 to 12 psi/gpm) during the venting period.

Seismic monitoring in GT-2B with an oriented triaxial geophone array, during the apparent enlargement (≥27 ℓ/s) of the fracture system below the casing in EE-1 in Expts. 203 and 195, has produced a unique history of events covering the inflation of the system from an initial size of 11 000 to 757 000 ℓ. The two successive experiments may provide valuable information about the possible growth of a fracture and its subsequent reinflation.

The initial pressurization during Expt. 203 at an average rate of 27 ℓ/s for a total of 635 000 ℓ (168 000 gal) produced a steady train of microseismic signals throughout the entire pumping period. The temporal density of these

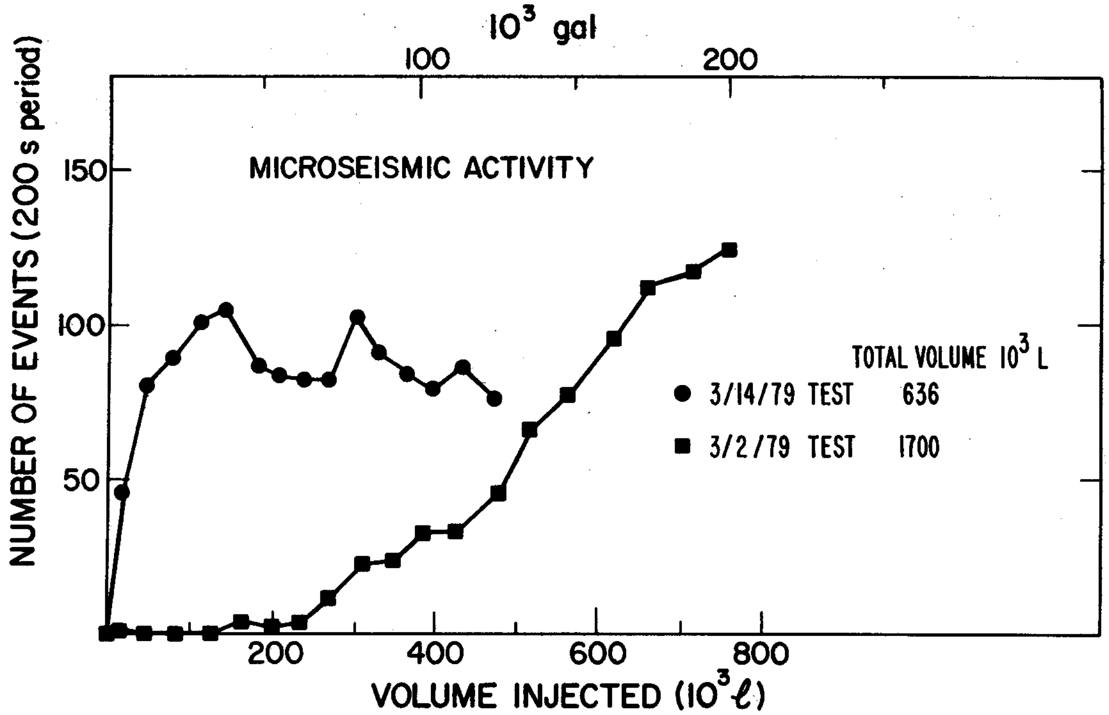
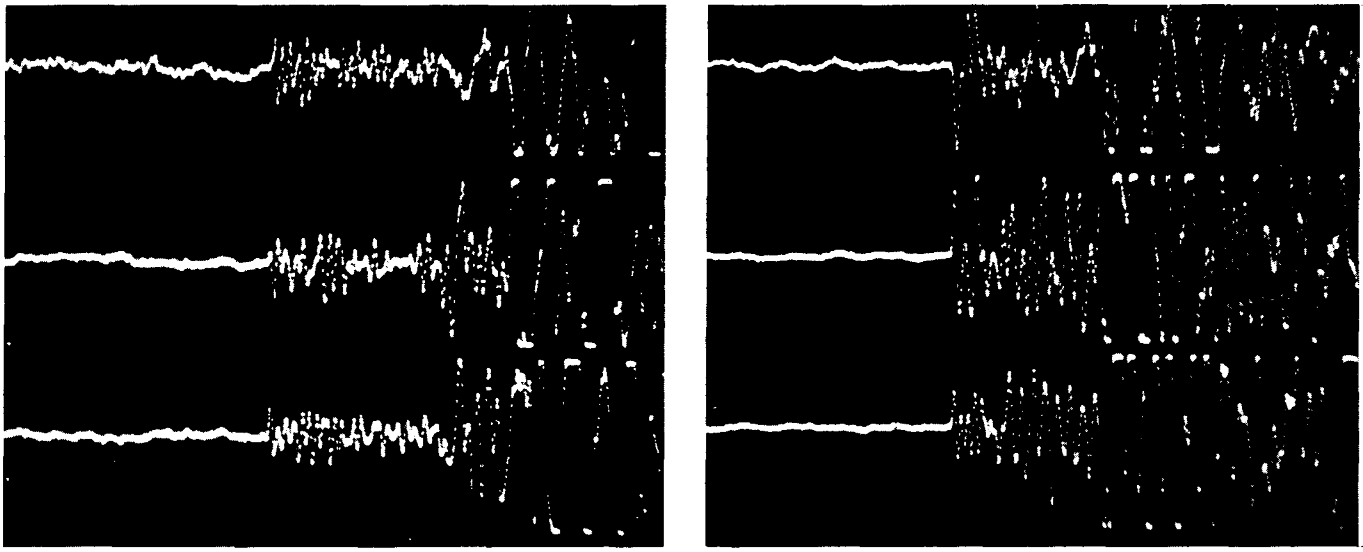


Fig. 3-6. Acoustic activity associated with high rate injection into EE-1 as estimated by on-line low-frequency recording.

signals, obtained from a chart recording, is shown in Fig. 3-6. Several Polaroid pictures of the output of a Biomation digital oscilloscope showed these signals to have well-defined phases and distinct first motions, which can provide a source location if a source mechanism is chosen. These signals, recorded on magnetic tape have not been completely processed so that a comprehensive history of the seismic behavior of Expt. 203 is to be determined.

The reinflation of the downhole system during Expt. 195 was accomplished at higher flow rates (11-16 bbl/min) and with a greater total volume pumped (757 000 ℓ). The seismic behavior of this experiment was greatly different from that of Expt. 203. As shown in Fig. 3-6, significant seismic activity was not observed until 227 000 ℓ (60 000 gal) had been injected, in contrast to Expt. 203 which exhibited almost immediate seismic response upon pumping. The microseismic event rate rose steadily after an initial quiescent period and approached a value ~50% greater than that seen in Expt. 203. This increase in seismic rate appears to be proportional to the increase in the EE-1 injection rate. As in Expt. 203, Polaroid records (Fig. 3-7) showed well-defined signals. Orientation of the geophone array in GT-2B stationed at 2696 m (8844 ft) was accomplished by measurement of the sense of first motions from several lead-azide detonators



2 hrs into pumping 4 1/2 hrs into pumping

Fig. 3-7. Polaroid pictures showing typical signals (recorded from an oriented downhole triaxial geophone array) that accompanied hydraulic fracturing in deep basement rock.

fired in EE-1, at the same true depth. An extensive series of Polaroid records, over 70 in number, was obtained during the entire seismic observation window. Examination of these records show an apparent decrease in the time between first arrivals of the two phases (P and S) with pumping time. This behavior could be interpreted as a movement or growth of a fracture towards the geophone array. In addition, coupling the S-P delay-time data with a first-motion analysis of the three components has given a preliminary indication of a vertical planar microseismic source. However a note of caution concerning this preliminary interpretation is appropriate. Although a number of signals were examined, they represent a very small fraction of signals recorded. The more detailed analysis that will follow will determine whether the Polaroid sequence is truly representative. At any rate, the quality and quantity of signals obtained is such that an excellent map of the source of acoustic events should be produced from the data.

3.2.6. Summary of Current Status and Future Plans. The present GT-2B/EE-1 system is characterized by relatively high impedance in the initial low and high back pressures of ~130 psi/gpm and 12 psi/gpm, respectively.

Putting geometric constraints aside for the moment, the location and behavior of communication between the old GT-2B/EE-1 and the new system is not clearly defined. Furthermore, our understanding of pressure-dependent impedance effects has been based on only one extensive field demonstration (run segment 3 Expt. 186 over 28 days). Further flow experiments giving information concerning the eventual mass production rate and long-term water losses that may result under low or high back-pressure operation of this system will be of considerable value in the design and management of the new Phase II system.

Sustained operation during heat extraction with these high pressures may be limited by water losses. However, our present interpretation of the system suggests that water is being consumed in two ways: first to inflate or extend a new EE-1 fracture system, and second to inflate the GT-2B system, which we have already characterized in run segments 1-3.

If pumping were to continue with the GT-2B pressure at 96 bar (1400 psi), the water loss from that side of the system would decrease rapidly from 6 ℓ/s (100 gpm) on the first day to less than 2 ℓ/s (35 gpm) on the eighth day as observed in run segment 3. Because of high EE-1 injection pressure (~2600 psi) at the end of this experiment, the long-term behavior of the ~13-ℓ/s (~200 gpm) water loss from this system is not known. However, even at this high EE-1 pressure, long-term water loss rates may still drop off significantly as previously observed for the old system operating at 90 bar (~1300 psi) in run segment 2 (75-day test).

3.3. Phase II System Planning and Operations

We have planned the drilling of Hole EE-2 and have decided to make the second hole (tentatively the redrilling of GT-2) temporarily interactive with the energy-extraction system instead of a DWETS (Deep-Wellbore Equipment Test Station) hole as previously planned. The planning and detailed design of GT-2C hole as a part of this system is now underway by LASL personnel and by our drilling consultants, Grace, Shursen, Moore, and Associates.

The specifications for the drilling rig were completed and submitted for bid, and the contract was let to the low bidder, Brinkerhoff-Signal Drilling Company, for the use of their Rig No. 56. The rig has been inspected and accepted and is presently being mobilized at the Fenton Hill site.

The DOE management has designated a LASL "technical manager" to direct the day-by-day activities of the drilling program. He is authorized to approve limited purchases of supplies by Brinkerhoff-Signal for the drilling program. Also, a drilling manager has been selected from Grace, Shursen, Moore, and Associates to serve as an advisor to the LASL technical manager.

The 28-in.-diam conductor pipe has been set for Hole EE-2 to a depth of 25 m (82 ft), and the "rat" and "mouse" holes have been drilled by the Zia Company.

Orders have been placed for the following items: directional drilling services, steering tool rental and service, electrical wireline service, turbodrill purchases and services, shock sub rentals and purchases, cementing services, mud motor rentals, gyro surveys, directional indicators, casing, soft- and hard-rock drill heads, float collars, and other drilling activities. These items will be used in the drilling of EE-1 and GT-2C.

4. ENVIRONMENT

4.1. Environmental Monitoring

Seismological Monitoring -- Continuous monitoring around the Fenton Hill Site has shown no locally-induced seismic activity from October 1, 1978 to the present. All microseismic activity generated by reservoir expansion and contraction during the various experiments continued to remain below the background noise level measured at the surface.

The current local network is being enhanced, and several of the new sites have been located. Actual implementation of the network is waiting until snowmelt allows access.

Hydrological Monitoring -- The routine sampling of both surface and ground waters from the drainages surrounding the site has continued on schedule. These data are summarized on an annual basis, and the next report covering the data for 1979 should be available by June 1980. To date, no hydrologic interaction between the geofluid loop and the local aquifers or proximate surface waters has been observed.

Biological Monitoring -- All biological field sampling programs ceased for the winter in November 1978. The existing data were put into the computer, and we are currently analyzing these data to determine if any significant changes have occurred in the ecosystem which can be directly tied to geothermal-related activities.

Climatological Monitoring -- The routine accumulation of meteorological data has continued, with the addition of pressure, humidity, and upper winds as of December 1978. During this reporting period, we experienced some mechanical failures because of severe weather conditions, losing several weeks' data. However, all systems are now functioning.

Pressure and humidity data have been reduced for the winter months of December 1978, January 1979, and February 1979, in addition to the regular monthly summaries of wind speed, wind direction, temperature, and precipitation.

During February, a program of weekly observations of the upper-air wind was initiated. The timing was coordinated with the routine Albuquerque afternoon radiosonde to test the comparability of the Fenton Hill and Albuquerque sites. Also, a White Rock sounding was made for additional comparison. Table 4-I is the data for February 7, 1979, the first sounding in this program. Albuquerque and Fenton Hill show good agreement in direction although a wind-speed maximum

TABLE 4-I

UPPER LEVEL WIND SPEED/DIRECTION

7 February 79

Altiude (km)	Albuquerque (1700 MST)	White Rock (1430 MST)	Fenton Hill (1450 MST)
1.62	8.2/010		
1.83	7.2/360		
2.06		2.2/062	
2.13	6.7/355		
2.17		2.9/087	
2.28		3.9/078	
2.38		2.7/056	
2.46	7.7/305	4.1/64	
2.58		5.8/076	
2.65			6.9/301
2.74	10.3/290	5.4/111	7.3/284
2.86			8.3/295
2.94		4.3/112	14.0/299
3.04	14.4/295		15.7/308
3.13		1.6/031	19.9/308
3.25			25.2/304
3.33		3.3/293	27.0/305
3.44			25.1/305
3.51		5.5/283	24.1/306
3.66	20.5/315	6.8/293	20/309
3.96	19.5/310		17.0/307
4.27	20.5/305		24.5/296

near the ridge top at Fenton Hill probably reflects terrain influence. Low-level directions at White Rock were very different from both of the other sites, reflecting topographic channeling, although above 3 km (ridge height) this sounding also came into good agreement. The purpose of the program is to test the response of Fenton Hill winds to large-scale synoptic air flows under a variety of meteorological conditions.

Although LASL's H Division has current responsibility for taking these data, G-8 is supplying supplemental data including pressure, humidity, and upper winds by pilot balloon.

The USFS will be connecting their retransmission platform to the LASL meteorological network upon completion of the new two-level tower. The tower purchase request and all instrumentation requests are in process.

4.2. Environmental Analysis

The adverse environmental inpacts and the potential for such impacts from past and planned operations at the Fenton Hill Site have been studied and reported in an Environmental Analysis. This Analysis has been published as an appendix to the Memorandum of Understanding between DOE and the US Department of Agriculture, Forest Service (USFS). Such environmental issues as the land status and uses, the physical factors, biological, economic, and social factors were studied in the present Fenton Hill project and presented in the study of alternatives. The alternatives were also evaluated.

The conclusions, as attested by the USFS in 1978, are that the Fenton Hill complex does not constitute a major federal action, does not involve an irretrievable commitment of resource, no discernable adverse environmental impacts have occurred, and therefore no Environmental Impact Statement is needed for Phase II, which is the operation of a deeper reservoir.

5. FENTON HILL WATER SYSTEM DEVELOPMENT

The operation of the deeper, Phase II reservoir will require an increased amount of water beyond what is obtainable from the present water supply well and the present appropriation. An application was drafted, and a conference with the New Mexico Engineer's staff was held, to obtain the detail required in a final application for a new water appropriation. As a result, a detailed hydrologic study was initiated to ensure that "no permanent damage to existing water right" would result from the larger withdrawal.

6. ANALYTICAL AND EXPERIMENTAL SUPPORT

6.1. Development of Radioactive Tracer Techniques for Reservoir Evaluation

The results from six experiments employing radioactive tracers to measure the movement of water through existing wellbore and fracture systems were examined. The first three experiments were a search for the location of flow entrances from the EE-1 borehole into the fracture system. The later experiments employed measurements of the tracer in both boreholes and were successful in providing information about the nature of the complex interborehole fracture system, particularly in its connections with the open-hole section of GT-2B.

The initial effort, Expt. 116, demonstrated conclusively that a major portion of fluid injected into EE-1 was returning behind the casing, in addition to the flow below the casing. The location of the formation-injection point behind the casing could not be determined from this experiment, but the results from temperature and cement-bond logs suggested a location near 2745 m (9000 ft). Another tracer test gave information about the location of two injection points in the original GT-2 wellbore.

A second use of the technique, Expt. 156, was successful in locating quite accurately the depth of the flow exit behind the casing in EE-1. This location agreed almost exactly with the fracture zone inferred from the initial 4-arm caliper log of EE-1. This was the first evidence that natural fractures rather than "new" fractures might be providing part of our flow system.

The third test, Expt. 177, provided further data on the proportion of flow entering the formation below the casing. The attempt to decrease the flow impedance of the system by injection of sodium carbonate, Expt. 138, occurred between Expt. 116 and 156. A significant change in the flow split showed that a smaller fraction exited below the casing. This experiment also indicated movement of fluid upwards through the cemented annulus -- a trend detected again by temperature and cement-bond logs. The combination of results from these three methods was powerful evidence that the cement was failing.

The next test, Expt. 181, was the first in which measurements were made in both the injection and the production boreholes. In addition, the injection and measurement of the tracer were made with LASL developed tools. Experiment 181 was run after the 75-day flow test and provided important new information. Several new inlets below the previous EE-1 main fracture were detected, and the flow upwards through the damaged cement increased. Measurements of the tracer entering the GT-2B borehole gave information confirming locations obtained from temperature and spinner logs and also a measure of borehole-to-borehole residence time for flow through individual fractures.

The next tracer test, Expt. 193, was notable for several reasons. It employed a completely new system using Br^{82} (created by neutron capture in the LASL reactor) as the tracer instead of I^{131}, a separated fission product. The shorter half life (1 1/2 days vs 8 days) and nonselective biological response of the bromine provides greater usefulness and safety.

In addition, the tracer was released and followed during a period of high flow rate and high back pressure (run segment 3). The results were therefore more useful in interpreting data from the major flow tests than were those from earlier tracer tests in which low flow rates were employed. The damage to the cement had increased to such an extent that a significant portion of the flow was exiting through this path. The movement of the tracer upwards behind the casing allowed a measurement of the amount of this flow. Measurements in GT-2B again showed the positions of the main connecting fractures and arrival times for the tracer at each fracture. Results from all of the tracer experiments will be used in developing a model of the complex wellbore-fracture system that comprises our reservoir. Figures 6-1 to 6-3 illustrate the type of data obtained from the two-borehole measurement system.

The last test to date, Expt. 194, measured the path that fluid now takes in the recemented EE-1 wellbore and subsequently in the GT-2B wellbore. The tracer leaves the EE-1 wellbore entirely below the casing, demonstrating the success of the recementing job.

