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*Hot Dry Rock Geothermal Energy
Development Program
Annual Report*

Fiscal Year 1986

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Hot Dry Rock Geothermal Energy Development Program

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Annual Report Fiscal Year 1986

Z. V. Dash, T. Grant, G. Jones, H. D. Murphy, and M. G. Wilson

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ABSTRACT

Preparation, execution, and analysis of a 30-day Initial Closed-Loop Flow Test (ICFT) of the Phase II reservoir were the primary objectives of the Hot Dry Rock Program in Fiscal Year 1986. The ICFT successfully tested the Phase II heat-extraction loop with the injection of 37 000 m³ of cold water and production of 23 000 m³ of hot water, extracting up to 10 MW_t when production reached 0.0139 m³/s at 192°C. By the end of the test, water loss rate had decreased to 26% and a significant portion of the injected water had been re-

covered, 66% during the test and an additional 20% during subsequent venting. Geochemical, tracer, and seismic analyses suggest reservoir fracture volume was growing throughout the test. A new technique, the "three-point" method, was developed to determine locations and orientations of seismically active

EXECUTIVE SUMMARY

planes. Fault or joint planes are identified in what superficially appears to be an amorphous microearthquake location set. Five planes were determined when the three-point method was applied to a location data set for the massive hydraulic-fracturing experiment conducted in 1983.

The Initial Closed-Loop Flow Test (ICFT) was the most significant of several major experiments for reservoir hydraulics conducted at the Hot Dry Rock (HDR) Fenton Hill geothermal site in Fiscal Year 1986. During this test water circulated from the injection well (EE-3A) to the production well (EE-2) for 30 days, extracting up to 10 MW_t from the Phase II reservoir.

The ICFT successfully tested the Phase II heat-extraction loop from May 19 to June 18, 1986. A total of $37\,000 \text{ m}^3$ (9.76 million gallons) of cold

water were injected at EE-3A; a total of 23 000 m³ (6.15 million gallons) of hot water were produced at EE-2. The injection rates at the surface ranged up to 0.0265 m³/s (420 gpm), although most of the pumping rates were 0.0106 m³/s (168 gpm) and 0.0185 m³/s (294 gpm) with the surface pressures around 26.9 MPa (3900 psi) and 30.3 MPa (4400 psi), respectively. The surface production pressure was around 3.5 MPa (500 psi), resulting in surface production flow rates from 0.0063 m³/s (100 gpm) to 0.0139 m³/s (220 gpm).

Production-well temperatures increased throughout the test and reached a maximum of 192°C near the end of the test; production power showed a corresponding increase and reached a maximum of 10 MW_t after 28 days. The power increase resulted from the rise in production temperature combined with a rise in production rate. This was consistent with model projections for a sustained flow rate of 0.0126 m³/s (200 gpm) and a reservoir temperature of 235°C. Projection of performance trends during the test, assuming no thermal drawdown in the reservoir, indicates that from 10–12 MW_t could be produced after one year if the flow rate stays between 0.0126 m³/s and 0.0158 m³/s. The production temperature should rise to 200–210°C.

Bottom-hole pressure in the injection well did not change much with injection rate or time, indicating fracture inflation and stimulation near the injection wellbore. The production rate from EE-2 showed an overall increasing trend. The overall reservoir impedance decreased throughout the test. The injection-well impedance decreased during the early part of the test as a result of near-wellbore cooling and pressurization. However, the injection-well impedance was only a minor portion of the overall impedance, indicating that future improvement strategies should concentrate on the production well.

The rate of water loss decreased from 70% after 4 days of pumping to 26% af-

ter 30 days of pumping. Reservoir inflation apparently caused the high water loss during the early portion of the test. Of the total injected water, 66% was recovered during this test; an additional 20% was recovered during vent-down.

There were leaks in the production well to shallow zones behind the 244.5-mm (9-5/8-in.) casing at 2865 to 3110 m (9400 to 10 200 ft), and the wellbore casing had partially buckled at 3200 m (10 500 ft), precluding any wireline logging below that depth. Therefore a draft procedure to repair EE-2 was prepared. The objectives for the repair of EE-2 were to (1) re-establish the pressure and production integrity of the EE-2 wellbore by isolating the 2990-m (9800-ft) deep zone of low pressure from the production zone; (2) clean out the bottom of the EE-2 production zone from 3550 to 3660 m (11 650 to 12 000 ft); and (3) re-establish a logging-tool conduit to the bottom of the production zone. The operations were to be done in FY 1987.

Ancillary activities such as diagnostic logging, environmental monitoring, and site maintenance continued. Numerous borehole surveys supported the pressurization and hydraulic-fracturing experiments conducted at the site. High-temperature well logs in the open-hole section of EE-3A determined good packer seat locations. Triaxial geophone detectors deployed during the operations located microseismic events for mapping fractures. Temperature surveys performed before and during the fluid injections confirmed fracture openings in the borehole.

We detected no adverse environmental effects from Fenton Hill operations. Surface and groundwater stations were monitored, and samples of sludge from all ponds and of soil from different locations were collected, leached, and analysed. Water samples were taken daily when the 5-million-gallon pond was emptied (to facilitate needed repairs) into the adjoining canyon late in the fiscal year.

Throughout the ICFT, activity was

measured to locate seismic events. Circulation fluids and gases were collected and analysed for major and trace components. Ponds that supplied water for the experiment and were used for containing the vent fluid were monitored.

Sulfate-reducing bacteria in the pond sediments are still a concern. Late in the fiscal year we began a study of other bacteria that might have an impact on health or safety at Fenton Hill or on the operational side of the geothermal system.

A wireline and mud-logging program was conducted in conjunction with redrilling operations in EE-3. In FY 1985 the trajectory for the new wellbore, EE-3A, penetrated a fractured zone stimulated from EE-2 and thereby established hydraulic communication. To test and stimulate selected zones in EE-3A, inflatable open-hole packers designed for high-temperature service were used. Potential packer seats were located using mud, temperature, and caliper logs. Drill pipe and open-hole wireline depths were correlated using gamma-ray/collar locator logs.

Although this logging program proved successful, significant improvements can be made in the selection process by combining the caliper and the gamma-ray detector/collar locator into a single tool. We plan to replace the three-arm caliper with a new four-arm caliper and incorporate the gamma-ray detector and collar locator into a single tool, which will eliminate the need to correlate wireline depth from separate well logs and will give a direct correlation between casing and wireline (variable) depth measurements.

State-of-the-art minicomputer technology allowed more extensive calibration processing, resulting in accurate on-line conversion of transducer output data to engineering units. A CEC 1000-9, high-temperature, strain-gage pressure transducer performed very well at 300°C; future tests will determine its performance at 350°C.

Reservoir engineering work during FY

1986 was primarily ICFT-related. The geochemical behavior of the produced fluid was monitored continuously during the test to determine the concentration of dissolved cations and anions, dissolved gases, and total suspended solids. Corrosion coupons were also placed in bypass lines in the surface system to monitor the corrosion rate as a function of temperature and time. In addition, two radioactive tracer experiments were performed to determine fracture volumes and dispersive characteristics at different stages of the flow test.

A heat transfer model was developed using tracer response to estimate the degree of flow channeling and its impact on heat extraction. The model predicts an initial thermal drawdown of about 50°C in the first 50 to 100 days of a longer flow test, followed by a much more gradual decline thereafter.