The results from these six experiments have provided valuable and sometime unique information about the downhole reservoir and the experience gained can be used in further tests of more advanced downhole systems.

6.2. Active and Passive Acoustic Mapping Techniques

We continued to analyze the signals generated during the dual- and single-well experiments (174 and 185) conducted with Dresser Atlas acoustic tools. Data were taken with the GT-2B reservoir at both hydrostatic and pressurized conditions. In addition, we continued to develop the software to improve our signal-processing capability. From approximately November 1978 to February 1979, several LASL people were involved in the collection and analysis of acoustic-emission data associated with the cavern depressurization at the Bryan Mound,

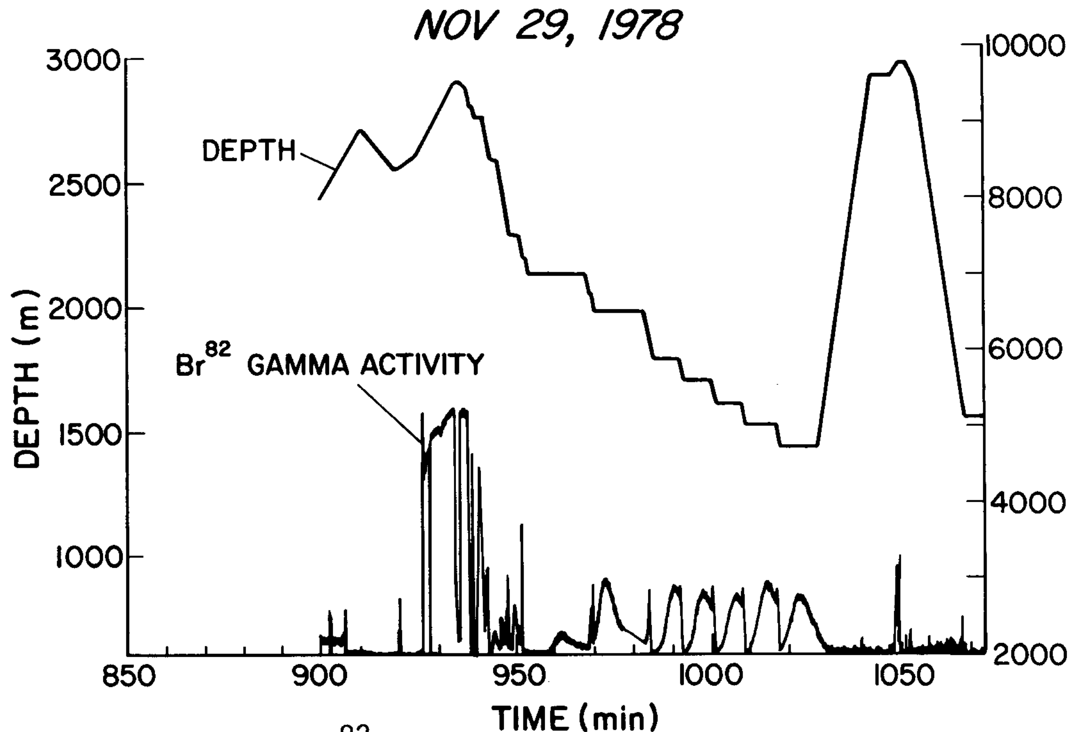


Fig. 6-1. The movement of Br^{82} tracer detectable from the EE-1 wellbore is shown. The upper graph shows the location of the logging tool whereas the lower shows its response to the tracer as a function of depth.

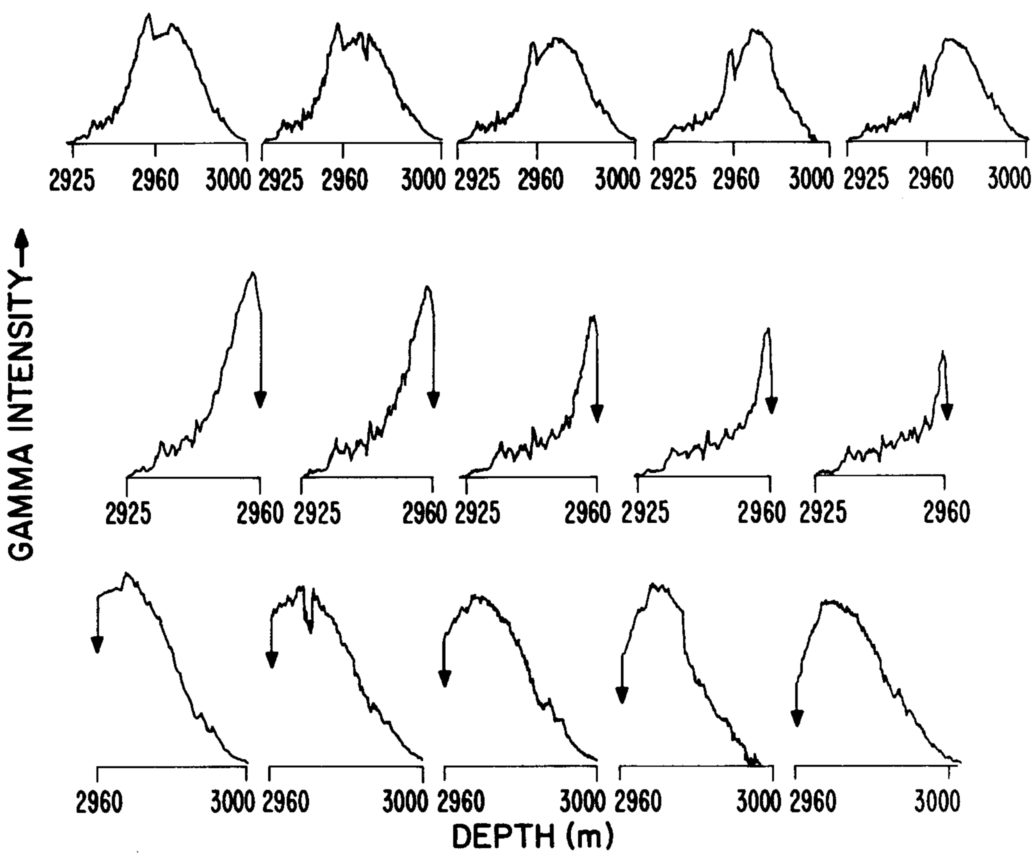


Fig. 6-2. Time sequence of tracer logs (top line) in EE-1 showing the disappearance of the Br^{82} tracer into a sink at 2960 m. The middle line shows the movement of tracer with pumping into the sink. The lower line shows the movement of tracer in the presence of a strong convective cell existing below 2960 m.

Texas, Strategic Petroleum Reserve. A report on this subject has been issued by LASL (March 16, 1979). The effort, as a whole, demonstrated that our downhole, microseismic-analysis equipment and techniques could be used to characterize the locus of events as they occurred during depressurization.

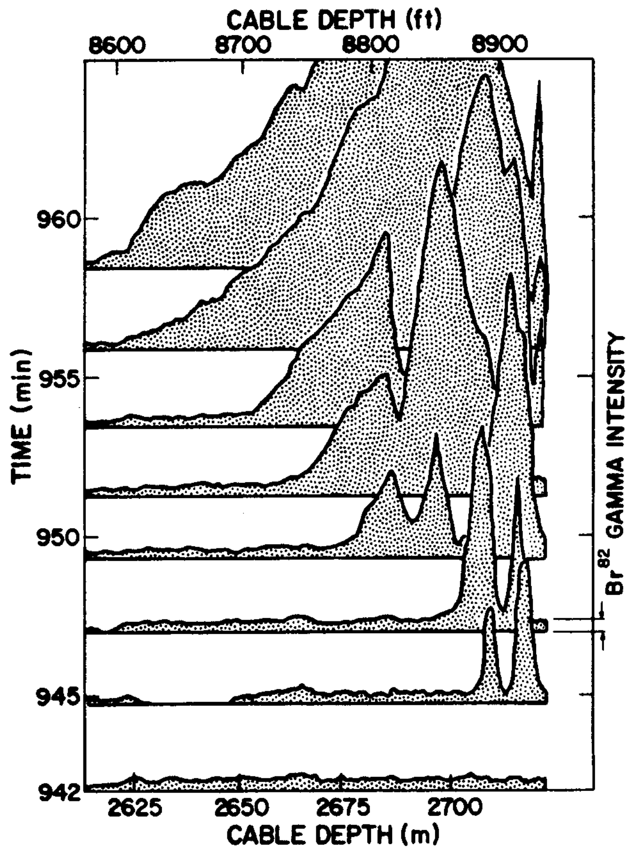


Fig. 6-3. The sequential appearance of Br^{82} tracer in the open-hole region of GT-2B is shown in a series of logs. The entry of the tracer through specific openings is shown.

6.3. Rock Mechanics and Rock Fracturing Processes

We successfully determined fracture toughness and rock elastic moduli using a number of laboratory techniques during the first half of FY79. These parameters are important to our understanding of in situ hydraulic and thermal-stress cracking phenomena as well as stress-dependent permeability and porosity effects, which are critical to the flow impedance and water-loss behavior of the system.

Three methods are being evaluated for determination of fracture toughness: (1) a three-point-bend loading system with a servo-hydraulic testing machine equipped with a highly sensitive LVDT displacement transducer enabling us to use feedback control based on the opening of the crack in the sample; (2) indentation methods developed for use on fine -grained ceramic composites, which utilize observations of crack length produced by a square pyramidal diamond indenter. Although rock grain sizes are much larger, it may be possible to use a statistical technique to obtain meaningful results; (3) Terra Tek's compact fracture toughness measurement that examines crack growth in the region of a chevron notch. Much smaller samples are required than in (1) above, which might make the system more adaptable to measurements at high temperature under fluid pore pressure. Fracture toughness (K_q) values to date for Berkeley granite have ranged from 2.3 to 2.8 $MPa\sqrt{m}$ with crack lengths 40-60% of the sample width.

Our modulus-measurement apparatus consists of a Rock Cell-10 triaxial vessel, which is presently being upgraded to reproduce a wide range of in situ conditions of temperatures up to 300°C and effective confining stresses of ~0 to 500 bar with fluid pore pressurization. Calibration measurements on Berkeley granite have been made for Young's modulus (0.71 x 10^6 bar) and Poisson's ratio (0.33) and are within the range of accepted values in the literature.

Other work on rock mechanics is under way at Northwestern University under subcontract to LASL. These activities focus on four major areas of importance to HDR: (1) theoretical calculations of fracture toughness in jointed heterogeneous rock, (2) laboratory simulation of hydraulic fracturing processes, (3) interaction of acoustic waves with fractured rock and (4) theoretical modeling of thermal-stress cracking effects. Both theoretical and experimental work on thermal-stress cracking is also being conducted at LASL with technical support from the University of New Mexico. Our basic objective here has been to understand thermal-crack initiation and propagation, so that we may exploit this technique to enhance reservoir capacity and lifetime.

During the last three months, the massive hydraulic fracturing (MHF) operation in the lower section of EE-1 was designed using the best available technology. Consequently, a comprehensive review of "the state of the art" was conducted. Cases with and without fluid additives were considered and the effect of formation properties such as permeability, porosity, and compressibility were examined parametrically for a range of injection rates. Because of the potentially high costs (up to $250 K) involved with fluid additives to control viscosity or to block formation porosity, the first MHF attempt used water as the fracturing fluid with the maximum total injected volume limited to our present storage capacity at Fenton Hill [1700 m^3 (450 000 gal)].

In all fracturing operations there are two factors competing for the volume of fracturing fluid injected. The first factor is the actual creation and inflation of the fracture itself. The fluid volume used in this manner is used effectively since all fluid goes into the formation of the fracture itself. However, there is the possibility that if too viscous a fluid is used, the fracture volume may be large because of large apertures, rather than the more desirable outcome, that is, large fracture radii. The second factor is that part of the fracturing fluid is simply lost by means of permeation to the surrounding rock formation, so that it is completely ineffective in creating fracture surface area.

Thus the design of a fracture treatment requires the selection of a fluid and a pumping rate that will achieve the desired fracture radius consistent with the total volume of fracturing fluid. Viscosities should be selected to minimize permeation losses and result in fracture apertures large enough so that the asperities of the fracture surface roughness have sufficient clearance to slide over one another, resulting in self-propping. However, the fracture aperture should not be so large that fluid is diverted into creating excessive aperture.

Two methods of calculating fracture radii, apertures, and volumes were pursued. In the first method, based upon the work of Geertsma and de Klerk*, analytical or near-analytical equations were used. In the Geertsma-de Klerk method, fracture apertures are controlled by pressure drops within the fracture. In the second method it was assumed that the pressure in the fracture was constant and that this pressure was controlled by a fracture mechanics criterion. This is commonly referred to as the "Sneddon-Sack" fracture. In the second method the permeation losses and fracture inflation volumes were numerically calculated as functions of time. In both methods the linear diffusion theory for semi-infinite bodies was used to estimate permeation losses. The boundary pressure at the fracture face did not change in time, and the starting time for diffusion from a newly created fracture area was coincident with the time of creation.

In Figures 6-4 to 6-7, the computed fracture radii are shown as functions of fluid viscosity (0.14-100 cp), injection rate (20-100 bbl/min), and the product of formation permeability, k, and compressibility, c, (2.7×10^{-11} to $\sim 2.7 \times 10^{-7}$ μdarcy Pa^{-1}).

While the variation is a mild one, that is, the radius is $(kc)^{-0.25}$, it is unfortunate that at the high pressures required for fracturing, k and c, are possibly several orders of magnitude greater than the values corresponding to the original pore pressures $(kc)_0$. At present we have no reliable way of estimating the high-pressure values of k and c that pertain to the lower sections of EE-1 still available for fracturing, following the recent recementing of EE-1. For this reason we have not presented a final recommendation but have instead calculated fracture radii as a function of kc for selected injection rates. Parallel calculations to study the effects of fluid viscosity indicate

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* J. Geertsma and F. de Klerk "A Rapid Method of Predicting Width and Extent to Hydraulically Induced Fractures," Petroleum Transactions, AIME, December 1969.

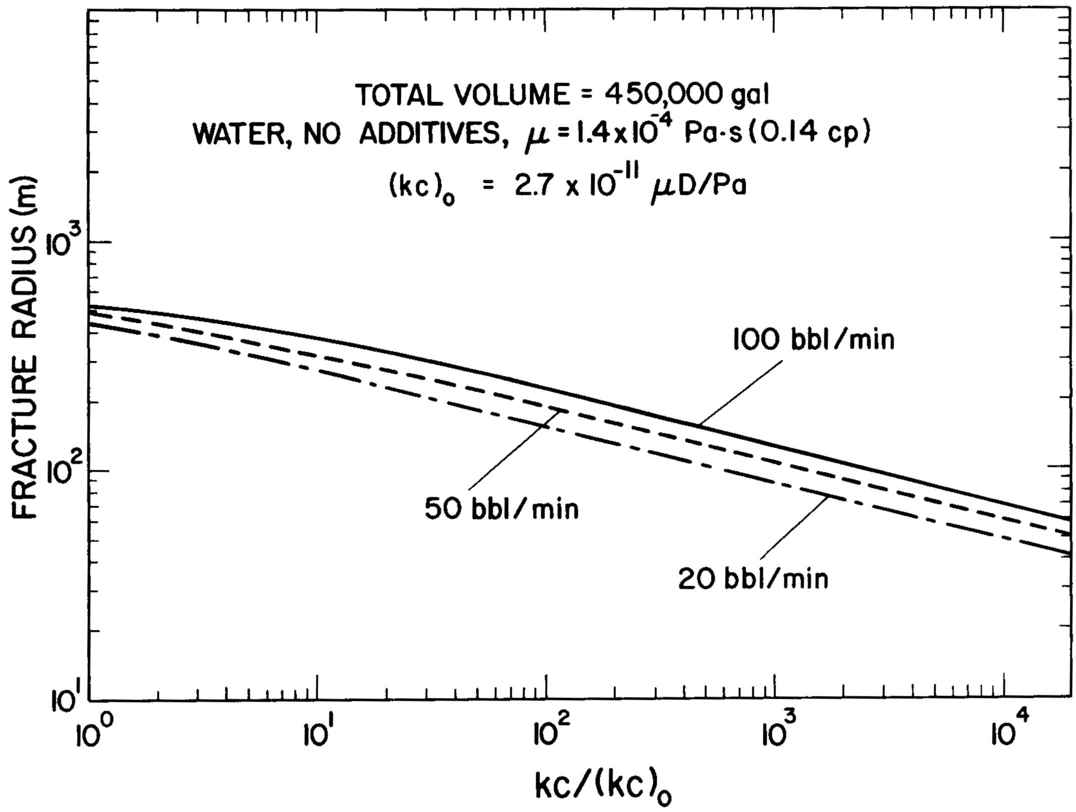

Fig. 6-4. Fracture radii using plain water. Geertsma-de Klerk method.

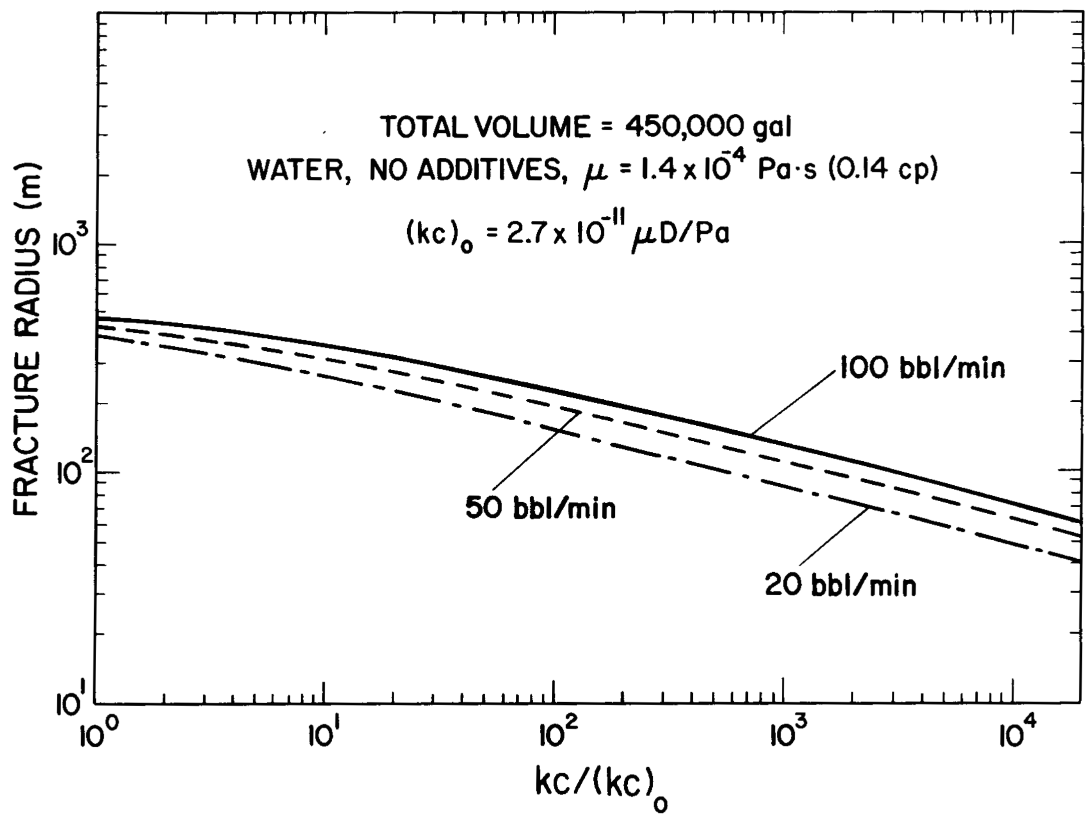

Fig. 6-5. Fracture radii using plain water. Sneddon-Sack numerical method.