Most of the 684 microseismic events that occurred during the ICFT were digitally stored. The resulting seismicity fell in the now familiar, nearly vertical, northerly striking tabular region, yet it only occupied half of the volume defined by seismicity from the Massive Hydraulic Fracture (MHF) experiment conducted in December 1983. Major differences were observed in the seismic data obtained from the MHF and the ICFT.

A new technique, the "three-point" method, has been developed to determine locations and orientations of seismically active planes. Fault or joint planes are identified in what superficially appears to be an amorphous microearthquake location set. Tests using synthetic data show the method is quite good at determining plane locations and orientations even when very few microearthquakes fall along the plane and a majority of the events fall randomly in space. A total of five planes were determined when the three-point method was applied to a limited location data set for the MHF (Experiment 2032) conducted in FY 1984.

The Los Alamos National Laboratory and the Energy Technologies Division of

the DOE Albuquerque Operations Office, with support from the Los Alamos Area Office, continue to field manage the HDR Program. The HDR Program Development Council (PDC) advises Program management and provides guidance in the development of a commercializable technology. The PDC met in Albuquerque in October 1985 and July 1986. The HDR International Steering Committee (ISC) resolves major programmatic problems and approves proposed changes with significant schedule and/or fiscal impact. The ISC met in Los Alamos in June and November 1986.

Under the auspices of the International Energy Agency (IEA), the Federal Republic of Germany (FRG) and the New Energy Development Organization (NEDO) of Japan have participated in the HDR Program over the past six years. The FRG ended its association with the Program on September 30, 1985. One year later, at the end of FY 1986, NEDO completed its participation in the Fenton Hill Project and started a major hot dry rock program of its own.

An Appendix to this annual report lists FY 1986 publications and presentations.

INTRODUCTION

The HDR Concept

The purpose of the HDR Program is to develop an economical, commercially usable technology for recovering thermal energy from naturally heated rock at accessible depths in the earth's crust. Although other methods of energy extraction are possible in different geologic environments, the Program has so far concentrated on the common case of hot crystalline rock of low initial permeability; the use of fluid pressure (hydraulic fracturing) to create flow passages and heat-transfer surface in that

rock; and operation of a closed, recirculating, pressurized-water loop to extract heat from the rock and transport it to the earth's surface. Large-scale field experiments are conducted at Fenton Hill in the Jemez Mountains of northern New Mexico, U.S.A., and supporting activities are performed primarily at the Los Alamos National Laboratory, about 35 km (21 miles) east of the Fenton Hill test site. These include development of new or improved downhole equipment and instruments, field and laboratory experimental and observational techniques, and analytical and numerical data analyses and modeling procedures. Many of these tools and techniques have been found useful in other experimental programs and in a variety of industrial applications.

Synopsis of the HDR Program Through FY 1985

The world's first hot dry rock geothermal energy system was completed at Fenton Hill in 1977, enlarged in 1979 by additional hydraulic fracturing, and operated successfully for more than a year. It was constructed by drilling a hole from the earth's surface to a depth of approximately 3000 m (9850 ft) into granitic rock with a temperature of 185°C; producing large hydraulic fractures centered at about 2600-m (8500-ft) depth; and then directionally drilling a second hole from the surface to intersect those fractures. Pressurized water circulated through the fractures brought heat to the surface at 135° to 140°C at rates up to 5 MW_t, some of which was used to operate a small, experimental, binary-cycle, electrical power plant. System operation was essentially trouble-free, and there was no detectable scaling, plugging, corrosion, or environmental effect.

(This first HDR system was referred to as the Phase I system.)

To extend the technology to the temperatures and rates of heat production required to support a commercial power plant, development of a larger, hotter, hot dry rock system was initiated at Fenton Hill in 1979 (Phase II). Two new holes, about 50 m (150 ft) apart at the surface, were drilled directionally, the deeper one to a vertical depth of 4390 m (14 400 ft) - where the rock temperature was 327°C. It was expected that hydraulic fractures produced from these holes would be substantially vertical and planar with an approximately north-northwest strike as happened in the shallower system described above. To provide the horizontal separation required to thermally isolate a series of such fractures, the bottom 1000 m (3280 ft) of each hole was drilled toward the east-northeast and inclined at 35° to the vertical, while the shallower hole was drilled 380 m (1250 ft) vertically above the deeper one.

In 1982, 1983, and 1984, a series of hydraulic-fracturing experiments were conducted at various depths in these two wells. Unexpectedly, the fracture systems produced were three-dimensional rather than planar, inclined rather than vertical, and did not meet each other or connect the two wells hydraulically. (This unexpected fracturing behavior probably relates to the presence of a cooling magma body beneath a volcanic caldera a few kilometers east of Fenton Hill.) Because it appeared unlikely that further hydraulic fracturing would produce the required connection, it was concluded that a more promising approach would be to redrill one of the wells directionally through a fracture system created from the other well.

The largest of the potential drilling targets was a fractured volume produced in December 1983 (FY 1984) by

the Massive Hydraulic Fracture (MHF) from EE-2 during which 21 300 m³ (5.6 million gallons) of water were pumped at 7000 psi into an isolated section of the deeper well in the depth interval 3529 to 3550 m (11 580 to 11 650 ft).

Early in 1985, a workover rig was skidded to EE-3. The new trajectory was initiated by sidetracking out of the existing hole with the aid of a whipstock and drilled out to about 27 m (90 ft). The workover rig was dismissed in February, the redrilling to be completed with a large drilling rig.

In March 1985, the larger drilling rig was mobilized over EE-3A to complete redrilling of the redirected wellbore. The redrilled well (EE-3A) was completed at about 3660 m (13 182 ft) in June after about two months of drilling. The drilling went relatively fast with drilling rates approaching 30 m (100 ft) per day. Diagnostic techniques to confirm the connection included pressure, flow, and temperature measurements, seismic monitoring during pressure experiments, and chemical analysis of tracers that were circulated and tracked through the giant geothermal loop.

After completing EE-3A as the Phase II reservoir injection hole, a series of stimulations and flow tests established the initial reservoir flow impedance, outlet temperature, and fluid geochemistry. During redrilling, pressurization tests identified a weak connection with the other well through a fracture at a depth of about 3490 m (11 450 ft) in the redrilled well, much better connections in the depth interval 3570 to 3835 m (11 700 to 12 600 ft), and indications of several minor connections at greater depths. An 84-hour flow test through the fractures below 3650 m (12 000 ft) was completed successfully in July 1985 in a section of the fractured reservoir where the rock temperature was about 265°C.

Figure 1. EE-3A well configuration after installation of a permanent packer at 3562 m (11 685 ft). The packer failed after three days and was removed.

Figure 2. EE-3A well configuration after installation of the cemented-in liner.

FENTON HILL SITE OPERATIONS

Workover Operations

To prepare EE-3A for high-pressure injection well service required for subsequent flow tests, the well was completed with a 139.7-mm (5-1/2-in.) liner. This liner would isolate the lower-pressure "leakoff zones" just below the 244.5-mm (9-5/8-in.) casing from the deeper, hotter zones that were strongly connected to well EE-2 (as demonstrated during open-hole packer Experiments 2059 and 2063). The leakoff zones would accept most of the injection fluid if they were left open to the wellbore, resulting in reduced fluid production at EE-2.

The first liner installed in EE-3A used a Baker Service Tool (formerly Lynes, Inc.) open-hole packer set at 3560 m (11 685 ft) to seal between the leakoff

zones and injection zones. The inflatable packer was tried first because (1) it was retrievable and could be removed if its seal depth was found to be incorrect and, after a stimulation of the selected zone, (2) it avoided the high-risk cementing operation that was required to seal in a conventional cemented-in liner. The packer was installed and successfully tested through a stimulation effort. A second inflatable packer test was conducted in combination with the completion tubing (see Fig. 1). During this test a leak was detected, and the packer was scheduled for removal.

The 139.7-mm (5-1/2-in.) liner was damaged during removal. While the few damaged joints of the liner were being repaired, preparations were made to cement it in. A puddling cement operation was used to minimize the risk of cement channels forming. In this operation the following steps are undertaken: (1) the

cement is circulated onto a sand plug at the bottom of the liner; (2) the liner is partially extracted from the cement slurry; (3) dilute lead cement slurry and tail slurry is circulated off the top of the remaining slurry; (4) a rubber wiper plug is circulated down and latched in the bottom of the liner; (5) the liner is lowered into the cement slurry; and (6) the liner is set on the sand plug and released. However, after extracting the liner from the slurry (step 2), an early set of the cement occurred that prevented re-insertion of the liner. As a result, the bottom of the liner was located at 3485 m (11 435 ft) instead of 3600 m (11 810 ft) as originally planned.

There was concern that the contaminated top slurry left around the outside of the liner would not provide an adequate seal. After drillout of the liner and removal of the sand plug below the liner, a cement bond log and an injection test were run. Both showed that a reasonably good cement seal had been obtained with about 400 ft of cement above the bottom of the liner. Completion tubing and a wellhead were installed, and the well was ready for injection service (see Fig. 2).

Initial Closed-Loop Flow Test

A schematic diagram of the surface loop for the ICFT (Experiment 2067) is shown in Fig. 3. Cold water was injected at EE-3A and hot water was produced at EE-2 under high pressures, then cooled and reinjected.¹ A total of 37 000 m³ (9.76 million gallons) of water were injected; a total of 23 000 m³ (6.15 million gallons) of hot water were produced. The injection rates at the surface ranged up to 0.0265 m³/s (420 gpm), although most of the pumping was done at rates of 0.0106 m³/s (168 gpm) and 0.0185 m³/s (294 gpm) with the surface pressures around 26.9 MPa (3900 psi)

and 30.3 MPa (4400 psi), respectively. The surface production pressure was controlled at around 3.5 MPa (500 psi), resulting in surface production flow rates from 0.0063 m³/s (100 gpm) to 0.0139 m³/s (220 gpm).

The production-well temperatures increased throughout the test, reaching a maximum of 192°C near the end of the test (see Fig. 4). The production power showed a corresponding increase, reaching a maximum of 10 MW_t after 28 days, as shown in Fig. 5. The power increase resulted from the rise in production temperature combined with a rise in production rate. This is consistent with model projections for a sustained flow rate of 0.0126 m³/s (200 gpm) and a reservoir temperature of 235°C. Projection of performance trends during the test, assuming no thermal drawdown in the reservoir, indicates that from 10–12 MW_t could be produced after one year if the flow rate is maintained between 0.0126 m³/s and 0.0158 m³/s and

Figure 3. Schematic diagram of the ICFT surface system.

Figure 4. EE-2 wellhead production temperature during the ICFT.

Figure 5. Thermal power production during the ICFT.

Figure 6. EE-2 production flow rate during the ICFT.

the production temperature rises to 200 to 210°C.

Bottom-hole pressure in the injection well did not change much with injection rate or time, indicating fracture inflation and stimulation near the injection wellbore. The production rate from EE-2 showed an overall increasing trend as shown in Fig. 6. The overall reservoir impedance decreased throughout the test, resulting largely from the stimulation of the injection well. The injection-well impedance decreased from 0.72 GPa·s/m³ (6.6 psi/gpm) to 0.002 GPa·s/m³ (0.02 psi/gpm) during the early part of the test as a result of near-wellbore cooling and pressurization. However, the injection-well impedance was only a minor portion of the overall impedance, indicating that future improvement strategies should concentrate on the production well. A plot of impedance for the test is given in Fig. 7.

As noted in Fig. 8, the rate of water loss decreased throughout the test, starting around 70% after 4 days of pumping and reducing to 26% after 30 days of pumping. The apparently high water loss values during the early portion of the test were caused primarily by reservoir inflation. Of the total injected water, 66% was recovered during this test and an additional 20% was recovered during a subsequent vent-down (Experiment 2068).

Planning and Preparation for the Second EE-2 Repair

The 9-5/8-in. casing in EE-2 had been severely damaged below 3260 m (10 700 ft). This occurred during the uncontrolled blow-down following a well-head failure that ended Experiment

2032. An interim repair with limited budget and objectives was attempted in December 1984. The repair was successful, but the condition of EE-2 continued to deteriorate. At the time Experiment 2067 (ICFT) was conducted, there were leaks to shallow zones behind the 9-5/8-in. casing at 2865 to 3110 m (9400 to 10 200 ft) and the liner and/or casing had collapsed sufficiently at 3200 m (10 500 ft) to preclude any wireline logging below that depth.

Based on analysis of production data from the ICFT, three objectives for the EE-2 repair were proposed: (1) re-establish the pressure and production integrity of the EE-2 bore by isolating the 2990-m (9800-ft) deep zone of low pressure from the production zone; (2) clean out the bottom of the EE-2 production zone from a current assumed depth of 3550 to 3669 m (11 650 to 12 000 ft), or if possible to a depth of 3810 m (12 500 ft); and (3) re-establish a logging-tool conduit to the bottom of the production zone. The repair of EE-2 was known to be a high-risk venture, so contingencies for reducing the objectives were specified in the operation plans. The repair workover was planned for the first quarter of FY 1987.

Diagnostic Logging

A summary of borehole surveys is given in Table I. These surveys were run in the Phase II system to support the pressurization and hydraulic-fracturing experiments conducted at the Fenton Hill site. The high-temperature well logs included a series of three-arm caliper and gamma-ray surveys in the open-hole section of EE-3A to determine good packer seat locations. Triaxial geophone detectors were deployed during the pressurization and hydraulic-fracturing operations

Figure 7. Total reservoir impedance during the ICFT.

Figure 8. Water loss during the ICFT.