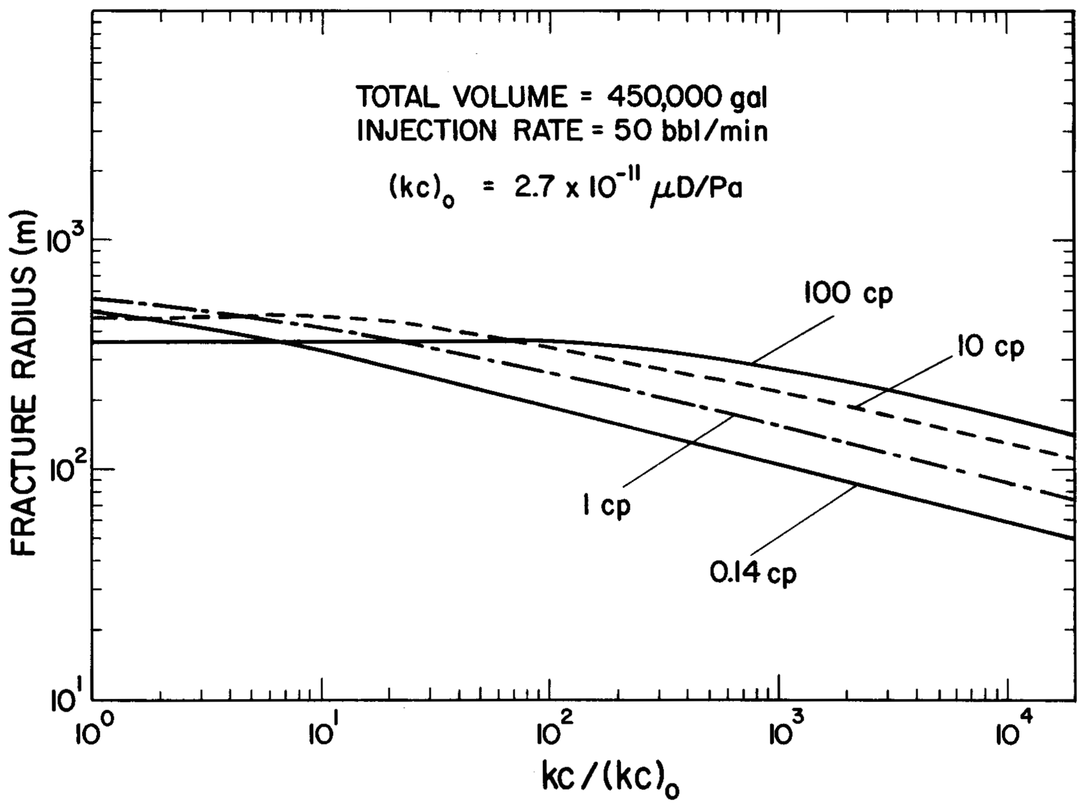

Fig. 6-6. Effect of viscosity on fracture radii. Geertsma-de Klerk model.

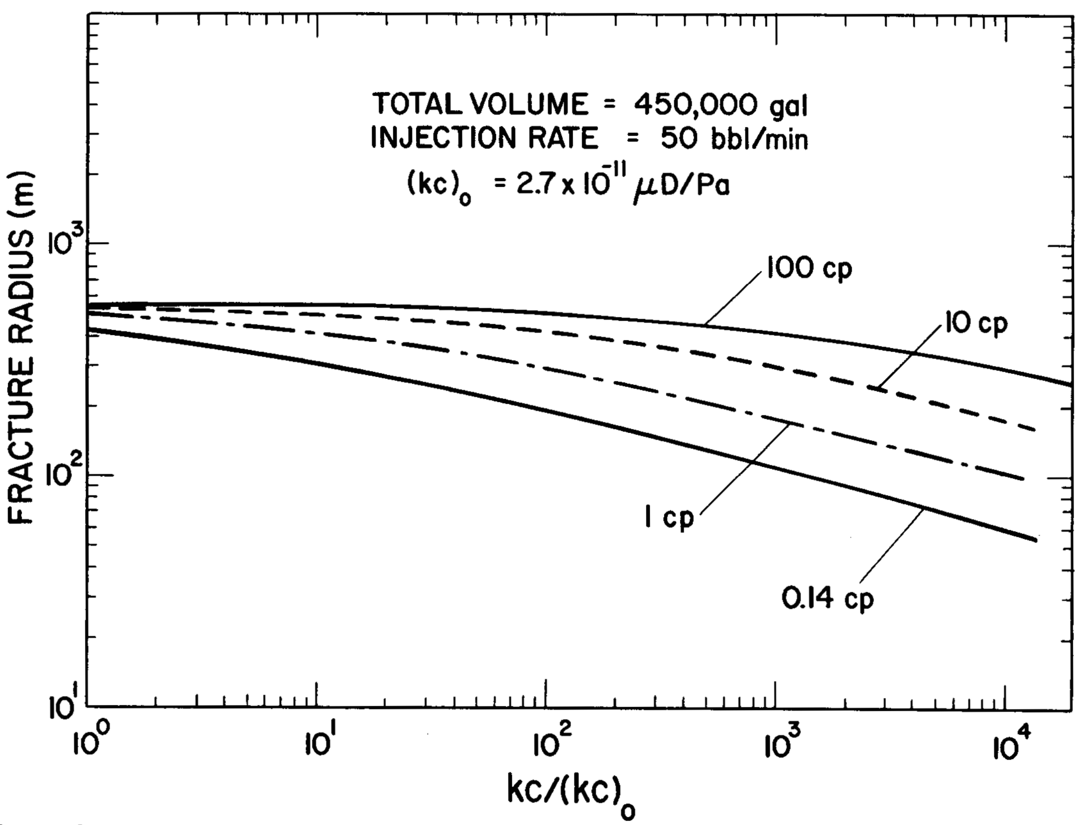

Fig. 6-7. Effect of viscosity on fracture radii. Sneddon-Sack numerical model.

that a tenfold increase in viscosity results in a 30 to 50% increase in fracture radius so long as formation fluid loss dominates fracture extension.

6.4. Reservoir Modeling - Heat Transfer and Fluid Mechanics

Heat Extraction Modeling. The computer program, GEO,is being developed for the investigation of water flow and heat exchange in a thermal fracture that branches from the primary hydraulic fracture. Three-dimensional heat flow in rock is coupled to a two-dimensional approximation for the time-varying convective patterns that result from both forced flow and buoyancy. The code has been written, essentially debugged, and successfully applied to the following test problems:

1. Water flow and heat transfer from the crack walls have been calculated with the lateral fracture closed, demonstrating efficient convergence of the numerical iteration procedure.

2. Heat and water exchange with the lateral fracture have been calculated for a thermal crack whose width varies with distance from the primary crack but is constant in time. Relatively high temperature at the tip of the lateral crack reduces water viscosity and produces positive (upwards) buoyancy. The calculation demonstrates the capability for these circumstances to generate a buoyancy-driven secondary circulation pattern in the lateral fracture, in addition to the forced-convective circulation driven by the water motion in the primary crack.

3. We have also calculated that the thermal-fracture crack width varies with time so that there is a net inflow of water into the crack. The results show no difficulty or loss of efficiency with this fracture.

Computer-generated display packages are being built into the code, which will then be used to explore the thermal-fracture dynamics for various ranges of the relevant parameters. A more detailed report is being prepared.

6.5. Geochemistry

Analysis of the fluid geochemistry data from both Segments 2 and 3 continued during the first half of FY79. By examining the composition-time behavior of a large number of the major and minor elements in the circulating fluid, we have developed a consistent model which incorporates pore-fluid displacement and kinetic dissolution rates (determined from laboratory tests on core specimens) into a differential material balance. The mass balance was constructed using recirculating, permeation, makeup flow rates, and residence-time distribution data, to show that a primary and a secondary flow path exist in the GT-2B/EE-1 system.

Our analytical capability at Fenton Hill has also been upgraded with the Atomic Absorption (AA) unit now fully operational and the substitution of improved procedures for sampling, filtering and analyzing for Al^{+3}, SO_4^{2-}, HCO_3^-/CO_3^{2-}, Cl^-, Br^-, and I^-. We are now able to extract and analyze for radon with a system very similar to that used by P. Kruger and Associates at Stanford. Dr. Kruger has been very helpful in providing analytical support and graduate student help for this project. Improved techniques for stabilizing aqueous SiO_2 have led to close agreement between spectrophotometric (I/I_0) and AA methods. In addition to those listed above, we can monitor the following major elements with equipment at Fenton Hill: Na, K, Mg, Mn, Ca, SiO_2,Fe, B, P, F, and pH, Eh, electrical conductivity, and turbidity. Gas-analysis techniques have also been developed for CO_2, NH_3, O_2, N_2, and H_2S using a chromatograph. Neutron-activation and mass-spectrometer work also continues on trace elements. We plan to include $^{18/16}O$ isotopic analysis to complement our already successful $^{86/87}Sr$ measurements.

We continued to study the interaction of rock (Biotite-Granodiorite rock, 18-24 mesh, from EE-1, 2914-2917 m or 9560-9570 ft) with water at 198°C and at 250°C to prepare for the Phase II system. We used the small-scaled autoclave reactors, rocked vigorously in Teflon and PFA cups.

In general, we used the same rock repeatedly for a given time series (1.3333 gms per 20 ml water) with fresh distilled water each time. In all cases analyses (I/I_0 and AA) were performed on unfiltered and filtered (0.1, 0.025, 0.01, and 0.001_3-μm pore-sized filters) solutions. Also some of the solutions were analyzed after the addition of 49% HF in various amounts. The HF treatment stabilizes the silica solutions and dissolves any colloids (undissolved rocks, particles, and/or silica) so that both monomeric silica (no HF) and total silica (with HF) were determined. HF was added to filtered solutions, and nothing more has been done with residues except to note the amount of material on the filters and to perform some SEM work on the residues.

In general, the concentration of silica decreases abruptly after the first water treatment and changes little, if at all, after the third or fourth treatment. For example, in successive 2-h runs each with fresh water but the same rock sample, the silica concentrations were 148, 120, 101, and 106 ppm. Similar results were also found when ultra pure, amorphous silica was successively treated with water at 198°C. The pH of the solutions was usually around 5.5 after the first rock-water treatment and rose to between ~7-8 upon successive treatments.

The difference between monomeric and total silica was in the range ~15 to 30%, and these differences were found for all solutions including those taken from the model geothermal system. We believe that the colloidal particles are mainly minute rock particles that get through the filters and are dissolved by the HF. Two samples from Fenton Hill are now being investigated in a similar manner. The first sample was water vented through EE-1 the week of March 12, 1979, and the second sample was GT-2 water from the 75-day test, taken on March 1, 1978. The amount of residue filtered out was greatest for the first and for the shortest (2- or 4-h) treatments and decreased greatly for the successive treatments or the longer (6- or 28-day) treatments. Also, the amount of residue which was examined from experiments in the titanium circulation loop was considerably less (with about the same amount of solution) than the residue from the shorter-time treatments in the Teflon cups. The titanium circulation loop has been reacting Tijeras Canyon granite (similar to GT-2B/EE-1 biotite granodiorite) with water at 200°C and at various flow rates.

Two rock samples were agitated vigorously for 2 h, washed, dried and then used successively in 6- and 28-day experiments. The autoclave reactors were placed on their sides and rocked in the oven at 190°C. Monomeric silica for the 6-day experiment averaged 190 ppm and for the 28-day experiment, 226 ppm. J. V. Walther and H. C. Helgeson (University of California, Berkeley) give 225 ppm as the solubility of α-quartz at 200°C (private communication). These same two rock samples have now been in the 198°C oven for 42 days and will be left there for about 60 days total. Tentatively, these data, combined with previous studies of rock-water interaction at 198°C, seem to indicate that a constant monomeric silica concentration is attained in about 10 days. In contrast, the first time a rock sample was treated with water at 250°C, the monomeric silica concentration averaged 381 ppm after 4 h of vigorous rocking in a PFA Teflon cup (Walther and Helgeson give 384 ppm as the solubility of α-quartz 250°C). This sample averaged 432 ppm total silica after HF treatment.

6.6 Permeability/Porosity Measurements and Modeling

6.6.1. Interpretation of Early Time Flow Histories. Since the formation and testing of the first fractures at Fenton Hill, we have found that the linear dependance of injection pressure on the square root of time suggests a one-dimensional early-time flow out of a large, low-impedance, main fracture into the surrounding matrix or joints. We interpret the early-time flow and pressure data in terms of the diffusion parameter and $\alpha = A\sqrt{k_0 \beta_0}$ where A is the area of a large, essentially zero-impedance fracture, and k_0 and β_0 are the formation permeability and compressibility, respectively. More recent developments make it necessary to examine other possibilities. Three different drillings of GT-2 (GT-2,-2A, and-2B) have failed to intersect a zero-impedance fracture. The lowest impedance connection was that of GT-2B and EE-1, which became the Phase I reservoir for run segments 1-3. Since the connecting, finite-impedance fractures are the ones being inflated during the measurement of the diffusion parameter, it is entirely possible that the impedance having this diffusion parameter is in the main fracture system. In this alternate interpretation, the early-time flow behavior is determined by the impedance and storage capacity of the main fractures themselves.

In this case, the parameters contributing to the diffusion parameter $\alpha = A_c\sqrt{k_f B_f}$ are the cross-sectional area of the fracture A_c, the fracture permeability k_f, and the fracture compressibility B_f.

The general picture that would allow this interpretation is as follows. Repeated pressurizations of the wellbore reduce the wellbore-to-fracture impedance by breaking down the rock adjacent to the wellbore or by opening existing connections into large natural fractures or into artificial fractures that are created by the same process. The subsequent pressure and flow histories are characterized by radial or linear flow into high-impedance fractures. If this interpretation is physically possible, then any intermediate case in which both fracture flow and permeation flow are important may also be possible.

This alternate interpretation must also give fracture parameters that are consistent with the other data such as those obtained from tracer studies, wellbore logs, and temperature logs. These features of the data are presently being examined and compared. To show internal consistency and agreement with the other data, we must meet several obvious criteria. Some of these are discussed briefly here.

1. Based on extensive testing at Fenton Hill, the early-time pressurization data always have characteristics that can be attributed to linear diffusion until a critical pressure is reached. During the linear phase, several fracture and flow geometries are possible: permeation flow from constant-pressure or constant-flux fractures of arbitrary shape; flow in fractures of finite conductivity; and flow in permeable zones. These possibilities are all being reviewed.

2. After the critical pressure is reached, the response of the system is determined by the pressure dependence of the geometry of the flow and storage volumes. The exact nature of the pressure dependence of the permeability, compressibility and impedance depends on the flow geometry. This relationship is being examined for evidence in favor of one of the possible fracture and flow geometries.

3. The diffusion parameters, α, impedance, and total stored volume give possible ranges of fracture size and formation properties, which must be consistent with those given by other data. This and the relationship of inflation to flow-through parameters are also being examined.

4. For flow in discrete fractures, the Reynolds number can be in the transition region between laminar and turbulent flow, so the possibility exists of flow-dependent permeability and impedance. The existing data are being examined to set the limits on the flow dependence.

6.6.2. The Compliance Matrix for Porous Rocks. It is apparent that we need more knowledge of the stress- and pressure-dependent compliance matrix that relates the six components of stress and pore pressure to the pore strains and solid strains of porous rock. This matrix may be applied to reservoir analysis, including seismic-measurement earthquake prediction and thermal-stress analysis. This may aid in determining the mechanical and hydraulic properties of the Fenton Hill reservoir and of core samples in the laboratory.

The nonlinear response of the porosity of rocks to fluid pressure and stress and the resultant pressure dependence of the rock and pore compressibilities and permeability can be attributed to the changing pore geometry and to pore-pore stress interactions. However, the extreme complexity of the pore structure limits the accuracy of the theoretical approach based on simplified crack structures. This is true of both the microstructure of pores associated with grain boundaries and large-scale fractures of the Fenton Hill reservoir.

Also, only limited data are available for both the in situ and laboratory conditions. In particular, any determination of shear moduli for the case of interest is nonexistent. Porous rock can also exhibit anisotropies arising from two sources. Intrinsic anisotropy can result from an anisotropic distribution of flat cracks. Induced anisotropies result from the response of the porosity to anisotropic stresses.

In view of the incompleteness of an entirely theoretical or entirely empirical approach, we are constructing a general compliance matrix that is consistent with known theory and data. What arbitrariness remains can then be removed by future work. The most general case to be treated will include stress and pressure dependence and anisotropy. The criteria used in the construction of the compliance matrix can be summarized in this manner: (1) It must fit existing data. (2) It must reduce to the linear case for high compressive stress and low pore pressure (closed pore conditions). (3) It must have the qualitative behavior derived theoretically for flat elliptical cracks. (4) Without intrinsic anisotropy, it must reduce to the isotropic case for isotropic stresses.

7. INSTRUMENT AND EQUIPMENT DEVELOPMENT

Downhole instrumentation is required that will be capable of characterizing the geothermal borehole environment, the hydraulic fracture system, and the resulting HDR geothermal reservoir. The instrumentation must have reliable sensors and electromechanical components that function properly in the hostile environment. Our continuing efforts, both in-house and with industrial contractors, have resulted in significant advances in several areas of downhole instrumentation and equipment development. Work accomplished during the first half of FY79 is described in the following sections.

7.1. Caliper Tool

The development of an independent multiarm caliper tool began with the design and fabrication of a prototype three-arm sonde, which can readily be adapted to six independent arms. The arms are evenly spaced circumferentially and are capable of measuring radii from 63.5 mm (2.5 in.) to 178 mm (7.0 in.) at a common depth (Fig. 7-1). Arm lengths can be varied to measure hole diameters up to 762 mm (30 in.) or can be designed for maximum sensitivity at given diameters. The arms are activated by motor and can be extended or retracted on command from the surface. Should the sonde become jammed in the borehole, the lower link will buckle and permit the arms to collapse.

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

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

The arms are spring-loaded to provide approximately 45 N (10 lb) force against the borehole wall. Motion of the arm, as it follows the hole contours, is transformed to the vertical movement of a follower rod. The vertical travel of the follower rod is then transformed to rotational motion of the external magnetic coupling with reference to the centerline of the tool (vertical axis) by use of a bead chain. The coupling's azimuthal position is determined by the use of a 350°, 5000-ohm potentiometer. The potentiometer shaft rotates with

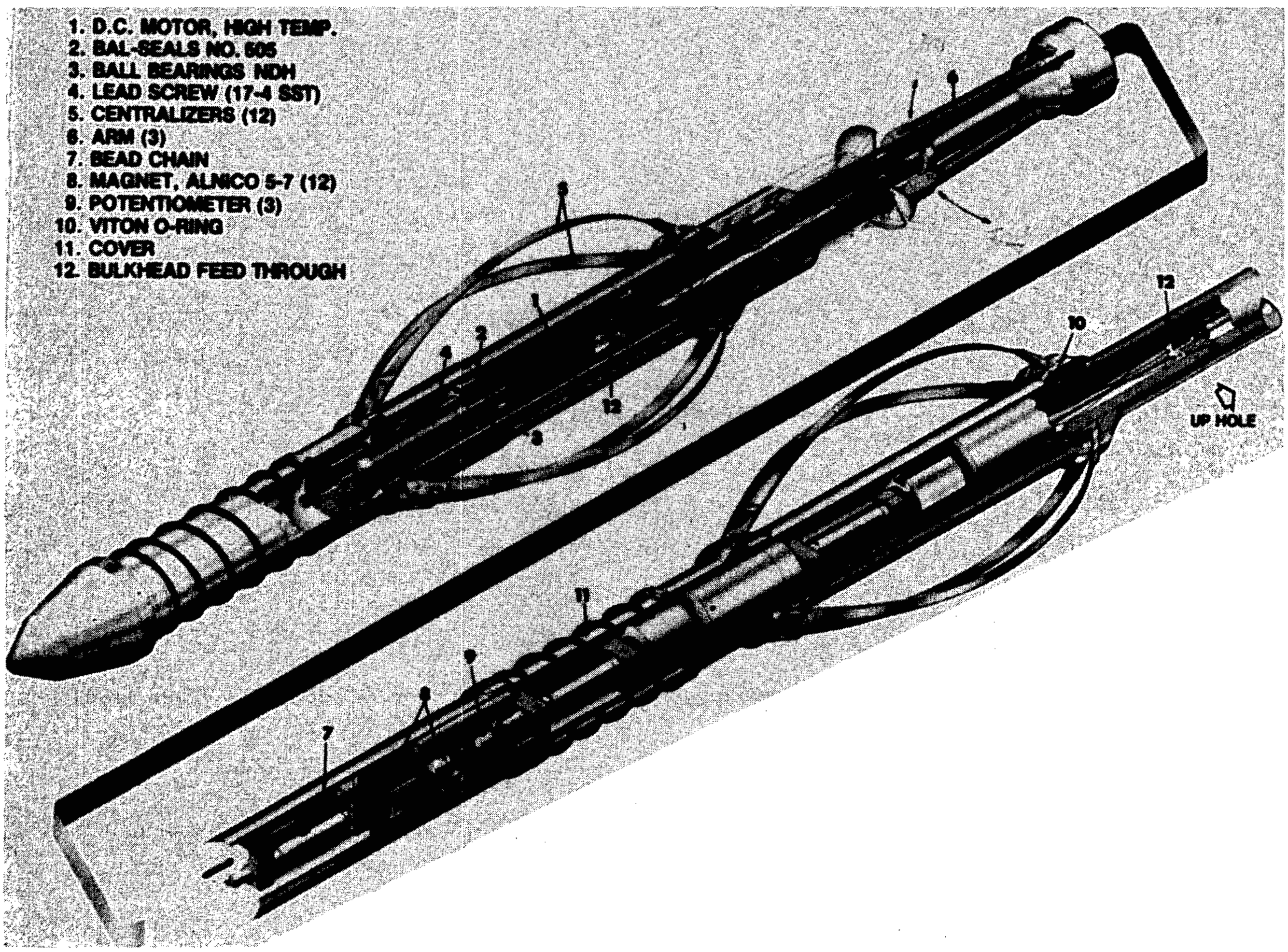

Fig. 7-1. Prototype caliper and contour tool that features three independent arms, three independent contours on strip chart, magnetic couplings, motor-operated arms, and high sensitivity.

feeler-arm motion, thus indicating arm position. The three potentiometers (one for each arm) are used as voltage dividers. A surface voltage feedback system monitors downhole voltage and maintains a constant 4 V, as sensed downhole, across the resistance elements of the three potentiometers to armor. The output signal is conditioned by low-pass filters at the surface. The data are stored on magnetic disks and plotted on-line by an HP 3050B/9830 data-acquisition system.

7.2. Spinner

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

The LASL version of the Worth Well spinner tool (Fig. 7-2) improved the sensitivity, repeatability, and resolution of the tool through modifications in several areas: the impeller size was increased from 34.5 mm (1.375 in.) to 74.2 mm (2.92 in.); the surface electronics were designed to provide better resolution and increase the analog output from 10 mV full-scale to 10 V full-scale; and a flow concentrator was designed to increase sensitivity as well as to protect the impeller. This flow concentrator does not increase the local fluid flow.

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

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

7.3. Dewar (Controlled-Environment Enclosure)

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

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

Laboratory tests demonstrated that the Dewar's instrument compartment temperature remains below 85°C for 12 h in an external temperature environment

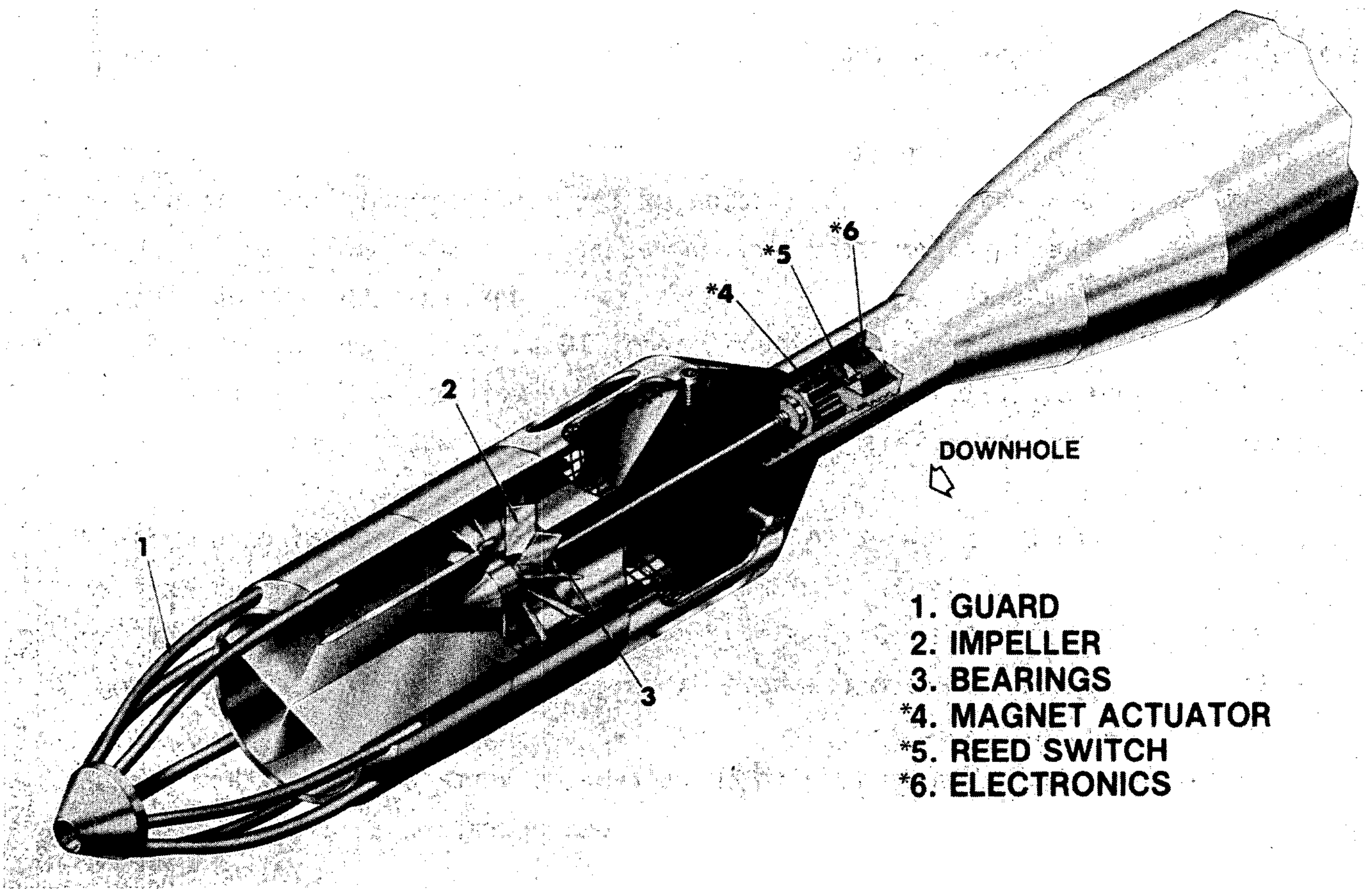

Fig. 7-2. Modified fluid-velocity spinner probe.

averaging 275°C. A source in the cavity dissipated 15 W of heat during each of the tests to simulate the output of an electronic package.

There are four Dewar sizes to hold electronics:

	External	Internal
1.	2.2 m x 114.3 mm diam (87 x 4.5 in.)	2.13 m x 87.8 mm diam (84 x 3.46 in.)
2.	0.96 m x 88.1 mm diam (38 x 3.47 in.)	0.91 m x 66.7 mm diam (36 x 2.55 in.)
3.	1.8 m x 88.1 mm diam (71 x 3.47 in.)	1.75 m x 66.7 mm diam (69 x 2.55 in.)
4.	1.82 m x 50.0 mm diam (72 x 2 in.)	1.77 m x 38.6 mm diam (70 x 1.52 in.)

7.4. Downhole Injector and Gamma-Ray Detector

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

High-purity amonium bromide is prepared by irradiation with neutrons at a nuclear reactor in Los Alamos. The ^{82}Br has a half life of 35.4 h and its principal gamma energies are from 554 to 1474 keV. For irradiation, the solid NH_4Br is sealed in a quartz ampoule. To prevent irradiation of personnel working with the sonde, the ^{82}Br is transported in a lead pig. The sonde is bolted onto the upper portion of the pig, which then comes apart to become part of the sonde (see Fig. 7-3).

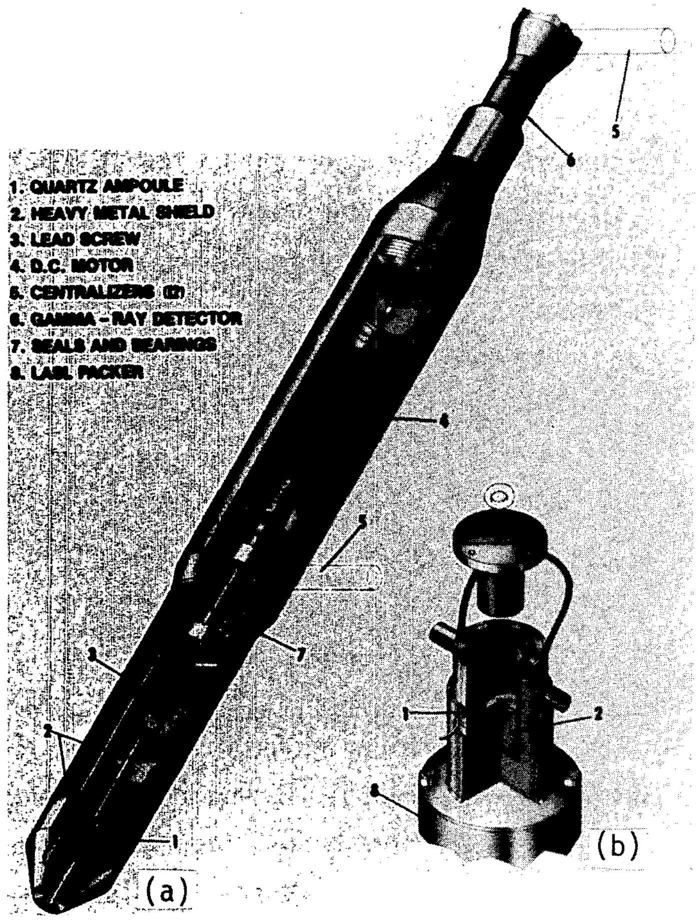

Fig. 7-3. (a) Downhole ^{82}Br injector and gamma-ray detector. (b) Lead pig assembly fixture.

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

7.5. Downhole Detonator Acoustic Source

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

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

The uphole unit was designed by Reynolds Industries. It consists of a variable trigger voltage and special connector to select manually any one of the 12 channels. A timer was added by LASL to control accurately the capacitor charge and automatically trigger the downhole firing module.

The detonator rack has three levels, each of which will accommodate four detonators. Connections to the detonators are made through Kemon coaxial boots and feedthroughs. All the detonators (RP 84) are HNS exploding-foil type, designed to withstand high temperatures (275°C) and pressures greater than 345 bars (5000 psi) and are inherently safe from accidental detonation during transit and handling.

7.6. Geophone Sonde

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

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

The downhole switching system is mounted on the outside of the Dewar to enable multiplexing of additional information. The switches are Teledyne DPDT Relays (part number 412H-12), which operate from -65°C to 265°C. The relays were tested in an oven at 270°C for a period of 4 h without failure.

The geophone sonde was field tested in the GT-2B borehole during a recent wellbore pressurization experiment. (See Expts. 195, 196, and 203). The field test data (borehole temperature of 170°C) were taken during continuous operation for 30 h. Further laboratory experiments will test the sonde to design criteria of 14 h at 275°C.

7.7. Instrumentation Cable Samples for Evaluation

Three 1000-ft multiconductor sample cables and four 1000-ft coaxial sample cables are being purchased for testing. Comparison of high-temperature materials, manufacturing process, electrical performance, and failure mode will be performed at LASL. A chamber has been designed that permits pressurizing, tensioning, and heating a 20-ft sample cable. Typical pressure, axial load, and temperature to simulate the average downhole environment have been selected as 20.6 MPa (3000 psi), 13.3 kN (3000 lbs) and simulation of a maximum environmental temperature of 275°C. Terminal ends of the electrical conductors are accessible for electrical characterization measurements during testing.

7.8. Downhole Instrumentation, Industrial Contracts

7.8.1. Borehole Optical Survey System. Two firms were selected to conduct a Phase I study of the borehole optical survey system (BOSS): Hydro Products and Measurement Analysis Corporation. This study should be completed by June 1979. The Phase I study provides a fixed-price, level-of-effort contract to each bidder, who may then further study the feasibility, preliminary design, and cost of the system. Results of Phase I will be used as the basis for LASL evaluation in awarding Phases II and III of the program for the preferred system.

Phase I response will provide the following:

1. Schedules for development, delivery, and testing;
2. Cost breakdowns for Phases II and III
    a) engineering design costs,
    b) fabrication costs,
    c) parts list for components comprising the system, cost of each, and identification of long-lead procurements/developments,
    d) 20 000 ft of armored coaxial cable,
    e) checkout of functional testing expense, and
    f) travel and other expenses;
3. Definition, in as much detail as possible, of the configuration selected for the total system;

4. Identification of the key problem areas encountered and the solutions provided or proposed;
5. Brief description of proposed bench tests and in situ tests for acceptance;
6. Sufficient technical data to permit engineering evaluation for award of Phases II and III (for example, compliance with LASL Specification HDRS-8547G);
7. Preliminary discussion of anticipated problem areas, definition of configuration, estimated cost for a follow-on real-time color system (this discussion shall address the cable issue in depth); and
8. A performance specification shall be supplied for a two-layer contrahelical-armored coaxial cable.

7.8.2. Acoustic Transceiver. The design review of the acoustic transceiver being developed by Simplec was held on February 5 and 6, 1979. Preliminary drawings of the transceiver were reviewed and design improvements were suggested. The mode of operation was discussed and complies with LASL specifications. Downhole electronics were also reviewed and will comply with specifications.

The coding technique that will be used for range identification (scaling) is a BCD code that will be transmitted uphole by a downhole UART (Universal Asynchronous Receiver Transmitter). A second UART at the surface will convert the word back to parallel.

The requirement for downhole orientation was discussed, and it appears superfluous since the receivers are nondirectional. Manufacturing has not yet begun; delivery is delayed 4 months.

7.9. Directional Drilling Equipment Development

A high-temperature turbodrill is being developed for directional drilling in the hot, dry, granitic rock. Over the past two years, the turbodrill design has evolved at Maurer Engineering, Inc. and is being fabricated and assembled by that firm. The turbodrill is 196.8 mm (7 3/4 in.) diam x 7.0 m (23 ft) long and is capable of developing over 1085 N-m (800 ft-lb) of torque at 150 rpm to turn a 310-mm-(12 1/4-in.-) diam drill bit in hard granite. It is designed to operate at rock temperatures up to 275°C. The drill was successfully tested in a laboratory in March 1979 and developed full torque at water flow rates of approximately 450 gpm. It was further tested by drilling into granite specimens in the laboratory in April 1979. The turbodrill design incorporates high-temperature roller thrust and radial bearings for long operating life while drilling. Special high-temperature shock absorbing tools have been designed and fabricated for use with the turbodrill to alleviate the deleterious impact loads associated with drilling in hard granite. These shock absorber tools were also tested in April 1979.