Table I. Summary of Diagnostic Logging Surveys

Survey	Well	Purpose
Experiment 2063		
Temperature	EE-3A	Background
Triaxial geophones	EE-1	Record microseismic events
String shot	EE-3A	Calibration for geophones
Experiment 2064		
Temperature	EE-3A	Background
Gamma ray	EE-3A	Background
Three-arm caliper	EE-3A	Locate packer seat
Gamma ray	EE-3A	Gamma signature for packer seat
String shot	GT-2	Calibrate Precambrian geophone net
Experiment 2065		
Three-arm caliper	EE-3A	Background caliper
Temperature	EE-3A	Temperature survey during fluid injection
Temperature	EE-3A	Second temperature survey during fluid injection
Experiment 2066		
Three-arm caliper	EE-3A	Determine new packer seat
Three-arm caliper	EE-3A	Second caliper run
Triaxial geophones	EE-1	Detection of microseismic events
Triaxial geophones	EE-1	Second deployment of geophone detector
Three-arm caliper	EE-3A	Confirm fracture intersection in borehole
Borehole televiewer	EE-3A	Field test prototype televiewer tool
Experiment 2067—ICFT		
Temperature	EE-3A	Background temperature
Three-arm caliper	EE-3A	Background caliper
Casing-collar locator	EE-3A	Check packer location
Temperature	EE-3A	Flowing temperature
Temperature	EE-3A	Static temperature (well shut-in)
Triaxial geophones	EE-1	Detection of microseismic events
Temperature	EE-1	Determine fluid flow
Temperature	GT-2	Determine fluid flow
Temperature	EE-3A	Temperature profile after completion of fluid injection
Temperature	EE-3A	Borehole recovery profile/2 months
Temperature	EE-3A	Borehole recovery profile/3 months

to locate microseismic events for "mapping" fractures. Temperature surveys were performed before and during the fluid injections to confirm fracture openings in the borehole.

Environmental Monitoring

Samples were collected at the geothermal site and from nearby locations as part of a continuing study begun in 1974 to determine the effects of Fenton Hill operations on the surrounding area.²⁻¹⁰ Surface and groundwater stations adjacent to the site and in the major drainage of the Jemez River and the Rio Guadalupe downgradient from the site were monitored (Fig. 9). Slight variations in the chemical quality of the waters have been noted; however, these variations are within normal seasonal fluctuations.

Water from storage ponds was sampled before and after pumping operations and after any chemical treatment (such as chlorination). The aquifer used to supply water for the site was also sampled. These fluids were analyzed at an on-site laboratory for all major inorganic components as well as for most trace metals of environmental concern. Sludge from the bottoms of all ponds and soil from different locations within the site were collected. These were leached, as described in the Environmental Protection Agency Toxicity Test Procedure,¹¹ and the resulting extract analysed. Comparisons were made between the natural soil and the sludge resulting from geothermal and drilling operations.

The 5-million-gallon pond was emptied during the late summer and early fall of 1986. This fluid was released down a canyon adjacent to the site, and samples of the water collected daily during the dump were sent to the Environmental Section of the Laboratory for analysis.¹²

During FY 1986 the major experiment of environmental concern was the ICFT. Seismic activity was measured during and following the test to study the lo-

cation of events. Circulation fluids and gases were collected at regular intervals and analysed for major and trace components. The ponds that supplied water for the experiment and were subsequently used as containments for the vent fluid were checked before their use and after venting had stopped.

Sulfate-reducing bacteria, which have been known to be present in the sediments of the ponds for the last few years, were unaffected by chlorination of the pond water and are still a concern. A study was begun late in FY 1986 to classify other types of bacteria that might have an impact either on health or safety, or on the operational side (corrosion, suspended solids, etc.), of the Fenton Hill geothermal system.

Figure 9. Surface and groundwater stations around the Fenton Hill site.

Site Maintenance

At the start of FY 1986 plans were made and carried out to clean the EE-1 pond to the best extent possible under limited funds. The pond was first stirred using site pumps; then the water was pumped to the GT-2 pond. When the sludge became too thick for pumping, a contract vacuum truck and then the site's front-end loader were used to transfer an estimated 1520 m³ (400 000 gallons) of water, sludge, and dirt. An estimated 760 m³ (200 000 gallons) remained. Cleaning operations were terminated when the GT-2 pond was full. After the pond-cleaning operation, the submersible pump was relocated in a section of 1.83-m (6-ft) diameter culvert at the east end of the pond.

Throughout the first quarter of FY 1986, a complete site cleanup was started. Major items here were the replacement of the fence, gates, and water risers on the northwest corner of the site

Figure 10. Four-arm caliper tool.

and interior/exterior painting and repair of several site buildings and trailers. The area around the EE-2 well was prepared for a possible rig skid.

The 30-hp pump in Water Well #1 was replaced by a 10-hp pump. Budget permitting, this will be upgraded at a later date.

Most of the second quarter was spent in fabricating the ICFT surface system, rig-related operations, and Experiments 2065 and 2066. Site-support activities included the modification and upgrading of the GT-2 tower to facilitate logging operations in that well.

Work in the third quarter was almost entirely ICFT-related. Fourth-quarter operations consisted of cleanup after the ICFT and preparation of the site for skidding the rig from EE-3A to EE-2. Most of the ICFT surface system had to be removed as well as a small storage building and the storage shed for drilling mud.

DOWNHOLE INSTRUMENTATION DEVELOPMENT

Instrument and Equipment Development

A wireline and mud-logging program has been conducted in conjunction with redrilling operations in well EE-3 at the Fenton Hill HDR site. In FY 1985 the trajectory for the new wellbore, EE-3A, penetrated a fractured zone stimulated from adjacent well EE-2 and thereby established hydraulic communication. To test and stimulate selected zones in EE-3A, inflatable open-hole packers designed for high-temperature service were used. The high initial temperature, large thermal cycles, high differential pressures, and abrasive open-hole environment created an extremely challenging environment for open-hole packer operations. Packer seats had to be selected to avoid enlarged, fractured, incompetent, or mechanically weak areas in the boreholes. Proper identification and selection of

packer seats were crucial to the success of the project.

Potential packer seats were located by using mud logs, temperature logs, and caliper logs. Open-hole and through-drill-pipe gamma-ray/collar-locator logs were used to correlate drill pipe and open-hole wireline depths.

The Los Alamos caliper tool was used to measure the diameter of the open-hole section in EE-3A and proved to be very useful in finding potential packer seats. The tool has three independent arms, configured to measure hole diameters from 127 to 355.6 mm (5 to 14 in.). Mechanical linkage, magnetic couplings, and high-temperature rotary potentiometers are used to convert borehole radius to an electronically measured output. Prelog and postlog calibrations were made to calculate corrections for the caliper pad wear, if any. The tool was run with two bow centralizers straddling the measuring arm (Fig. 10).

A Geiger-detector, gamma-ray sonde was run in the open hole of EE-3A to tie the natural gamma-ray depth signature to the project's wireline depths. The electronics for the tool are thermally protected in a dewar housing with a Cerrobend heat sink (Fig. 11). The tool operates at temperatures of 300°C for more than six hours. The gamma-ray signature obtained was readily correlated with signatures obtained with the commercial through-drill-pipe log.

The logging program provided input to the successful packer operations and also added significantly to the reservoir description process, complementing injection and tracer data. Results that contributed to the reservoir description included depth correlation of drilling data with wireline data and location of active fractures, mineral-filled fractures, and foliation and formation changes.

The importance of multiple-arm caliper logging and good wireline depth corrections was demonstrated during these operations. High-temperature wireline logging has been shown to be a very useful investigative tool in granitic rock.

Although this logging program proved very successful, significant improvements can be made in the selection process by combining the caliper and the gamma-ray detector/collar locator into a single tool. Plans are to replace the three-arm caliper with a new four-arm caliper and incorporate the gamma-ray detector and collar locator into a single tool. This new tool will provide a much more efficient logging operation by eliminating the need to correlate wireline depth from separate well logs.