A high-temperature downhole steering tool has been developed by Eastman Whipstock, Inc. for use with the turbodrill to enable accurate directional drilling.

Because the turbodrill rotary speed is not directly proportional to the fluid flow rate, the optimum rotary speed is difficult to control from the surface while drilling. An instrument that will indicate rpm directly at the surface is being developed by Sperry Research Center for use with the turbodrill.

8. EVALUATION OF RESOURCE POTENTIAL AND SITE SELECTION

8.1. Introduction

The geologic activities discussed in this section have two major objectives: (1) to define large areas of the United States where HDR geothermal extraction techniques might be utilized, obtain an estimate of the number of sites that might be developed within these areas, and calculate the amount of thermal energy that might be ultimately available; (2) locate specific sites for testing the HDR method under different geologic conditions. The dual objectives of the work have led to the creation of two interacting and overlapping but separate series of tasks. Collection of new data for the evaluation of resource potential also leads to the selection of areas for reconnaissance and detailed site-selection investigations. In turn, data obtained from site-selection investigations further quantify our estimates of the HDR resource potential.

The evaluation of the HDR potential of the United States is closely tied to the geothermal assessment activities of the US Geological Survey (USGS). To ensure that the programs and activities are complementary, several meetings have been held between LASL staff and Robert Christiansen and Donald Klick of the USGS. Summaries of these meetings have been sent to both DOE/DGE and the USGS. Extremely good working relations have been established, and there is a very free exchange of data between the USGS and LASL.

HDR program activities in resource-potential evaluation have concentrated on stimulating the production of high-quality heat-flow measurements by the academic heat-flow community. To help accomplish this task, a meeting was held at Los Alamos in December 1978 which was attended by heat-flow experts from the USGS and many universities. Means of stimulating more heat-flow measurements were discussed, and ultimately several new proposals were received from the group. We are now funding Decker of the University of Wyoming for work in Wyoming, Colorado, Utah, and Nebraska; Eckstein, Heimlich, and Palmer from Kent State University for work in Ohio and Pennsylvania; and Costain, Glover, and Sinha from Virginia Polytechnic Institute and State University (VPI and SU) for work in Maryland. Subcontracts are being negotiated with Smith of the University of Florida to work in Florida, Mississippi, Alabama, and Louisiana; Roy from University of Texas-El Paso for work in Arkansas; and Steeples from the Kansas Geologic Survey for work in Kansas. In most cases, existing drill holes are used for the heat-flow measurements — a cost-effective method of acquiring new data.

We define large regions of high heat flow by deep penetrating geophysical methods. Presently, methods such as magnetotelluric (MT), gravity, and aeromagnetic (Curie-point-depth determinations) are being used. Several reconnaissance MT lines have been run in New Mexico and Arizona, and additional work is being contracted for measurements in Arizona, Oregon, and Nebraska. A variety of geological and geophysical evidence of high geothermal gradients was used to select the MT sites.

About ten areas in the United States were examined for possible site prospects during FY-78 and the first quarter of FY-79. Results of these investigations were presented to the Site Selection Advisory Panel for their consideration. The Panel's deliberations will be discussed in the next section. In brief, however, the Panel recommended two areas to DGE for detailed investigation during the remainder of FY-79 and early FY-80.

Concurrently, reconnaissance work has continued on the remaining eight areas, not recommended at this time, and on several additional areas.

8.2. Exploration Philosophy

There are multiple goals for the HDR program. Of major importance is the need to find additional sites where the technology of HDR energy extraction may be tested successfully. A second important consideration is the need to demonstrate that energy can be extracted from hot, low-permeability rock in a variety of different geologic environments. This second consideration removes some of the constraints imposed by the very limited distribution of hydrothermal geothermal systems. These goals are to some degree contradictory because different geologic environments will require modifications of the extraction technology to accommodate the differences in permeability, physical nature, and chemistry of the potential reservoir rocks. Ideally, the current extraction technology would be tested in at least one other area as similar as possible to Fenton Hill. At that time, reservoir conditions could be gradually changed so that the extraction techniques would vary only slightly from one site to the next. Unfortunately, neither the time nor the money is available for such a logical but leisurely approach. More abundant heat sources must be sought and the extraction technology must be adapted rapidly to meet the new conditions.

Successful exploration for any type of natural resource requires development of an exploration philosophy. This philosophy is simply a statement of a hypothesis or series of hypotheses that relates observations to the existence and genesis of the resource. In other words, the exploration philosophy postulates possible origins for the resource and then attempts to determine where these processes may have taken place by examining geological evidence. To be useful, the philosophy must specify the types of evidence that are suggestive of the occurrence of these processes.

Young, silicic calderas of the Valles Caldera type, unquestionably represent some of the highest grade portions of the HDR resource base. Unfortunately, however, these features are relatively rare and not geographically convenient for users. Because of their very nature, they are scenic areas with particularly rigid environmental and institutional constraints on development.

Larger, lower grade, but more widely distributed heat sources, appear to offer the greatest ultimate potential for widespread utilization of the HDR method. These heat sources can be produced in a number of ways. In the western United States, entire geologic or tectonic provinces have heat flows considerably above the worldwide average. Some of these, for example, the Rio Grande Rift, are related to deep crustal or mantle processes that heat the upper crust. Such regions are attractive prospects for HDR exploration. Widespread, voluminous, intermediate-to-basaltic vulcanism of long duration can also cause thermal anomalies producing large areas suitable for HDR development. Examples include the Cascade Range, Snake River Plain, and Jemez Lineament.

In the eastern United States and in the mid-continent region, the absence of significant volcanism and tectonism and the concentration of population and hence of energy users, make still lower-grade heat sources attractive targets for exploration and development. Much effort is currently being directed toward the search for plutons enriched in radioactive, heat-producing elements, buried beneath thick blankets of insulating sediments. Impermeable basement rocks beneath deep basins may, in the future, become geothermal targets.

Each of these different heat sources has a different genesis and thus requires a different exploration philosophy. Although all require an integration of geological, geophysical, and geochemical methods, emphasis will vary with the type of heat source sought.

The high heat-flow tectonic province is probably best sought by a combination of traditional geologic mapping, geophysical measurements, and modern tectonic theory. Aqueous geothermometry, as utilized by workers such as Swanberg, may also contribute to the recognition of such provinces. Although heat-flow measurements are undoubtedly important, this is not a particularly cost effective reconnaissance exploration method, and more emphasis should be placed on the correlation of other geophysical, geochemical, and geological methods with high heat flow. In the United States, we appear to be far behind the Europeans in such efforts.

Regions of voluminous intermediate-to-basaltic vulcanism are more amenable to exploration because young igneous rocks serve as surface indicators of possible elevated heat flow. Again a combination of techniques is best suited for the characterization of these heat sources. Geologic mapping and geochronology define the igneous activity in space and time. Geochemistry, including radiogenic and stable-isotope tracer investigations, aids in evaluating the amount of crustal interaction. Geophysical investigations clarify geologic structure in potential reservoir rocks; the highest-grade parts of the area are defined on the basis of heat-flow measurements.

The buried plutons of the eastern U.S. are the most obscure geothermal targets because of their great depth of burial and the blanketing effect of the overlying sediments. Detection of these "blind" targets requires use of geophysical techniques such as gravity, aeromagnetics, and seismic investigations. The VPI and State University group has demonstrated the effective use of heat-flow drilling after regional and detailed gravity, aeromagnetic, and seismic surveys. Analogy with known geologic features has also proven useful.

8.3. Work in Progress

8.3.1. Evaluation of Resource Potential. Some level of effort is now being expended in 30 states. These efforts, which are summarized in Table 8-I, vary from literature searches to heat-flow investigations, gravity and MT surveys, and reconnaissance geologic mapping. Because of the limited manpower available at LASL, much of this work is performed by academic and industrial subcontractors with LASL personnel acting as technical managers and coordinators. These subcontracts are summarized briefly in Table 8-II. Technical work by LASL staff has been concentrated in Arizona, New Mexico, Arkansas, and Idaho.

TABLE 8-I

EVALUATION OF RESOURCE POTENTIAL
SUMMARY OF CURRENT ACTIVITIES

	Literature Search	Data Compilation	Heat Flow	Mapping	Water Geochemistry	Other Geophysics	Geo-chron-ology
Alabama			1				
Alaska	+	+					
Arizona	+	+	+	+	+	+	+
Arkansas	+	+	1	+	+		
California	+	+					
Colorado	+	+	+				
Florida			1				
Georgia			1				
Idaho	+	+	1	1	1	1	
Kansas			1				
Louisiana			1				
Massachusetts			1				
Maryland	+	+	+	1	1	1	
Mississippi			1				
Nebraska	+	+					
Nevada	+	+					
New Hampshire	+	+					
New Mexico	+	+	+	+	+	+	
New York	+	+	+		+	+	
North Carolina	+	+				+	
Ohio			+				
Oregon	+	+				1	
Pennsylvania			+				
South Carolina						+	
South Dakota	+	+				+	
Texas	+	+					
Utah	+	+					
Virginia	+	+	1	1	1	+	
Washington	+	+					
Wyoming			+				

+ = Work in progress. 1 = Contract under negotiation.

Most of the subcontracts listed in Table 8-II were negotiated during the quarter of FY-79, and the work is only now getting started. Despite this, the results are encouraging. Some of the highlights of these efforts are summarized below.

(1) First heat-flow measurements were obtained in Ohio.

(2) Nine new heat-flow measurements were obtained in Colorado. Values range from 1.58 to 3.62 HFU.

(3) Three new heat-flow values were obtained from Wyoming. Values range from 1.1 to 1.62 HFU.

(4) Residual Bouguer gravity map of New Mexico was published.

(5) Report of MT survey of Jemez Mountains, New Mexico published. J. Hermance, Brown University, recognized a 15-km deep magma body under the southeast side of the mountains.

(6) Reconnaissance MT survey of Arizona and New Mexico was completed. Interpretation is in progress.

(7) Gravity survey (~4000 stations) was completed in Virginia, North Carolina, and South Carolina to assist VPI group.

(8) A geophysical lineament map of Arizona has been generated and is being prepared for publication.

Although at the present time we are very much in the data-collection and compilation mode, contacts have been made with Paul Grim of NOAA (National Oceanic and Atmospheric Administration) to arrange for preparation of new gradient maps.

8.3.2. Site Selection. During the past six months, reconnaissance-scale exploration has begun or continued in several areas throughout the U.S. LASL-internal efforts have concentrated on three general areas: Zuni Mountains, New Mexico to Springerville-St. Johns, Arizona; the Aquarius region of Arizona; and the Lucero Uplift area of New Mexico. LASL personnel have also worked closely with USGS personnel investigating the hydrothermal geothermal potential of the Mt. Hood and Snake River Plains regions. Much of the information generated by the USGS in these areas is pertinent to our investigations. Heat-flow measurements performed by the USGS in northwest Arizona have contributed significantly to our work in the Aquarius area.

Several new prospects have recently been selected for reconnaissance work during the remainder of FY79. These include the Brothers fault-zone region in

TABLE 8-II

HDR FEDERAL PROGRAM SUBCONTRACTS
IN RESOURCE POTENTIAL EVALUATION AND SITE SELECTION

RESOURCE EVALUATION

Subcontractor	Institution	Abbreviated Statement of Work
Dennis Hodge	SUNY-Buffalo	Evaluation of HDR potential of New York and Massachusetts using gravity, heat flow, and water geochemistry.
John Costain Lynn Glover III Krishna Sinha	VPI and SU	Study contract to investigate distribution of 300 m.y. granites in eastern U.S. and their potential as HDR heat sources. Amendment covers heat-flow drilling of Baltimore gabbro.
Paul Hammond	Portland State Univ.	Compile and publish geologic map of southern Cascade Range.
Williston, McNeil Associates	Portland State Univ.	Magnetotelluric reconnaissance survey of parts of Arizona and New Mexico.
Stan Davis	Univ. of Arizona	Organize and chair a workshop on the hydrology of crystalline basement rocks.
L. K. Lepley	Private Consultant	Compile a geophysical lineament map of Arizona.
Carlos Aiken	Univ. Texas-Dallas	Synthesize and interpret geophysical data long MT lines in Arizona.
Yoran Eckstein Richard Heimlich Donald Palmer	Kent State Univ.	Determine HDR potential in Ohio and Pennsylvania. Both heat-flow and heat-generation measurements being made.
E. R. Decker	Univ. of Wyoming	Perform heat-flow measurements in Wyoming, Colorado, Utah, and Nebraska.
Paul Morgan Randy Keller	New Mexico State Univ. Univ. of Texas-El Paso	Passive and active seismic studies of potential HDR prospects Arizona and New Mexico. Investigations include fault detection and determination of base-level seismic activity.

TABLE 8-II
(CONTINUED)

Subcontractor	Institution	Abbreviated Statement of Work
John Kaur	Digitgraph Computer	Gravity survey of N. Carolina, S. Carolina, and Virginia to assist in HDR evaluation of Atlantic Coastal Plain.
Don Steeples	Kansas Geological Survey	Deepen two drill holes in Kansas Precambrian basement and obtain heat-flow measurements (in negotiation).
Robert Roy	Univ. of Texas-El Paso	Perform heat-flow measurements in Arkansas (in negotiation).
Douglas Smith	Univ. of Florida	Perform heat-flow measurements in Florida, Alabama, Mississippi, and Louisiana (in negotiation).
John Husler	Univ. of New Mexico	Perform water analysis for geothermometry.
John Husler	Univ. of New Mexico	Perform whole-rock chemical analysis for HDR exploration.
In Negotiation	-----	Perform detailed geologic, geophysical, and geochemical investigation of 100 sq mile area in eastern US.
In Negotiation	-----	Perform detailed geologic, geophysical, and geochemical investigation of 100 sq mile area in western US.
Dr. Merlivat	DRA/SRIRMA, France	H^2 and O^{18} analysis of geothermal water samples.
Robert Ferguson	Argonaut	Reconnaissance MT survey in Arizona and New Mexico.
In Negotiation	-----	Detailed MT, AMT, and telluric profiling survey.
Marc Sbar	Univ. of Arizona	Seismic-refraction survey in Arizona to determine crustal thickness and nature of Colorado Plateau and Basin and Range boundary.
D. Krummenacher	San Diego State	Perform K/Ar dating for HDR exploration.
Peter Hoyser	Washington State Univ.	Perform whole-rock chemical analysis for HDR exploration.

southeast Oregon, a portion of western Nebraska, an area of high heat flow near Yuma, Arizona, and the Williams Air Force Base near Phoenix, Arizona. Multiple lines of evidence suggest that these regions may be abnormally hot and suitable for HDR exploration.

In the eastern U.S., Dennis Hodge of SUNY-Buffalo, under a subcontract, has identified two regions of higher than average gradient near Buffalo and Syracuse, New York. Although these areas were not recommended for detailed investigations in FY79, the level of funding to this group has been increased to accelerate the reconnaissance exploration.

The Los Alamos Scientific Laboratory has subcontracted with VPI and SU to drill two heat-flow holes in the Baltimore gabbro. This work will be completed during the next 6 months. Arrangements have also been made with DOE, VPI, and Gruy Federal for LASL to fund the deepening of the Gruy Federal drill hole near Crisfield, Maryland. Deepening of this hole will provide information on the metamorphic basement, which presumably serves as a heat source in this area. It will also provide the opportunity for hydraulic fracturing in a geologic environment different from that at Fenton Hill.

8.3.3. Target Prospect Selection. On February 1 and 2, 1979, the HDR Site Selection Advisory Panel met at Los Alamos. The panel consists of R. Christiansen, USGS, G. Crosby, Phillips Petroleum Co., H. Olsen, AMAX Exploration Co., Y. Isachsen, New York State Geological Survey, and M. Wright, University of Utah Research Institute. R. Christiansen was elected chairman of the panel.

The first part of the meeting was devoted to presentations concerning the geologic and institutional aspects of seven potential HDR sites. Two of these areas were to be selected for detailed geologic and geophysical characterization during FY79.

8.4. Summary of Site Presentations

8.4.1. Atlantic Coastal Plain. (J. Lambiase and R. Gleason, VPI and State University.)

Researchers at VPI are exploring low-temperature heat sources beneath the Coastal Plain and testing a model for predicting the location of these heat sources. The model predicts that granitic plutons with relatively high concentrations of U and Th will serve as low-temperature radiogenic heat sources and that overlying Coastal Plain sediment will act as an insulator. VPI is testing aquifers, heated by these thermal sources, located at the base of the Coastal Plain. This is a potential hydrothermal source but, if drilling is extended into the granitic plutons, a HDR resource may also be identified.

Patterns of geothermal gradients (75% are >30°C/km) and Bouguer gravity data suggest that numerous granitic plutons are located in the basement beneath the Atlantic Coastal Plain. These data indicate that the line of plutons extends under the Virginia Coastal Plain, encompassing much of the Chesapeake Bay and Delmarva Peninsula Region.

Two possible locations for HDR development are Stumpy Point, North, Carolina, and Wallops Island, Virginia, because of relatively high geothermal gradients and thick sedimentary sections that should produce basement surface temperatures of ~90°C. The Stumpy Point area is located over a large, subcircular 45 Mgal gravity low and the geothermal gradient is 13°/km higher than gradients located off of the gravity low.

Wallops Island, Virginia, is part of a belt of high geothermal gradients near Chesapeake Bay and the Delmarva Peninsula and is thought to be related to a large concordant pluton within a northward extension of the Hatteras Belt. Estimated basement surface temperature is 90°C, below 2.16 km of coastal plain sediments.

8.4.2. Aquarius Plateau, Arizona. (F. Goff and F. West, LASL). In searching for a geothermal province to be developed as a HDR resource, a cross-correlation of regional geophysical data for Arizona indicated a region of anomalously high heat flow in northwest-central Arizona. The region, named after the Aquarius Mountains, lies on the west edge of the Colorado Plateau at the boundary with the Basin and Range province. The geology of these mountains consists of Precambrian granitic and metamorphic rocks overlain by lavas and tuffs, predominantly of Miocene age. There have been three episodes of silicic vulcanism in the area in the Fort Rock volcanic field (pre-17 Myr), Aquarius Mountains (pre-17 Myr) and Black Mesa volcanic field (past 17 Myr). Small isolated springs were sampled; chemical geothermometry and isotope data indicate that the waters have equilibrated at temperatuares of ≤115°C. There is little "wet" geothermal potential in the area, but HDR development may be possible in the structurally intact basement beneath the Aquarius Mountains if the geothermal gradient and heat flow are high enough.