Figure 11. Gamma-ray detector.

Instrument Calibration and Maintenance

State-of-the-art minicomputer technology, providing relatively large memory and data storage capacity along with very high speed throughput rates, allows the use of more extensive calibration processing, resulting in accurate on-line conversion of transducer output data to engineering units. The significance of using good calibration practices is illustrated in the following description of the CEC 1000-9, high-temperature, strain-gage pressure transducer.

The transducer was calibrated for the pressure range from 0 to 34.47 MPa (5000 psi) at six discrete temperatures of 20, 100, 150, 200, 250, and 300°C, using

Figure 12. Pressure transducer temperature calibration.

an excitation voltage of 5 V dc. Calibration data at temperature are plotted in Fig. 12. The same calibration was repeated with the excitation and output signals transmitted over 6096 m (20 000 ft) of logging cable. Because the excitation voltage is sensed at the gauge, the power supply (at the uphole end of the cable) compensates for line losses. Thus, the ratio of output voltages versus excitation voltage corrects for line losses.

A least-square fit combining both temperature and pressure calibration will provide accurate conversion of transducer output voltage to pressure units while running the log in the geothermal well. The deviation using a second-order fit for pressure and a third-order fit for temperature results in a standard deviation of 0.584 with a maximum deviation of 1.384 (Fig. 13). The proper coefficients for this particular transducer can now be entered into the computer program. Real-time data are plotted on-line using the equation:

$$p = a + bV + cV^2$$

where V is the ratio output volts/excitation volts and:

$$a = a_1 + a_2T + a_3T^2 + a_4T^3$$

$$b = b_1 + b_2T + b_3T^2 + b_4T^3$$

$$c = c_1 + c_2T + c_3T^2 + c_4T^3.$$

The CEC 1000-9 pressure transducer has proven excellent performance up to at least 300°C. Future testing will determine its capability at 350°C.

Borehole Acoustic Televiwer

The Borehole Acoustic Televiwer (BAT) (Fig. 14) is currently being developed jointly by LANL and WBK of West Germany to aid in investigating the location of the downhole fracture system and its intersection with the wellbore, inspecting the casing, and determining borehole conditions. The instrument, designed for high-temperature geothermal use, minimizes the high manpower requirements of existing systems, simplifies assembly and maintenance procedures, implements proven fluid-sealing methods for high-temperature and high-pressure applications, and utilizes proven window and pressure balance systems currently being used by the Laboratory.

The theory of operation of the tool consists of a piezoelectric crystal, acting as a receiver-transmitter and mounted on a rotating head, which emits a burst of acoustic energy that propagates through the fluid in the borehole with a portion of the energy reflected by the borehole wall back to the crystal. The time of travel and the amplitude of the reflected signal are transmitted to the surface and serve as the basis for quantifying the condition and location of borehole wall features.

The borehole televiwer can be divided into two major subsystems, the receiver-transmitter module and the

downhole electronics system.

The receiver-transmitter module houses all the components required to support the rotating crystal head and provide the necessary position parameters. One high-frequency (1.6 MHz) and one low-frequency (625 kHz) piezoelectric crystal are each mounted 180° apart on a head that is rotated at 360 rpm by an ac synchronous motor. A fluxgate magnetometer is attached to the rotating head and, when keyed to the crystal, provides azimuthal orientation of the crystals. If operation is in a borehole casing or in a confused magnetic flux field, a switch, also attached to the rotating head, provides a once-per-revolution orientation mark. Electrical signals and control of the head are via a 10-channel slip ring assembly.

A thin TFE Teflon acoustic window separates the borehole fluids from the rotating crystal assembly. This assembly is mounted in an oil-filled cavity where the internal pressure is maintained to within 5 psi of the fluid pressure in the borehole using a pressure balance system. The TFE Teflon window is designed to "float" in the sealing mechanism to allow for thermal expansion when subjected to the high-temperature borehole fluids.

The downhole electronics system is designed around an Intel 8085A-2 military-version microprocessor, which is utilized to control data acquisition, processing, and transmission. The microprocessor clock frequency is 10 MHz. The onboard instruction set is stored on EPROM, but RAM is available in the system to run programs sent via wireline using PCM format from the surface.

Raw data are fed to the CPU using two analog-to-digital converters. Acoustic data from the crystals are bandpass amplified and input to a TRW 700 8-bit video A/D converter and stored in a fast RAM. The data are then entered into the CPU from the RAM. The sampling rate of the TRW A/D is 10 MHz, and the same 10-MHz clock is used to step through 2048 addresses in the fast RAM.

Therefore, the sampling window for the acoustic data is 204.8 μ s. Data from the fluxgate magnetometer, X, Y, and Z inclinometers, fire voltage, and two dewar temperatures are multiplexed and feed to an Analog Devices 12-bit CMOS A/D converter with a sampling rate of 96 kHz. The microprocessor controls the sample and hold circuitry as well as the multiplexer and A/D converter in order to read and process orientation, temperature, and fire voltage data at various intervals during 1 revolution or 128 crystal firings or shots.

Data are transmitted to the surface through a 64-kb/s PCM link via seven-conductor wireline. The downhole processor controls a Harris 15531 PCM encoder/decoder that transmits two 24-bit PCM words per shot. Each 24-bit PCM word is composed of three 8-bit bytes. For each byte or segment of a byte, the microprocessor assigns a reduced data value or process variable to be sent to the surface. Appending these three bytes forms the 24-bit PCM words.

The downhole microprocessor and peripheral electronics system initiates

Figure 13. Pressure transducer standard deviation.

Figure 14. Borehole acoustic televiewer (BAT).

tool and PCM data-transmission format parameters. It also gathers and processes data in five steps. These five steps include the motor-start/system-initialization sequence and four cycles of a 3-kHz clock that is wired to one of the interrupt ports on the 8085 CPU. The four clock cycles are used to fire the crystal, and acquire, analyze, and transmit data to the surface. The time of each cycle is the period of the 3-kHz clock (approximately 333 μ s). After the fourth cycle is completed, the CPU loops back to the first clock cycle and the four-step process is repeated.

The advantages of the "smart" system approach as implemented in the downhole electronics are threefold. The microprocessor-based digital system with the duplex PCM telemetry link allows for modifying various logging parameters, such as transducer frequency, amplifier gains, and number of shots per revolution, by simply reprogramming the system from the surface. This eliminates time-consuming tool retrieval, disassembly, rewiring, and assembly. Also, the digital-based system lends itself to a "stop and listen" approach to decrease noise, and the crystal firings can be synchronized to nontransition times in the high-voltage motor-driven waveform to reduce crosstalk and enhance the acoustic signal. Finally, the microprocessor-based system rotates the transducer at 360 rpm, which permits logging speeds of up to 0.5 m/s (100 ft/min) depending on desired resolution. Increased logging speed maximizes the utilization of precious downhole logging time.

The downhole electronics system is contained in a specialized dewar flask to protect the system from the harsh geothermal environment. The internal temperature in the electronics compartment of the dewar is expected to be less than 100°C after six hours of operation with the flask outer temperature at 275°C for five hours of residence time. This allows for one-hour insertion and one-hour removal time. After seven hours of operation, the internal temperature is less than 120°C. The electronics system dissipates a 15-W heat source and includes 0.53 m (21 in.) of heat sink in the form of Cerrobend. A specialized electric package housed within the dewar flask includes a 16-pin bayonet connector mounted on each end to provide a protected direct connection between the electronics inside the dewar and the sensors mounted below the dewar (Fig. 15).

The uphole unit for the borehole televiewer provides the user interface to receive incoming data, control peripheral

equipment, store data, and perform real-time caliper and amplitude analysis.

The tool can operate on either a standard seven-conductor cable or through a coaxial logging cable.

RESERVOIR ENGINEERING

Reservoir Hydraulics

The main experiments for reservoir hydraulics conducted during FY 1986 were Experiments 2066, 2067, 2068, and 2070 (see Table II for pertinent information on these and other experiments). Of these, Experiment 2067, termed the Initial Closed-Loop Flow Test (ICFT), was the most significant. During this test, water was circulated from the injection well (EE-3A) to the production well (EE-2) for 30 days (May 19 to June 18, 1986), extracting up to 10 MW_t from the Phase II reservoir. A detailed description of the ICFT (Experiment 2067) was given in an earlier section. Brief descriptions of the other three experiments—2066, 2068, and 2070—are given here.

Experiment 2066 was a deep injection experiment into EE-3A. Approximately 3770 m³ (1 million gallons) of water were pumped into EE-3A frontside. Pumping was started on January 31, 1986, and stopped three days later. The injection interval centered around 3830 m (12 577 ft) and was isolated with a down-hole packer. Injection rates ranged up to 0.0265 m³ (420 gpm), but most of the pumping was conducted at 0.0199 m³/s (315 gpm) with surface pressures of 46.9 MPa (6800 psi). During this test, pumping of a viscous gel was carried out to evaluate the feasibility of injecting viscosified fluids into EE-3A. No hydraulic flow connection to EE-2 was observed during this test. However, several seismic events were discerned and located during the experiment.

Experiment 2068 consisted of venting EE-2 following the ICFT. The venting was done from September 24 to November 9, 1986, during which time about 7400 to 9850 m³ (1.96 to 2.6 million gallons) of water were recovered. This was 50 to 70% of the water lost during Experiment 2067.

Experiment 2070 (in the first quarter of FY 1987) was a short pump (24 hours) into EE-3A to determine post-ICFT injection pressures. A total of 690 m³ (182 340 gallons) of water was pumped on December 5–6, 1986, at rates ranging from 0.008 to 0.0075 m³ (133 to 120 gpm). The injection pressures were considerably lower than those during the ICFT, reaching a maximum of 15 MPa (2200 psi) after 21 hours of pumping. The lower injection pressure is explained by the massive thermohydraulic stimulation of the injection region during the ICFT. It is not clear if the lower injection pressure will persist after the reservoir is inflated; a longer test with about 7500 to 11 500 m³ (2 to 3 million gallons) of injection needs to be conducted to evaluate this.

Figure 15. Dewar showing integral 16-pin connector.

Table II. Reservoir Hydraulics Experiments

Experiment Number	Date	Wellbore	Open-Hole Parameters			
			Open-Hole Interval ^a (m)	Volume Injected (m ³)	Nominal Rate (m ³ /s)	Nominal Pressure (MPa)
2018	07/19–20/82	EE-2	3528–3656	910	0.0315	48.3
2020	10/06–07/82	EE-2	3528–3656	3090	0.0928	46.9
2023	11/08/82	EE-3	3162–4084	150	0.0172	12.9
2032 ^b	12/06–09/83	EE-2	3528–3550	21 200	0.1140	48.0
2042	05/15–19/84	EE-3	3420–3588	7600	0.0265	41.4
2052	04/16–05/01/85	EE-2	3528–3550 ^c	4880	0.0050	14.5
2059 ^d	05/27–28/85	EE-3A	3516–3719	1590	0.0106	31.7
2061	06/29–07/02/85	EE-3A	3827–4017	5230	0.0106	31.0
2062 ^d	07/18–20/85	EE-3A	3651–3825	5770	0.0106	35.9
2066	01/30–02/01/86	EE-3A	3755–3914	3770	0.0199	46.9
2067 ^d (ICFT)	05/19–06/18/86	EE-3A	3487–3750	37 000	0.0106	26.9
					0.0185	30.3
2068	09/24–11/09/86	EE-2	^e	NA	0.0022	10–15
2070	12/05–06/86	EE-3A	3487–3750	690	0.008	15.0

^a Actual injection intervals are based on temperature surveys.

^b The EE-2 Massive Hydraulic Fracture (MHF), attributed with creating most of the reservoir flow paths connecting EE-3A to EE-2.

^c Injection also occurred at 3280 m where the 244.5-mm (9-5/8-in.) casing is damaged.

^d Reservoir connection between EE-3A and EE-2 was demonstrated by flowing EE-2.

^e Uncertain because of wellbore condition.

Geochemistry

During the ICFT the geochemical behavior of the produced fluid was monitored continuously to determine the concentration of dissolved cations and anions, dissolved gases, and total suspended solids. Corrosion coupons were also placed in bypass lines in the sur-

face system to monitor the corrosion rate as a function of temperature and time. In addition, two radioactive tracer experiments were performed to determine fracture volumes and dispersive characteristics at different stages of the flow test. There were two purposes for this intensive monitoring of the produced fluid: (1) to evaluate the potential for chemistry-related problems in the

long-term operation of the reservoir and (2) for reservoir characterization and to provide information to be used in reservoir modeling studies.

The corrosion coupon studies indicated generalized corrosion at an average rate of 10 mils per year (mpy) with little pitting. A post-experiment examination of the surface equipment uncovered small deposits of calcium sulfate and arsenic sulfide, but little or no silica or calcite scale. No equipment failures or operating difficulties have been attributed to corrosion or scaling.

Gas sampling was carried out to determine the total weight percent of gas and dry gas composition. The dry gas was composed predominantly of CO₂ (90 to 95% by volume), with smaller amounts of nitrogen, oxygen, hydrogen sulfide, and occasionally hydrogen, methane, and ethane. The concentration of dissolved CO₂ in the fluid declined to a nearly steady level of about 0.3% by weight, with occasional excursions estimated at 1%. The periods of high gas concentrations, lasting several hours in most cases, suggest that a separator be included in the final surface system design for future experiments.

The behavior of the dissolved anions and cations was qualitatively similar to that of previous flow experiments at Fenton Hill, but the absolute concentration levels of the inert species were two to three times higher than in the past, probably because of the higher reservoir temperature. Ion ratios of most species were the same as in previous experiments, suggesting a similar source for the underground pore fluid. The concentration-time histories at the beginning of the experiment showed several classes of behavior. Conservative species such as chlorine and boron, which do not interact with the reservoir rock, started at initially high concentrations and declined to their injection concentrations as the reservoir pore fluid was gradually swept from the system. Concentrations of reacting species such as SiO₂ remained constant because of active dissolution. Other elements such as magne-

sium reached lower concentrations than their initial injection values, suggesting deposition on the rock surface. Finally, silicon and sodium-potassium-calcium geothermometer measurements are in general agreement with the known reservoir temperature of about 240°C. Total dissolved solids averaged slightly over 4000 ppm.