8.4.3. Buffalo and Syracuse, New York. (D. Hodge, State University of New York-Buffalo and C. Swanberg and P. Morgan, New Mexico State University). Preliminary work, examining the American Association of Petroleum Geologists (AAPG) temperature gradient maps have revealed the existence of several areas in New York State that have higher than normal temperature gradients and may represent low-temperature geothermal prospects. Two of these anomalies are located just southeast of Buffalo, New York, and southwest of Syracuse, New York. Both have temperature gradients of ~36°/km and are associated with negative temperature anomalies, which are being interpreted as granitic plutons, whose radioactivity is responsible for elevated temperatures. The basement is overlain by 1 to 2 km of paleozoic sedimentary rocks that may act as an insulator. Heat-flow measurements, with maximum values of 1.55 and 1.72 HFU, were made just south of the two anomalies.

8.4.4. Cascade Range, Washington and Oregon - General Case. (J. Eichelberger, LASL). The Cascade Range has been the site of persistent but episodic vulcanism for the last 40 Myr. Tertiary- and Quaternary-age volcanic fields extend unbroken from Lassen Peak in California to Mt. Rainier in Washington. Within northern California and north of Mt. Rainier, Paleozoic and Mesozoic plutonic and metamorphic rocks underlie the volcanic fields. Elsewhere the older basement is not exposed and may be more than 3-km deep. However, isolated Tertiary-age plutons, comagmatic with the older Cascade vulcanism, crop out within the high Cascades as far south as Mt. Hood. These may be present throughout the range at depth.

The southern Cascade Range has a history of extensive Pleistocene and Holocene vulcanism where it is overlapped by Basin and Range structure in California and Oregon and northwest-trending folds in Washington. Most of the major volcanoes have erupted within the last 10^4 years. Lassen Peak erupted in 1915.

Young silicic lavas are more abundant south of Newberry Crater and Crater Lake, Oregon. Some of these fields may have active magma chambers within a few km of the surface. There are active fumaroles in Lassen Volcanic National Park. Once the potential basement reservoir rocks are identified, there are many potential HDR reservoir sites in the Southern Cascade Range, asociated with shallow silicic magma bodies.

8.4.5. Snake River Plain, Idaho. (D. Mabey, USGS and R. Pettitt, LASL). The Snake River Plain (SRP), a major tectonic feature, extends as a huge arc from eastern Oregon to the Yellowstone Plateau in western Wyoming. The western half of the Plain is a deep trough, originating 10 to 15 Myr ago and filled with Cenozoic volcanic rocks and sediments. The eastern part of the plain may be a regional downwarp, due to an episode of vulcanism which progressed from southwest Idaho to Yellowstone Park. Silicic volcanic rocks have ages ranging from 9 to 13 Myr in western Idaho to 0.6 Myr in eastern Idaho. Young basalt flows (10 000-yr old) occur all along the SRP. On the southwest margin of the plain, in the Rexburg area, a large (45-km-diam) caldera has been identified and is partly covered by younger basalt flows.

Heat-flow values average 1.7 HFU in the center of the western SRP and 2.5 HFU in granitic rocks along the margin. Heat-flow values of 1 HFU are encountered in the center of the eastern SRP, with values of 3 to 5 HFU in the southern boundary.

The western SRP is characterized by large but relatively simple gravity and magnetic anomalies. A model that will produce the total combined gravity and magnetic anomalies assumes a simple deep structure producing the regional gravity high, with the local gravity lows reflecting shallow Cenozoic rocks. On the basis of a resistivity profile run across the eastern SRP, Paleozoic basement occurs at 3 to 4.5 km depths within the SRP.

8.4.6. Springerville, Arizona (C. Stone, State of Arizona). On the basis of moderate to high geochemical temperatures and the presence of very young volcanic rocks of the White Mountain volcanic field, an area between St. Johns and Springerville, Arizona, may be anomalously hot. The volcanic field overlies sedimentary rocks of Pennsylvanian to Quaternary age. One drill hole located north of Springerville encountered bedrock at a depth of 700 m. Active volcanism of the White Mountain volcanic field began in late Miocene and continued intermittently into recent time. High temperatures, as indicated by high Na-K-Ca geothermometers, coincide with deposition of youthful travertine mounds between St. Johns and Springerville.

Several lineaments intersect in this area and a negative Bouguer gravity anomaly coincides with a postulated rise of the Curie isotherm to a depth of 5 to 10 km. A single gradient of 50°C/km has been measured in the area.

8.4.7. Zuni Uplift and Volcanic Field, New Mexico. (G. Heiken, LASL). The Zuni Uplift is a northwest-trending, oval uplift about 120 km long and 50 km wide, located in west central New Mexico. Precambrian igneous and metamorphic rocks are exposed along the west, and Permian through Mesozoic age sedimentary rocks crop out along the flanks of the uplift. Heat-flow values around the uplift range from 1.4 to 1.7 HFU along the east and northeast flands and 2.0 to 3.9 HFU on the southwest and northwest flanks. Within the uplift itself, heat flow values range from 1.4 to 2.4 HFU.

A positive, northeast-southwest trending gravity anomaly, 90 km long and about 30 km wide, extends southwest from the highland. The Zuni volcanic field, a line of basaltic vents, is parallel to the eastern edge of the gravity anomaly. Although data are incomplete, we think eruptions along this chain occurred over a period of about 3 Myr to the present (youngest date is about 1000 yr).

The large gravity anomaly may be due to a large basement structure that has controlled sedimentary depositional patterns in the area since Cambrian time, the orientation of the volcanic chain, and deformation of the sedimentary section.

Elevated heat flow in the area may be due to young basaltic intrusions, radiogenic heat contributions from Precambrian granitic rocks, or both.

8.5. Recommendations of the HDR Site Selection Panel

The panel ranked the sites presented, through considerations of geology, demography, and institutional considerations. A major controlling factor in their ranking was the requirement of a ~125°C temperature at 3-km depth. The rankings were as follows:

1. Snake River Plain and Cascade Range,
2. Zuni Uplift and Springerville,
3. Aquarius Mountains, and
4. New York and Atlantic Coastal Plain.

The SRP was highly rated due to the high temperatures and known occurrence of crystalline rocks in the Idaho Batholith along the north flank of the SRP between Boise and Weiser. Access, permitting, and market within the region are also favorable.

The Cascade Range, with many appropriate heat sources in the form of shallow magma bodies, was also highly rated. The large extent of this region and limited knowledge of it make selection of specific sites impossible at this time. Due to new geologic work in the area, the Cascades may be the location of several prime HDR sites within several years.

The Zuni Uplift and volcanic field are promising, but more work, including heat-flow measurements, is needed before further consideration of the area for HDR development.

The Springerville, Arizona, area was not rated highly due to lack of data at this time. The Aquarius Mountains were not highly rated due to lack of heat-flow data and indications that heat-flow is normal for Basin and Range Provinces.

The New York State and Atlantic Coastal Plain areas were at the bottom of the list due to fairly low temperatures (which could, however, be used for heating and industrial processing).

8.6. Selection of Two Areas for Detailed Geological and Geophysical Investigation

Two contracts, one for the eastern U.S. and one for the western U.S., are for detailed geological and geophysical characterization of areas of about 260 Km^2 (100 mi^2). On the basis of those results, HDR Site No. 2 may be selected. Subcontracts are now being negotiated with geothermal companies for the detailed investigation of the two target prospect areas. The work statement for subcontracts for the western area follows

8.6.1. Objectives. The primary objective of this effort is the detailed evaluation of the hot dry rock potential of a previously selected prospect comprising an area of approximately 100 square miles (3 townships). This evaluation shall consist of determination of the geothermal gradient present within the prospect and an assessment of the expected reservoir permeability at a depth where the temperature appears to be sufficiently high for utilization for either electrical generation or direct application of thermal energy (DATE). The evaluation shall conclude with recommendations for a specific deep exploratory drilling program, including site locations, specified additional exploration work, abandonment of the prospect, or perhaps testing for the existence of possible hydrothermal systems.

A secondary objective is to record the contribution of this detailed prospect evaluation to the development of a cost-effective exploration program for locating HDR deposits and selecting sites for their development.

In summary, the objectives of this Target Prospect evaluation shall be:

(1) determination of thermal gradient,

(2) estimation of reservoir rock permeability at depth,

(3) recommendations for further action, and

(4) identification of HDR contribution exploratory techniques.

8.6.2. Background. Although differences exist among estimates of the size of the HDR resource base, all agree that it is immense. If even a fraction of this resource base can eventually be tapped as an alternate energy source, the effect upon the world's budget will be tremendous. The first step in moving from resource base to resouce has been made at the LASL Fenton Hill site in northern New Mexico, where it has been demonstrated that artificial geothermal systems can be created in and energy extracted from hot dry rocks.

To advance from resource base to resource, two other demonstrations must be made concurrently. The economic feasibility of the extraction system must be evaluated and additional sites must be selected to demonstrate the widespread nature of the resource. This effort addresses the second of these demonstrations, locating and evaluating additional sites.

In 1971, several LASL staff members conceived the HDR geothermal energy extraction concept, and the search began for a region in which to test this method. The intent of the exploration was to provide a drill site at which to develop a method for extracting geothermal energy that was broadly applicable, particularly in regions where natural hydrothermal resources are lacking, or in portions of geothermal systems where hydrothermal resources are known not to exist. Because the first site was intended to be used as a test of the extraction method, it was decided to minimize costs by selecting an area where adequate rock temperatures could be reached at moderate depths. Thus, at the first drill site, it was hoped that impermeable rock (less than 0.01 millidarcy) at a temperature of at least 200°C would be encountered at depths of less than 3 km. In addition, it was recommended that to prevent fluid leakage to the surface, the top of the artificially generated fracture should lie at a depth below the surface at least equal to the diameter of the fracture. Environmental criteria for the drill site such as low seismic activity, minimal disturbance of land, water, vegetation, and aesthetics were also proposed.

The area selected by LASL for the location of Geothermal Test Hole No. 2 (GT-2) and the first borehole of the energy extraction system (EE-1) is at

Fenton Hill, within the Jemez Mountains, Sandoval County, New Mexico. It is located on the western flank of the Valles Caldera, about 32 km west of the city of Los Alamos, with access provided by the New Mexico Highway 126. The area lies within a large burned-over area on US Forest Service land where the environmental impact of drilling has been minimal. In terms of regional geologic setting, the Valles Caldera is a large, young silicic volcanic complex occurring along the western margin of the Rio Grande Rift.

The selection of the Fenton Hill site was unique in the sense that the goal of LASL, as originators of the hydraulic-fracture concept for HDR geothermal energy extraction, was to locate a test site where the extraction method could be tested and demonstrated. Location of impermeable rock suitable for an experimental program to test the feasibility of the extraction technology was of primary importance. At the time the Jemez Mountain region was selected, no formal goethermal energy project existed at LASL, and evaluation of regional and areal geology for targeting a drill site was done by volunteers in the evenings and on weekends. This limited the area that could be evaluated to one near Los Alamos. In addition, only limited funding was available for regional evaluation and collection of new data. Because of these two constraints, considerable reliance was placed on published maps and reports, and on open-file maps and reports made available by the Department of Interior, USGS.

Despite the unique purpose anticipated for the Fenton Hill area, its selection and evaluation proceeded logically in a series of phases or steps. The first phase consisted of the selection of a suitable general region (the caldera) and the collection and assessment of available data for that region. During the second stage, new data were collected and evaluated, narrowing the region to the west side of the caldera. In the third phase, a slim hole was drilled into the Precambrian basement rocks, confirming that the western side of the caldera contained suitable HDR. At the end of the third phase, the Fenton Hill area was selected for deeper drilling and as a test site for the hydraulic-fracture and energy-extraction experiments.

As stated previously, the area available for evaluation by project personnel was restricted because of shortages of manpower and funding. Fortunately, LASL is situated on the eastern flank of the Valles Caldera, one of the youngest large calderas in the U.S., a recognized geothermal system, and designated a known geothermal resource area (KGRA) by the USGS. An excellent geologic map and an interpretative cross section of the caldera indicate that a magma chamber or pluton probably exists beneath the caldera. THe cross section shows a diameter for the pluton approximately equal to the diameter of the caldera ring faults, that is, about 24 km. The volcanic activity that produced the caldera occurred in two major episodes, 1.4 and 1.1 Myr ago, and the youngest dated vulcanism in the area occurred about 40 000 years ago. The youth, magnitude, and duration of activity suggested that a local heat source was still available beneath the caldera. Supporting this conclusion is the presence of numerous hot springs within and adjacent to the caldera. The Valles Caldera is obviously a major geothermal system.

At the time of the first phase of operations, preliminary drilling had been completed within the caldera by private interests in an attempt to locate natural hydrothermal resources. Newspaper accounts indicated that high temperatures and geothermal fluids had been encountered in some drill holes.

With a heat source indicated, it was then necessary to locate impermeable reservoir rocks which would lead to the selection of a drill site, that is, determine what parts of the geothermal system might contain HDR. The geologic map and cross sections showed that Precambrian igneous and metamorphic rocks were exposed locally at the surface on the west side of the caldera. It was apparent from the geologic map and cross sections that areas could be found west of the caldera where the overlying Paleozoic and Cenozoic cover was less than 1 km (3000 ft) thick. Mineralogical and textural evidence from exposures of the Precambrian rocks indicated that these rocks should be impermeable. The relative scarcity of large faults on the west side also suggested that impermeable hot rock could be found there.

Thus, at the conclusion of the first phase, it seemed likely that both adequate temperatures and impermeable rock could be found associated with the Valles Caldera geothermal system, particularly on the west side of the caldera -- outside the ring fracture.

The second phase of the site selection and evaluation consisted primarily of collecting new heat-flow data near the caldera to confirm the presence of HDR.

Because the presence of numerous faults within the interior of the caldera suggested that it would be difficult to find impermeable rock in this area, heat-flow measurements were confined to the area outside the ring faults.

Initially, seven shallow holes were drilled around the periphery of the caldera. These holes, which penetratd to depths of up to 30 m, indicated that the heat flow was indeed highest on the west side of the caldera. Conductive gradients in shallow holes are readily perturbed by the local hydrology; therefore, four additional heat flow holes were drilled to depths of 152 to 229 m to confirm the shallower heat-flow results. Three of these, forming an arc 2.4 km outside the western caldera ring fault, indicated high heat flow (5.5 HFU). A decrease in heat flow with radial distance from the caldera was shown by the fourth drill hole where the heat flow was 2.2 HFU at a distance of 6.4 km from the ring fault. This value falls within the range (1.5 to 2.5 HFU) reported for the Basin and Range Province, which may represent a background value for the Jemez Plateau area.

Because of the necessity of selecting an area where impermeable rocks could be found, considerable attention was paid to the tectonic setting of the caldera. Faulting is more common on the east side of the caldera where it overlaps the Rio Grande Rift. This area is broken by many north striking faults, apparently associated with the rifting. The Precambrian basement is not exposed on this side of the caldera and, because of faulting, it is assumed to be buried to a considerable depth.

The USGS provided unpublished geological and geophysical data suggesting that the west side of the caldera is structurally simple and therefore would be better suited for the HDR extraction experiment.

At the conclusion of the second phase, it was apparent that the magma chamber or pluton beneath the Valles Calera had thermally perturbed the rocks in the immediate area. The magnitude of the perturbation decreased with radial distance from the caldera. High heat flow and a higher probability of finding impermeable rock on the west side of the caldera indicated that further work was warranted in that area. To test this conclusion and to provide a borehole for initial hydraulic-fracturing experiments, a deep, slim hole, GT-1, was located at a drill site in Barley Canyon. It was anticipated that this hole would intersect the Precambrian basement at a depth of considerably less than 1 km. The drilling and subsequent experiments and measurements composed the major portion of the third phase of the exploration efforts. The initial results of a study of faults and seismicity and a report on seismic activity also became available at this time.

These preliminary reports indicated that the Barley Canyon drill site and Fenton Hill area were within a large fault block bounded by the caldera ring fault to the east, the Virgin Canyon and Jemez Springs faults to the southeast, the Caldera Canyon fault to the north, and the Rio Cebolla fault to the west. The closest of these is one of the caldera ring faults, 1.5-km east of the Fenton Hill area. The main ring fault is about 3-km east of the site. The interior of this block is free of observable faults.

The seismic history of the area was reviewed and it was concluded that the area is seismically quiet. This work indicated that the seismic-energy release per unit area is about an order of magnitude less than in California and Nevada. There have been no reported earthquakes with epicenters near the drill sites.

The location for GT-1 was selected on the basis of the results of the prior heat flow measurements, shallow depth of the Precambrian basement, and absence of faults in the area. GT-1 was drilled to a total depth of 785 m, intersecting the Precambrian unconformity at a depth of 642 m. Continuous coring was used for the botton 47 m of the hole, within the crystalline rock.

After GT-1 was drilled, temperature measurements were made in the hole. The average gradient was 129°C/km in the Paleozoic sedimentary rocks and 45°C/km in the top of the Precambrian rocks. An abrupt change in gradients occurs in the lower Madera Limestone near the contact with the underlying Sandia Formation. This is undoubtedly due to the movement of warm water through the permeable limestone downdip away from the caldera.

The expected impermeability of the resource rocks was confirmed by a variety of direct and indirect evidence. In situ permeability measurements made in GT-1 gave values of 5×10^{-8} to 6×10^{-3} darcys for overpressures of 13 to 177 bars. Eight successful hydraulic fracturing experiments at pressures of approximately 100 bars also indicated that the rocks were impermeable. Indirect evidence for impermeable rock was obtained from the petrographic study of GT-1 cores. It was found that most of the core consisted of granitic gneisses with minor amphibolite content. Although fractures were common in the cores, they were almost invariably sealed by calcite or chlorite.

At the completion of the third phase and before the commencement of the drilling of the deep boreholes, GT-2 and EE-1, it was possible to postulate a refined model for the Fenton Hill area. The heat source had locally perturbed an already high geothermal gradient providing temperatures sufficiently high for the proposed experiments.

Mapping of fault locations indicated that the proposed site lies within a large block of crystalline rock that is free of any faults with surface expression. This information, in addition to the evidence that most fractures in the Precambrian rocks were sealed suggested that low permeability rocks could be found within the Precambrian section. Slim-hole drilling of GT-1 indicated that the basement rocks would be encountered at a depth of about 640 m.

The fourth phase of operations began in February 1974 with the drilling of GT-2 and has continued through the drilling of EE-1, the hydraulic fracturing experiments, loop formation, and the current circulation experiments. The drill site was selected for GT-2 and EE-1 with the belief that it was geologically similar to the GT-1 site but better situated logistically.