Tracer Work

The radioactive tracer experiments employing ⁸²Br suggested that the reservoir fracture volume was growing and a greater number of fluid flow paths were being exposed throughout the 30-day ICFT test, as evidenced by the longer residence times and lower tracer recoveries. At the end of the experiment, the fracture modal volume was 354 m³. A heat-transfer model¹³ has been developed using tracer response to estimate the degree of flow channeling and its impact on heat extraction for the upcoming Long-Term Flow Test (LTFT). The model predicts an initial thermal draw-down of about 50°C in the first 50 to 100 days, followed by a much more gradual decline thereafter.

TelevIEWer Studies

Previous studies that extracted foliation features from logs of GT-2 were controversial because the features had not been reported previously and because they could be seen only in imagery made at Fenton Hill by certain tools, not from others. Recent studies of EE-3A, using the US Geological Survey televIEWer, confirm the identification and support the explanation that the features are obliterated in some tools by the low-pass filtering used to reduce electronic noise.

Certain parts of EE-3A were selected as packer seats on the basis of multi-log studies, mainly gamma, televIEWer, and wellbore diameter. The selections

Figure 16. Three views of the locations of seismic events that occurred during the ICFT with a histogram of event arrivals versus time.

proved successful in subsequent reservoir stimulation.¹⁴ The criteria for selection were low roughness, low fracture density, and high circularity. A new, detailed study of televiewer data shows that the selections were intervals of low abrasability (i.e., the resistance of rock to abrasion). The zones of low abrasability are probably due to variations in lithology.

Foliations show that the Precambrian gneiss in EE-3A has a markedly different geological structure to the gneiss at shallow depth in GT-2. In EE-3A,^{15,16} between 3290 and 3720 m (10 800 and 12 200 ft), the foliation is essentially horizontal, and the folds visible in GT-2 between 760 and 1400 m (2500 and 4600 ft) are absent. This is consistent with the difference in metamorphic ages of the two gneisses.

Wellbore roughness in many areas

was found to be due to breakouts.¹⁷⁻¹⁹ These were identified visually because of their lower reflectivity that was due to scattering and the narrow, sharply defined specular reflection from their interior (causing a "bright spot" in the data from the BAT).

The general conclusions are that (a) the special geological effects and imaging artifacts due to inclined holes in Precambrian gneiss (as contrasted to previous industrial experience with vertical holes in stratified rocks) have been identified, so the televiewer can now be deployed in routine operations with some confidence and (b) the minimum horizontal principal stress direction is probably 110° E of N, which is substantially different to old estimates from reservoir engineering^{20,21} and seismic radiation patterns.²² However, it agrees with estimates from tectonophysics.²³

This suggests either the stress control of fracturing in the upper reservoir was not as it was earlier thought or the stress field rotates very rapidly with depth.

Microseismic Analysis

A total of 684 microseismic events were located from data collected during the ICFT. Because the MASS-COMP/RAVEN seismic data acquisition system was employed to detect and record seismic events automatically, almost all the events that occurred during the experiment were stored digitally. Of the 684 events located, 611 locations were considered to be reliably determined. Figure 16 shows three views of the locations of the seismic events.

The resulting seismicity fell in the now familiar, nearly vertical, northerly striking tabular region, yet it only occupied half of the volume defined by seismicity from Experiment 2032, the massive hydraulic fracture (MHF) conducted in December 1983. The activated portion fell entirely in the southern (or injection) end of the MHF seismic volume. The lack of seismicity in the northern portion of the MHF seismic zone may have been caused by the higher pressure in the neighborhood of the injection wellbore within the zone. The shorter flow paths between the two wellbores existed aseismically, whereas slower-moving, high-pressure fluid in the southern portion of the reservoir caused the fracturing or slippage. This would imply that seismicity, and possibly water loss, could be lessened by introducing additional production intervals surrounding the injection point. Furthermore, the seismic cloud from Experiment 2067 (the ICFT) was centered 100 m to the east of the MHF cloud, indicating extension in that direction. Extension was also indicated by shallow seismicity that fell outside the MHF bounds; the shallow region was especially active in the latter half of the experiment. The ICFT seismicity fell into very well defined subvolumes. This is especially apparent when viewing

the tabular seismic volume broadside. Similarly situated yet less well defined clustering can be seen in the MHF data. Because the ICFT locations lie slightly to the east of the MHF zone, as mentioned above, the patterns seem to be eastward extensions of these previous seismic distributions. Thus, there may be some east-west trending structure that controls the seismic pattern.

An interesting seismic subvolume lying well to the north was active only after the shut-in following the end of the flow test. Many of these anomalously located microseismic events were large enough to be seen by the surface seismic network, as well as by the downhole Precambrian network used in event location. The large size of many of these events is curious because shut-in pressures should not have been enough to exceed the fracture threshold. This indicates that these events may have occurred in the lower-pressure, Phase I reservoir region.

A new seismic data acquisition system was developed that digitally records seismic data on site at Fenton Hill in real time. A schematic of the system is shown in Fig. 17. The hardware employed is a UNIX-based digital data acquisition system that is commercially

Figure 17. Schematic diagram of the seismic digital event detecting and recording system.

Table III. Planes Determined by Application of the Three-Point Method

Plane Strike	Plane Dip	Number of Events on Plane	Number of Standard Deviations Above Mean
N31W	74E	130	11.4
N90W	24N	35	6.8
N29W	67W	50	6.1
N7E	67E	81	5.8
N29E	60W	28	4.1

available from MASSCOMP, Inc. Software was contracted to NEWT, Inc., of Seattle, Washington. The software is basically a high-speed version of that used by regional seismic networks to detect and record seismic data. Our system allows up to 48 channels to be digitized and recorded. For each 16 channels, we can software select the digitizing rate. We typically use rates of 50 000 samples per second for close-in downhole stations such as those in EE-1 or EE-3, 5000 samples per second for all other Precambrian network stations, and 500 samples per second for surface network data. The data from the Precambrian network (downhole seismic stations located in the vicinity of Fenton Hill) are monitored in real time to determine when a seismic event occurs. When an event is detected at a preset number of stations, data from

all stations are stored for later analysis. A pre-event memory exists for each channel so that data for some time before an event can be stored. This allows arrival times at all stations to be determined from the stored data. The system was first successfully deployed during Experiment 2066 in January 1986. It was also used during Experiment 2067.

A new method has been developed to determine locations and orientations of planes along which microearthquakes occur. Although it is generally accepted that microearthquakes occur along pre-existing faults, the distribution of microearthquake locations is often so smeared that the fault or joint structures along which the microearthquakes occur cannot be inferred from visual inspection of location plots. The "three-point" method identifies fault or joint planes

in what may otherwise appear to be an amorphous microearthquake location set.

To apply the method, all hypocenters in the event set are taken three at a time to determine strikes and dips of all possible planes and their respective poles within the set. The range of all possible poles is grouped into boxes, and the number of planes corresponding to each box is determined. A correction must be made to remove the bias introduced by the shape of the region in which the events occur. After this correction is applied, the orientation (one or more) that occurs most often is taken as that of the orientation of the planes or joints along which the microearthquakes occur. Locations of the planes are determined by plotting hypocenters of those groups of three events where the connecting plane is parallel to the direction found most often.

Tests using synthetic data show that the method is quite good at determining the orientations and locations of planes where even very few microearthquakes fall along the planes and a majority of the events fall randomly in space.

The three-point method has been applied to a location data set for Experiment 2032. A total of five planes were determined from the data. Table III lists the orientations of the planes. Figure 18 shows one of the planes determined from the locations.

Figure 18. One of the planes determined from the location data set of Experiment 2032.

PROGRAM
MANAGEMENT

Program Organization

In FY 1986 only minor changes in management responsibilities were made in the Hot Dry Rock Program. In October 1986 Hugh D. Murphy was made Program Manager, replacing Richard

Benson who became Leader of the Laboratory's Human Resources Division. Michael E. Berger, Deputy Associate Director for Energy Technology under John Whetten, Associate Director for Energy Research and Applications, serves as Program Director for Hot Dry Rock in the Laboratory. Hugh Murphy and the balance of the management staff are members of the Earth and Space Sciences Division, headed by W. Doyle

Figure 19. Diagram of the HDR programmatic organization structure.

Evans, Division Leader.

The programmatic organization structure as of September 30, 1986, is shown in Fig. 19. As indicated, the HDR Program continues to be field managed jointly by the Los Alamos National Laboratory, as described above, and the Energy Technologies Division of the DOE Albuquerque Operations Office with support from the Los Alamos Area Office, under the overall purview of the HDR Program Director in the DOE Headquarters Geothermal Technology Division (GTD).

Program Development Council

The Program is reviewed by the HDR Program Development Council (PDC), an advisory body to Los Alamos, whose membership includes representatives of industry, academia, and other government agencies. This group is specifically chartered to provide guidance to Program management in the development of a commercializable technology. It met twice this fiscal year in Albuquerque, New Mexico.

The 10th meeting of the PDC was held on October 24, 1985. Present were the following committee members:

- S. K. Bazant (Plains Electric Cooperative)
- R. Greider (Geothermal Resources International)
- G. V. Keller (Colorado School of Mines)
- P. Mathusa (New York ERDA)
- S. Oba (NEDO)
- D. Yueh (Stone and Webster)

Los Alamos staff members presented an overview of technical progress since the last meeting of the PDC. Committee members discussed various options for repair of wellbore EE-2 and industrial participation in the planned ICFT of the Phase II system at Fenton Hill.

The 11th meeting of the PDC Executive Committee was held on July 15, 1986. Present were the following committee members:

- S. K. Bazant (Plains Electric Cooperative)
- R. Greider (Geothermal Resources International)
- P. Mathusa (New York ERDA)
- S. Oba (NEDO)
- V. Roberts (Electric Power Research Institute)
- R. M. Ward (California Department of Conservation)
- D. Yueh (Stone and Webster)

Others attending included ex-officio members from Los Alamos and the DOE and Japanese NEDO assignees to Los Alamos.

Dr. Shigeyoshi Oba reviewed the HDR Development Program in Japan. The Los Alamos staff presented an overview of technical progress since the last meeting of the PDC in October 1985.

Detailed reports were submitted on the results of the successful ICFT. Vasek Roberts discussed preliminary results of the Electric Power Research Institute's study of the economic potential of hot dry rock energy systems.

Considerable discussion centered on the various repair options for wellbore EE-2 and on plans for the Long-Term Flow Test (LTFT).

International Steering Committee

Under the auspices of the International Energy Agency (IEA), the HDR Program has welcomed the participation of the Federal Republic of Germany and Japan over the past six years. On September 30, 1985, the FRG ended its association with the Program, and one year later the Government of Japan completed its participation.

The progress of the Program is reviewed by its International Steering Committee (ISC), which has jurisdiction over resolution of major programmatic problems and approval of proposed changes with significant schedule and/or fiscal impact.

Two ISC meetings were held during 1986, in June and in November.

The 12th meeting of the ISC was held in Los Alamos, New Mexico, on June 17 and 18, 1986. Committee members attending this meeting were

J. Bresee (DOE), Chairman
J. Rannels (DOE)
G. Tennyson (DOE)
H. Iseki (NEDO)
T. Shirahase (NEDO)
K. Uesugi (NEDO)

This meeting was held shortly after the completion of the ICFT, and most of the presentations and discussions were

dedicated to review of the results of this 30-day flow test. Five of the Japanese assignees to Los Alamos participated in the presentations.

Donna Fitzpatrick, Assistant Secretary, Conservation and Renewable Energy, DOE, attended the ISC meeting on June 18 and presented a very positive statement on the successful progress of the HDR Program.

The 13th meeting of the ISC was held in Los Alamos, New Mexico, on November 19 and 20, 1987 (more than a month after the end of FY 1986). Members attending this meeting were

J. Bresee (DOE), Chairman
J. Rannels (DOE)
G. Tennyson (DOE)
N. Nagata (NEDO)
Y. Takebayashi (NEDO)
T. Tomita (NEDO)

Attendees at this meeting reviewed the Fenton Hill activities since the ISC meeting in June, along with summary reports of the ICFT.

The Japanese had previously announced that their official participation in the Fenton Hill Project through the IEA would end on September 30, 1986. Much of the ISC meeting was concerned with continued contact with the Japanese and technology transfer activities.

NEDO of Japan is channeling its hot dry rock research to its project at

Hijiori. Presentations were made concerning the progress in this project.

Plans for Fiscal Year 1987

In FY 1987 we will continue preparations for the LTFT, beginning with another repair effort in EE-2. The test, expected to last at least a year, will provide complete operating characteristics of the Phase II reservoir and yield reliable estimates of the ultimate heat production capacity of the reservoir. Preliminary steps to be undertaken before the LTFT are to finish repairs of casing damage in well EE-2 and complete the design of the surface piping, instrumentation, and control system for the LTFT.

To ensure complete and accurate assessment of reservoir performance, scientific and engineering support will continue. Three-dimensional models for heat transfer in fractured rock will be completed and tracer tests will be used to constrain values of porosity and permeability, leading to improved predictions of reservoir thermal behavior.

Chemically reactive tracers are being developed using the principle that chemical reaction rates are exponentially dependent upon temperature. By injecting several chemicals with different temperature chemical kinetics behavior, the internal distribution of temperature within the reservoir can be inferred.

Work will be completed to identify suitable chemicals that possess reaction rates within the desired temperature range and are not excessively adsorbed on the rock.

Emphasis in tool development will continue to be on the improvement and consolidation of present tools rather than on the design of new tools. For example, the temperature tool will be combined with a gamma detector and collar locator so that thermal "signature" can be correlated, in a single log, with formation lithology as inferred from gamma-ray counting. Incorporation of the collar locator will avoid the depth uncertainties, by relating to casing depths, that occur from one survey to another as a consequence of slightly differing cable stretch. Using the collar locator to identify known depths of casing joints allows self-calibration of every survey.

Earlier in this annual report we described initial results of the "three-point" method of detecting fracture planes within zones of microearthquakes. In FY 1987 this method will be improved by examining large sets of seismic data and extending the method to additional hydraulic-fracturing experiments. Depths of intersection of the "three-point" fracture planes with the wellbores will be correlated with other indications of fracture intersections that are provided by temperature surveys and tracer experiments.

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