To demonstrate the widespread occurrence of HDR, it has been determined that the target prospect to be evaluated next in this work is not to be associated with a young silicic volcano, but will derive its heat from some other type of source.

8.6.3. Regional. LASL is collecting, interpreting, and evaluating regional data in the Arizona-New Mexico and Washington-Oregon areas, preparatory to identifying Target Prospects (TPs) in each. The rest of the TPs will then be selected for further study under their contract (see Task 1). This selection will be concluded in late September 1979. The factors being used in this evaluation include

- elevated heat flow; that is, above 2.5 HFU's,
- heat source other than a young silicic volcano,
- low incidence of faulting and fracturing in potential reservoir rocks,
- absence of significant apparent hydrothermal system,
- low seismic activity, and
- institutional and economic factors, such as land ownership, prior leasing agreements, proximity to potential users, environmental issues, and estimated extent of thermal system.

8.6.4. Scope. The TP to be evaluated in this effort will consist of an area of approximately 100 mi^2 located within one of the following two geographic regions or general areas: Arizona/New Mexico or Washington/Oregon. On the basis of the geologic and other information about the regions or general areas, as summarized by LASL, a prospect will be selected by LASL to have a high HDR potential. The selected subcontractor of the TP shall be expected to design, implement, and manage a program to achieve the objectives stated above through a detailed evaluation of the TP as outlined in the Tasks below.

8.6.5. Specific Tasks. To complete the required detail TP evaluation, the subcontractor shall (a) conduct all eleven required Tasks and (b) select from a list (as indicated in Task 4 below) of surveys or methods as outlined in optional Tasks 12 through 37.

8.6.5.1. Required Tasks. To achieve the objectives of the HDR target prospect evaluation, the subcontractor shall complete the required Tasks 1 through 11.

Task 1 - Assignment of Target Prospect

The selected subcontractor shall meet with LASL HDR staff as soon as this subcontract is issued, and (1) learn of their assigned prospect, (2) receive and review all data used by LASL to select prospect.

Task 2 - Data Compilation

A data compilation and literature search shall be conducted.

Task 3 - Permitting for Required Tasks

Permit requrests needed for conduct of the evaluation shall be initiated.

Task 4 - Review and Agreement, Final Plan

Within 30 days of contact award, the subcontractor shall submit a final plan to LASL for those Tasks 12 through 37 to be accomplished. After Discussions and review, mutual (written) agreement shall be reached on the complete final plan for the detailed evaluation of the assigned TP. This final plan decision shall be decided on a bilateral mutual agreement basis.

In the development of the final plan, the subcontractor shall consider the following selection criteria for the location of a deep drill hole:

- confirmed local extent of elevated heat flow,
- high probability of permeability of reservoir rock,
- depth to reservoir rock not to exceed 3 km, and
- area of low seismicity risk.

Task 5 - Permits

All needed permits shall be obtained for all subsequent work as necessitated by the final plan.

Task 6 - Map of Surface Geology

Field work and photo interpretation necessary to generate 1/24 000-scale map of surface geology shall be performed. Particular attention shall be paid to faults which may intersect potential reservoir rocks at depth.

Task 7 - Fracture Analyses

Using the geologic map produced in Task 6, fracture analyses with results displayed as rose diagrams, shall be performed.

Task 8 - Heat Flow Survey

Using shallow (~150 m) heat-flow holes, geothermal gradient within prospect shall be determined. The results shall be overlaid on the geologic map of Task 6.

Task 9 - Hydrology

Using surface data information obtained from heat flow holes and other available data, hydrology of the prospect shall be evaluated. The results shall be summarized as an overlay on the geologic map of Task 6.

Task 10 - Seismicity

Existing seismic data shall be compiled and new data sufficient to evaluate seismic activity of the prospect shall be collected. These data shall be summarized as an overlay on geologic map of Task 6.

Task 11 - Comprehensive Final Report

Following the completion of Tasks 1-10 and completion of those selected in the final plan from Tasks 12 through 37, the subcontractor shall forward a draft comprehensive report (scheduled to arrive at LASL not later than September 15, 1979). This draft final report shall summarize the data collected, evaluation of the prospect, and recommended actions. The draft report shall be returned to the subcontractor for revisions (if any) and five copies of the final report shall be forwarded to LASL no later than October 15, 1979.

8.6.5.2. Optional Tasks. In addition to the required Tasks 1 through 11 which are applicable at any site, there are other optional Tasks which may be site-specific. These include, but are not necessarily limited to the following:

Task 12. Using K-Ar method, determine age of young (~3 Myr) igneous rocks which may have served as heat sources.

Task 13. Perform detailed MT-AMT survey of the prospect or a portion thereof.

Task 14. Perform resistivity survey of prospect or a portion thereof.

Task 15. Perform thin-section analysis (including preparation of section, identification of minerals, modal analysis, and interpretation) on pertinent samples of igneous rocks, which may have acted as a heat source and/or potential reservoir rocks.

Task 16. Identify and characterize, if samples are available, potential reservoir rocks. Characterization should include but not necessarily be limited to mineralogy, modal composition, whole rock chemistry, primary and secondary permeability.

Task 17. Using surface geologic data and pertinent geophysical data, estimate depth to potential reservoir rocks.

Task 18. Perform analyses of spring and well water samples.

Task 19. Apply silica and/or cation geothermometers to results of water analyses to obtain estimate of reservoir temperature.

Task 20. Perform aerial photography.

Task 21. Perform low sun angle photography.

Task 22. Perform IR photography.

Task 23. Perform lithologic logging of heat flow holes.

Task 24. Perform hydrologic testing of heat flow holes.

Task 25. Perform microseisms (ground noise) survey.

Task 26. Perform teleseisms survey.

Task 27. Perform reflection seismic profiling.

Task 28. Perform refraction seismic survey.

Task 29. Perform self-potential survey.

Task 30. Perform telluric profiling survey.

Task 31. Perform AFMAG survey.

Task 32. Perform TDEM survey.

Task 33. Perform electrical soundings.

Task 34. Perform gravity survey.

Task 35. Perform aeromagnetics survey.

Task 36. Calculate depth to Curie isotherm.

Task 37. If a geothermal resource is identified, develop conceptual model of the system.

Specific tasks from this list, or additional items as proposed by the subcontractor in Task 4, shall be selected by the subcontractor and LASL staff to complete the detailed HDR evaluation of the assigned TP.

8.6.6. Deliverables. In addition to the final report (Task 11) informal-letter monthly status reports shall be submitted to LASL by the subcontractor. These will summarize accomplishments and problems of the previous month and display the expenditures of manpower and funds.

Copies of all supporting data maps, field notes, etc. shall be prepared and forwarded to LASL in a form suitable for open file records by LASL.

A draft of the final report shall be required by September 15, 1979, with the final draft submitted to LASL at completion of the contract. This report will summarize all results obtained during the evaluation. The final report shall conclude with a recommendation of an HDR drilling site, abandonment of the prospect, or perhaps specific additional work. The final report shall also contain a section indicating how the evaluation has contributed to HDR exploration technology.

8.6.7. Information to be Furnished to Subcontractor. LASL shall provide to the subcontractor all geologic and other data used for the selection of the TP area. LASL shall also furnish to the subcontractor all new data acquired by LASL during the period of the subcontract.

8.6.8. Monitoring of Subcontract. LASL shall provide a technical monitor for the evaluation program. This individual will monitor the implementation of this program, review data periodically, and provide technical advice to the subcontractor.

8.7. Recommendations

8.7.1 Western Snake River Plain. The top recommendation of the site selection panel, the SRP, has been selected as one of these areas. The study area will be along the margins of the western SRP, near Boise, where Brott et al.*

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* Brott, et al., "Tectonic Implications of the Heat Flow of the Western Snake River Plain, Idaho," Geological Society of American Bulletin, v. 89, p. 1707 -1967, December 1978.

(1978) suggests that elevated heat flow is due to refraction of heat from thinned crust and intrusion below the plain. There may be additional heat due to radiogenic heat production of epizonal Tertiary-age granitic rocks at the edge of the plain. Granitic rocks of the Idaho batholith are exposed along the plain margin and have been encountered at depth of 2.9 km within the plain near Mountain Home. The bottom hole temperature in that well was 194°C at 2.9 km.

Detailed study of this area should provide information on structure (especially faulting and joint patterns), hydrology, lithology, and more geothermal gradients.

8.7.2. Crisfield Maryland - Wallops Island, Virginia. An area extending from Crisfield, Maryland to Wallops Island, Virginia - and called the CRIS-WAL area - will be analyzed, supplementing existing work there by the VPI and State University. Much of the geological rationale for this site is summarized earlier in this report. Geothermal gradients range from 34° to 46°C/km. The Bureau of Reclamation is now completing negotiations for heat-flow drilling within the area based on the previously acquired data. Less intensive but similar effects have been initiated to evaluate potential heat sources in northwest and southwest Arizona and in the strip between Tucson and Phoenix.

In New Mexico, LASL work in the Jemez and Zuni Mountains and in the Albuquerque and Lucero Uplift areas contributes to both the Arizona-New Mexico and federal HDR programs. New MT measurements, geochronology, water geothermometry, field mapping, petrology, and gravity compilations will aid in evaluating several potential heat sources near Albuquerque, Grants, and Gallup. Contacts have been made with the leadership of the Zuni Pueblo so that an assessment of the geothermal potential of the Pueblo can be tied to HDR exploration within the Zuni Mountains.

During FY-79, LASL has been conducting a geothermal evaluation of Arkansas for DOE/DGE. Field work and data compilation performed under this contract are contributing new information on geothermal gradients within Arkansas. Federal HDR program activities in New York, Maryland, Virginia, Florida, Mississippi, Alabama, Louisiana, Ohio, and Pennsylvania will asist DOE/DGE in evaluating the geothermal potential of the eastern United States.

8.8. Site Selection

Information concerning laws, regulations, general land ownership, and permit lead-time and requirements for exploration and possible facility siting was obtained and compiled for Arizona, Idaho, North Carolina, Nevada, New Jersey, New Mexico, New York, Maryland, Oregon, Virginia, and Washington. This input for the selection of a target prospect area presented the possible constraints in permit requirements and lead time. This information was given to the Program Development Council's Site Selection Committee. A summary of the permit requirements and nominal process lead time is shown in Table 8-III.

TABLE 8-III

SUMMARY OF STATE PERMITS

	Geothermal Act	EIS	Permits							Siting
			Environmental				Drilling			
			Air	Water	Waste	Noise	Exploration	Development	Water	
Arizona	X	X 1 yr	X	X	A	A	X 10d	X 90d	X 90d	- 90d
Idaho	X	R 60d	X	X	A	-	X 6 wk	X 6 wk	X ?	- 1 yr
Maryland	X	X 4 yr	X	X	A	-	X 30d	X 4 yr	X 90d	X 4 yr
New Mexico	X	R 1-2 yr	X	X	A	-	X 30d	X 90d	X 60d	- 1 yr
New York	O&G	X 120d	A	X	X	-	X 60d	X 60d	X ?	X 2 yr
North Carolina	-	X 60-90d	X	X	A	-	X 60-90d	X 60-90d	X 60-90d	- 90d
Oregon	X	R 45d	X	X	L	A	X 30d	X 45d	X 45d	X 9 mo
Virginia	-	X 4 mo	A	X	A	-	X 60d	X 60d	X 6 mo	X 1-2 yr
Washington	X	X 6 mo	X	X	A	A	X 30d	X 6-8 wk	X 30d	X 1 yr

X - Permit required
R - Review
A - Approval required
L - License required

9. INSTITUTIONAL AND INDUSTRIALIZATION ACTIVITIES

9.1. Drilling and Related Hardware for Fenton Hill

During the first half of FY79 a number of significant drilling-hardware and related projects have been completed. Most of these projects consisted of modifications and adaptations of commercial hardware or service tools for the high temperatures anticipated in the EE-2 drilling campaign. These upgrading efforts necessitated a consistent program to monitor fabrication and test procedures through closely coordinated liaison with the several firms involved. Especially significant for HDR technology are the two new types of high-temperature open-hole packer systems developed to HDR project specifications for hydraulic fracturing. These two packer systems were developed without use of R&D funds from the HDR project. They will contribute to other geothermal development projects of both the federal and private sectors. They may also be used in stimulation experiments in hydrothermal reservoirs.

A second major coordination and liaison effort was conducted to assure attainment of technical requirements and project schedules for the high-temperature turbodrill under development by Maurer Engineering Inc. (MEI) in Houston, Texas. All fabrication and assembly are now complete for the 7 3/4"-in.-diam unit, and flow tests have verified the basic fluid-mechanics aspects of the design. Following these ambient-temperature run-in tests, drilling tests in granite blocks at Terra Tek's Drilling Research Laboratory were scheduled for early April. Coordinated with the turbodrill project are the required high-temperature shock absorbers and steering-tool services. Both these latter projects have been accomplished with no R&D funds contribution by the HDR project. These improvements can also be expected to contribute to cost reductions in the drilling of hydrothermal wells.

9.2. Institutional Issue Mitigation

Several institutional issues concerning HDR implementation by industry have been recognized. Among the more important are: economic feasibility, ownership and the right to use the resource, environmental acceptability, permit processes and requirements, and public perception of desirability. A large body of information has been accumulated for the permit processes, by type of land ownership, for several states, as discussed under Site 2. The issues relative to the public perception of implementation desirability are purposely left for handling at a more appropriate time. However, the subjects of economic feasibility, ownership, and environmental acceptability have been considered in detail as briefly discussed below.

9.2.1. Economics. A request for proposals was widely advertised for conducting "an Industrial Assessment of the Economic Feasibility of Hot Dry Rock Geothermal Systems." Following the technical evaluation of the 17 proposals received, 2 were selected as outstanding by a panel of 7 including experts from outside LASL. Negotiations narrowed the preferred bidder to one and culminated in award of a contract to Bechtel National, Inc. to perform this study. The major tasks to be performed for this nationwide study are

- survey present HDR status and project reservoir and energy utilization concepts,
- survey current geothermal economic analysis methods and literature,
- identify and establish ranges of important factors in HDR commercialization,
- establish HDR cost and financial relationships,
- develop analysis methodology and model HDR systems, and
- define areas of insufficient information and data.

The products of this 2-yr effort are to be (1) a final report for wide distribution particularly within the industry, and (2) a series of related papers to be published in professional journals and presented at society conferences. This distribution, publication, and presentation is intended to reach a broad coverage within industry, government, and the public and achieve a high degree of credibility with all parties concerned.

9.2.2. Legal. Many legislative acts define geothermal energy in a manner which relates this resource to water or mineral, leaving the ownership of HDR open to a litigatory question. An analysis methodology has been designed for a professional legal study of this problem. The firm to be selected for this study will have the highest level of credibility and acceptability within the legal profession. The final report from the study will provide a suitable base from which an initial thrust for legislative change to existing legislation can be made and more appropriate definitions developed in those states now contemplating geothermal legislation. The study output is scheduled for widespread dissemination individually and in leading law journals in time for consideration by the next state legislative sessions.

9.2.3. Environmental. A general perception of reduced adverse environmental impacts from geothermal developments in comparison with other energy extraction and conversion technologies, seemingly exists. This perception is based primarily on the experience gained at the Geysers, for electricity generation and other somewhat lesser known examples of DATE as at Klamath Falls and other sites. A methodology has been designed for a study that will compare the environmental residuals from HDR, hydrothermal, and the other presently used energy producing technologies. The study may be performed by a university having a leading environmental science center and the necessary experience and resource to conduct it in a manner which provides a high level of industrial, governmental, environmental, and public credibility and acceptance. The final report will have widespread distribution and serve as a basis for obtaining industry and public acceptance of HDR industrialization.

9.3. Site 2 Solicitations of Interest

Two solicitations-of-interest were prepared and issued for the HDR Site-2 development contract, and possible well-acquisition or collaborative efforts in existing hot dry wells (Fig. 9-1). These solicitations were conducted following the widespread public notice of the HDR program that appeared in the national press, GRC journal, Geothermal Magazine, (Fig. 9-2), etc. Each solicitation appeared as CBD announcements, journal advertisements, and direct mailings. The Site-2 development solicitation yielded a significant response and will augment the source list for that request for proposal (RFP). The dry-hole availability solicitation elicited only five replies. An active search for appropriate existing hot dry wells seems necessary.

9.4. Magnitude of Subcontracts

During the first half of FY-79 the HDR programs issued approximately $675 000 in subcontracts. Many of these items (Table 9-I) were related to the Fenton Hill drilling slated to start early in April.

9.5 Industrialization Planning

The technical development at Fenton Hill and the milestone decision date of FY-86 provides the time-frame within which certain industrial program activities will be conducted. These activities will be structured to provide a smooth and increasing level of interest to better achieve industrial support and to motivate private investment in HDR developments.

LOS ALAMOS SCIENTIFIC LAB TO MANAGE NATIONAL HOT DRY ROCK GEOTHERMAL ENERGY PROGRAM

LASL will manage a national hot dry rock geothermal energy program in association with the U. S. Department of Energy. The program resulted from the Laboratory's successful geothermal reservoir experiments at Fenton Hill, New Mexico. Three 100-square-mile areas in the United States will be chosen as prospective sites for the development of prototype geothermal energy extraction systems. Choice of the sites will be made by LASL working with the National Hot Dry Rock Program Development Council. Industrial firms, under contract to the DOE and LASL, will investigate the sites for technical feasibility, and one or more areas will be pinpointed for a deeo drilling test and possibly a pilot or demonstration plant. Drilling at other sites may proceed after additional field studies and regional assessments. The national program will determine the potential of hot dry rock geothermal energy as a significant energy source and provide a basis for its timely commercial development. LASL's Geological Applications Group is conducting field studies in several states to assess hot dry rock potential; other Laboratory groups will provide management and technical expertise, and advice on legal and institutional questions. A major part of the national program will be conducted through contracts with private industry. The potential for hot dry rock geothermal energy is enormous, LASL scientists believe. They point out that the energy from a 40-cubic-mile block of hot granite equals the energy from about 12 billion barrels of oil, or nearly the total energy used in the United States in 1977. The new manager of the national program is Dr. Gerald P. Lewis, former director of technical programs for Allied Chemical Corporation in New Jersey. Lewis joined the LASL staff September 25.

Fig. 9-1. Solicitation-of-interest issued for HDR Site 2.

During the past 6 months we have been planning the distribution of appropriate information and compiling lists of interested individuals and organizations. Distribution lists include resource developers and their allied service companies, utility companies and potential direct users, equipment manufacturers and suppliers, financial institutions, environmental groups, government agencies, universities, professional societies, and news media. Dissemination of information will be by conferences and public forums, expanded technical report distribution, newsletters, brochures, and discussion meetings with industry, government, and environmental groups. In addition, LASL's Industrial Staff Member program, wherein scientists and engineers from industry are temporarily assigned to the laboratory to participate in any of several programs, is another vehicle for disseminating information.

Research and Development Project

Management and Technical Direction of Hot Dry Rock Experimental Field Project

This project is an element in the DOE Division of Geothermal Energy (DGE) Hot Dry Rock Geothermal Energy Program. A DOE-Los Alamos Scientific Laboratory (LASL) Hot Dry Rock Management Office has been established at LASL to provide overall technical management of elements of the program. The HDR Management Office intends to issue a request for proposal for the management and technical direction of the Hot Dry Rock (HDR) experiments to be conducted at a second HDR site, as a part of the DOE's Geothermal Energy Program, which places emphasis on commercialization of geothermal energy sources as economical and environmentally acceptable alternative energy sources.

The selected firm, or consortium of forms, will be responsible for the management and direction of the HDR Site-2 activities with the HDR Management Office in the role of technical manager. The extent of and duration of the Site 2 activities will depend upon the nature and characteristics of the reservoir developed.

The contractor must be thoroughly familiar with DOE and Federal Procurement Regulations, experienced in subcontracting procedures under these regulations, and qualified to negotiate subcontracts, to perform procurements and administer both in an environment of Federally regulated purchasing and subcontracting. Familiarity with both non-covered and covered subcontracting under the Davis-Bacon Act and the Service Contract will be required.

The research and development work will involve an interdisciplinary research and management effort, led by a commercial or industrial firm that will provide the technical direction and site management for a second HDR experimental 'drilling location. The initial effort will include evaluation of the existing exploration, environmental, and land-use data, and the preparation of a technical development plan and an environmental impact/assessment report, filing for permits for the planned development, preparations for, supervision of, on-site construction, access control, housekeeping, access roads, and communications, arrangements and subcontracts for environmental baseline data collection and monitoring, activities such as those concerned with design and emplacement of a seismic monitoring network, development and implementation of a hydrologic sampling program, provision for a climatological recording station, and support for ecological studies. Following the initial efforts, subcontracts for slim hole drilling, if required, deep well drilling and related services and supporting activities will be needed. Experiments to form the reservoir, by hydraulic fracturing or other means, and testing of the HDR reservoir will follow. Subsequently, affirmative decisions on prototype heat extraction and pilot-plant or demonstration systems will require extensive procurement, construction and operation activities.

The contractor will be required to interact strongly with the HDR Management Office and the project technical staff who will provide access to data and the details of the technical aspects of the ongoing DOE-DGE sponsored HDR geothermal energy research and development effort at LASL and especially the heat extraction experiment underway at experimental Site 1, (Fenton Hill) in north central New Mexico. As one mechanism to provide insight into and familiarity with the project, an Industrial Staff Member (ISM) program is available. Interested firms can obtain preproposal access to the HDR project by assignment of technical staff to LASL. The direct costs of the ISM assignments are funded by the interested firms. Details on the ISM program can be obtained by contacting the office shown below. Participation in the ISM program is not a consideration to participation in the HDR project.

Site exploration and location efforts are currently underway and it is planned that final Site-2 selection will be made in about September 1979, with initiation of Site-2 development projected to be October 1979. However, exploration and site selection is a high risk activity and Site-2 initiation could be delayed.

Prospective sites currently under regional evaluation are, in the eastern U.S., (1) north central New York state, (2) eastern coastal plains, and in the western states of (3) Washington-Oregon, and (4) Arizona-New Mexico. If the necessary site-selection information and funding are available, a Site-3 selection may also be made and a different contractor selected to manage its development.

The estimated first year maximum project cost is about $500,000.00 and the subsequent yearly budgets will depend on initial technical results, the rate of technical progress, DOE budgets and funding, and contractor performance. The contractor performing this work must be an established firm, or consortium of firms, with relevant experience in operation and management of geothermal or other energy resource field experiments and directing geoscience or geomechanical field operations.

Interested firms are invited to submit their indications of interest and qualifications to:

Los Alamos Scientific Laboratory
HDR Management Office
P.O. Box 1663
Los Alamos, NM 87545
Attn: Gerald P. Lewis, MS 575

mailed to arrive in Los Alamos no later than December 15, 1978. This is not a request for proposal

LOS ALAMOS SCIENTIFIC LABORATORY
University of California

RESEARCH AND DEVELOPMENT

DRY GEOTHERMAL WELLS FOR HOT DRY ROCK EXPERIMENTAL-DEMONSTRATION SITES

As a part of the Department of Energy's (DOE) geothermal Energy Program, which emphasizes commercialization of geothermal energy resources as economical and environmentally acceptable alternative energy sources the DOE-Los Alamos Scientific Laboratory (LASL) Hot Dry Rock (HDR) Geothermal Management Office is seeking information on existing 'dry' geothermal wells that might be technically suitable and otherwise appropriate for future HDR experimental sites. This project is an element in the DOE-Division of Geothermal Energy (DGE) Federal Hot Dry Rock Geothermal Energy Development Program.

The HDR Management Office at LASL is seeking to locate owners of dry geothermal wells that could be made available to LASL through transfer of ownership, loan, lease, or by formation of collaborative or cooperative arrangements, or cost-shared projects, for possible experimental sites for HDR tests, experiments, and demonstrations.

Candidate dry wells will be expected to meet the following technical requirements. They should reach depths at which rock temperatures are high enough for either direct use or electric power generation, bottom in formations with very low fracture and matrix permeabilities, have been logged lithologically or to be in areas whose lithology is well known, and be no closer than 1 km to any surface manifestation of present hydrothermal activity or to any well from which there has been evidence of significant actual or potential production of steam, hot water, or hydrocarbons. Wells will be selected so as to exclude use of those that might have a high probability of being suitable for hydrothermal stimulation experiments. The well should have a minimum depth of 1 km, be no closer than 1 km to major faults, and be in an area of low seismic activity and risk. After initial logging and testing, including fracturing and reservoir tests and other downhole experiments, drilling of an adjacent well may be required to complete a heat-extraction loop, followed possibly by construction of a pilot plant or demonstration system. Occupancy of a surface area of several acres for a period of from a few months to several years may be required.

Interested firms in control of such dry geothermal wells are invited to submit particulars and their indication of interest to:

Hot Dry Rock Geothermal Management Office
LOS ALAMOS SCIENTIFIC LABORATORY
HDR Dry Well Experimental Sites
P. O. Box 990, Los Alamos, NM 87545

ATTN: Mr. W. A. Barr

mailed to arrive in Los Alamos no later than January 25, 1979. This is not a request for proposal.

LOS ALAMOS SCIENTIFIC LABORATORY

University of California

Fig. 9-2. Public notice of HDR Program.

Although the strategy planning is not yet complete, activities in all of the above areas have been initiated, and the design will be completed in the next 6 months. This strategy will continue to include the use of existing industry organizations, such as the Geothermal Resources Council and the Society of Petroleum Engineers (AIME) and others, as principal interfaces.

9.6. Industrialization and Economics

R. Cummings of the University of New Mexico is continuing to direct the economic modeling of generic HDR systems under a direct subcontract with DOE/DGE. Specific activities included an expansion of parametric studies to examine the effects of reservoir thermal drawdown, variable plant design temperatures, discount and interest rates, and drilling and plant costs. These studies are coordinated with LASL staff. In addition, an evaluation is under way of the results from a study conducted by Republic Geothermal to improve our estimates of drilling costs in crystalline rock. Preliminary work has also begun on examining the potential of HDR for cogeneration with the Crown Zellerbach operation in Camas, Washington as the first case study.

TABLE 9-I

SUMMARY OF INDUSTRIAL PARTICIPATION
VIA SUBCONTRACTS (1000$)

DOE Drilling Contract EE-2/GT-2		(2,100)*
Resource Potential & Site Investigation		45
Instrumentation and Other		345
Energy Extraction Loop Site-1		250
Drilling Related		160
	TOTAL	675

* Committed in first half of FY-79, but costed in second half.

10. PROGRAM MANAGEMENT

10.1. Program Management Office

On October 1, 1978, the Program Management Office was established at LASL within the Geosciences Division. It assumed principal responsibility for planning, management, fiscal control, and reporting of HDR activities both at LASL and elsewhere. Gerald P. Lewis, initial program manager resigned in November and Gregory J. Nunz, Assistant Division Leader of G-Division, was named to the management position with Morton C. Smith as his Deputy. W. Porter Grace, DOE/ALO Special Programs Division, was named Associate Program Manager to provide a direct involvement by DOE/ALO. The Program Organization is shown in Fig. 10-1. Five staff members and an executive secretary serve full time in the Program Management Office.

A National HDR Program Development Council representing industry, academia, and government was organized to advise the Management Office and periodically review the progress of the program. The management plan for the HDR program was approved by DOE/ALO, DOE/DGE, and by LASL/G-Division on March 5, 1979.

Program Office representatives have since met with the Program Director at DGE on Dec. 20, 1978 and March 14, 1979 for formal quarterly reviews of program progress, planning, and budgets. In addition, there have been several informal meetings and day-to-day telephone discussions with him and other DGE personnel. These have been supplemented with brief, written, monthly progress reports and special reports of several types. The Annual Report of the HDR Program for FY-78 was prepared and distributed.

The draft HDR Program Plan has been extensively revised. However, final revision has been delayed pending further discussions with the Program Director concerning its scope and schedule.

An environmental appendix for the DOE/U.S. Forest Service Memorandum of Understanding concerning the Fenton Hill site has been prepared and reviewed by LASL and the USFS. It has been revised for formal transmittal to the USFS by DOE/LAAO. It has also been reviewed and discussed with Oak Ridge National Laboratory (ORNL) personnel, both at LASL and at ORNL, to assist them in preparing a formal Environmental Assessment for future operations at Fenton Hill.

The Executive and Site Selection Committee of the National Hot Dry Rock Program Development Council met jointly at LASL on November 17, 1978, and the Site Selection Committee met again at LASL on February 1 and 2, 1979, to consider a list of candidate areas throughout the United States that appear

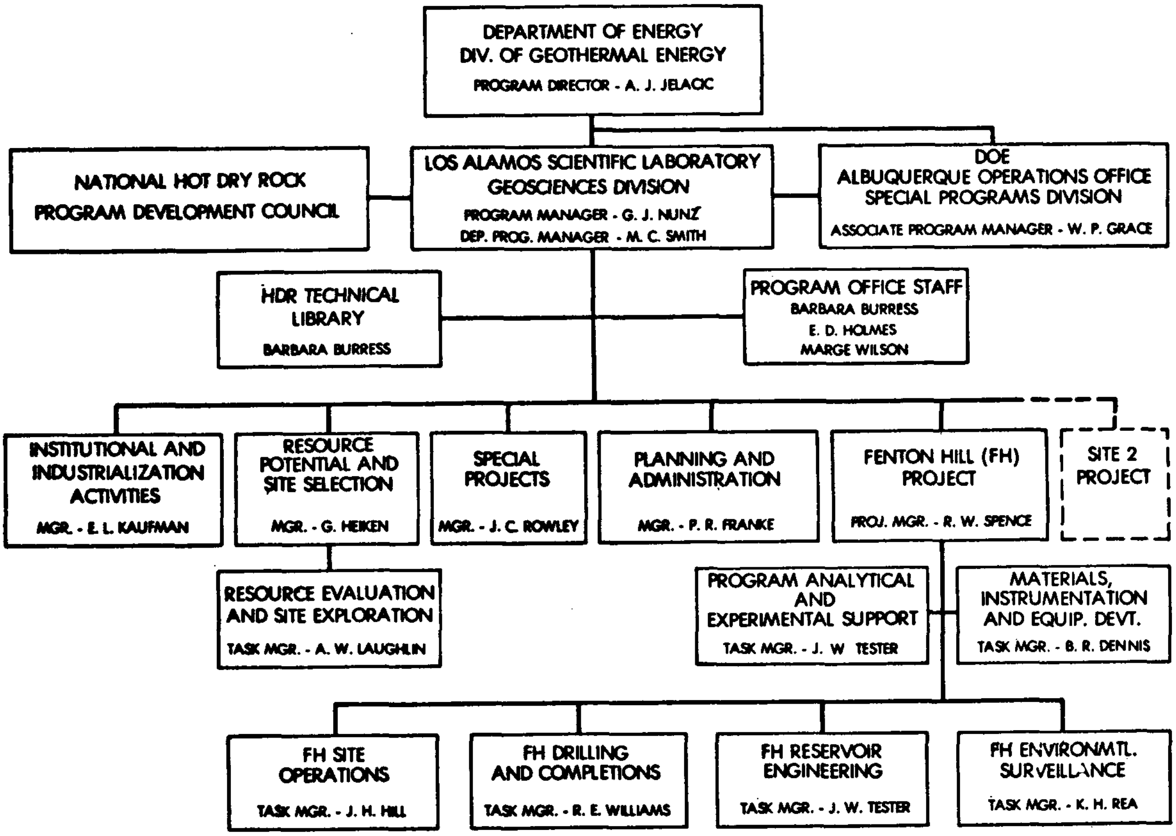

Fig. 10-1. HDR Geothermal Energy Development Program Organization.

promising for future HDR development. The Site Selection Committee prepared a prioritized list of areas recommended for detailed investigation during the next year, which the Program Office has reported to the DGE Program Director together with its own recommendation of two specific prospect areas to be investigated in detail by subcontractors.

10.2. Budget Planning and Control

Planning efforts during the early part of this year were devoted to establishing a program organization based on activity descriptions. A major milestone status chart has been developed and progress measured against this on a monthly basis.

For cost accounting a work breakdown structure was established and integrated with the LASL Program Code and Cost Center System. Operating plans based on this task structure were developed with G-Division and the LASL Financial Management Office (FMO).

We are using the DOE Uniform Contractor Reporting System (UCRS) for our reports. The Contract Management Summary Report (CMSR), Form DOE 536, is prepared and submitted monthly to the Division of Geothermal Energy. The March 1979 report is shown in Fig. 10-2. A major project was initiated during March

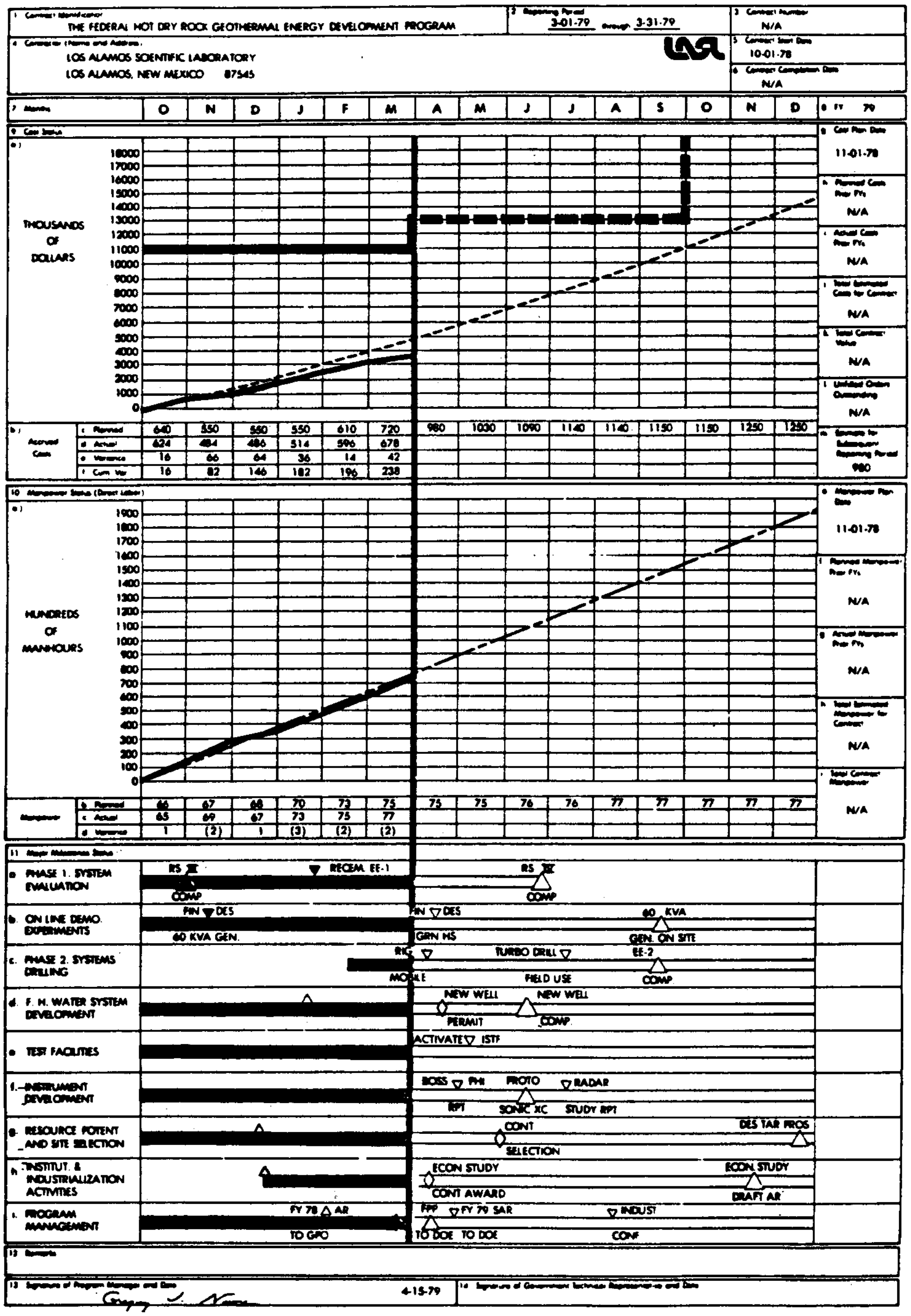

Fig. 10-2. Contract Management Summary Report.

for drilling EE-2 and redrilling GT-2 wells at Fenton Hill. A project directive was established for an estimated total of $5.5 million covering both LASL and DOE-LAAO contract costs. A draft Project Management Plan was prepared in co-operation with the LASL Engineering Department and DOE-ALO/LAAO officials. Currently, we are setting up a computer system to track the project costs and progress. This control uses the EZPERT system by Systonetics, Inc.

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