Hot Dry Rock Geothermal Energy Development Program

Annual Report
Fiscal Year 1985

Los Alamos

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Aerial view of the Fenton Hill Test Site.

ABSTRACT

The primary objective for the Hot Dry Rock Program at the Los Alamos National Laboratory during Fiscal Year 1985 was to complete the Phase II reservoir connection and to begin flow testing the resulting reservoir. The connection was achieved through redrilling one well and additional fracturing operations, and progress was made toward developing a detailed understanding of the fractured region through a variety of reservoir interrogation methods. Other accomplishments during the fiscal year included improvement of the high-temperature, inflatable, open-hole packer used to isolate sections of the uncased wellbore in collaboration with the Baker Corporation and the design and fabrication of a high-temperature borehole acoustic televiewer in a cooperative program with a research institute in West Germany. Progress was also made in techniques for the collection and analysis of microseismic data. Reservoir-engineering activities and geochemical studies, as well as the more routine support activities, continued in FY85.

EXECUTIVE SUMMARY

In Fiscal Year 1985, efforts of the Hot Dry Rock (HDR) Program at the Los Alamos National Laboratory were concentrated on achieving a hydraulic connection between the two deep wells, EE-2 and EE-3, at the Fenton Hill Test Site. At the outset of FY85, a workover/drilling rig was mobilized at the HDR Project site to repair the EE-2 wellbore, necessitated by damage to the casing and frac strings during the rapid vent of EE-2 after the Massive Hydraulic Fracture (MHF) (Experiment 2032) in FY84. The objective of EE-2 repair operations was to re-establish pressure and flow continuity into the MHF zone and to provide diagnostic logging (wire-line) continuity through the upper half of the fractured region.

Following the completion of EE-2 repairs in December 1984, a series of reservoir interrogation experiments was conducted at EE-2 to study the fractured region's response to pressurization and to better define the top of the MHF-created fluid reservoir. These experiments used both radioactive tracer and temperature techniques during a sequence of reservoir reinflation steps.

Early in 1985, the 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. The new trajectory was 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 of 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 of more than 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 in a section of the fractured reservoir where the rock temperature was about 265°C. Both before and after that test, a num-

ber of brief pressure-flow experiments were run to characterize the connected fracture system. At the end of FY85, unsuccessful attempts were made to stimulate the minor fracture connections detected in the deepest, hottest section of the redrilled well. All of these preparatory fracturing and testing experiments utilized the developing open-hole packer.

The improved high-temperature, inflatable, open-hole packer was used to isolate sections of the uncased wellbore. Further improvements appear possible, but its excellent performance during such experiments as the 84-hour flow test mentioned above indicates that the present design is superior to any packer of this type previously available.

In a cooperative program with Westfälische Berggewerkschaftskasse of Bochum, FRG, a high-temperature borehole acoustic televiewer has been designed and fabricated and was being prepared for field testing at the end of FY85.

In addition to conventional analyses of microseismic data collected during pressurization tests, special studies addressed low-frequency long-period events that occur early in pressurization and may represent tensile fractures. Investigations of downhole-tool coupling phenomena led to a better design of geophone sondes. There has been further improvement of the hodogram technique of microseismic-event location, and software is being developed for a new MASSCOMP computer that is expected to greatly increase the speed, accuracy, and number of on-line event locations during pressurization/flow experiments. Good progress has been made in correlating fault-plane solutions with microseismic-event locations.

Reservoir-engineering activities during FY85 have included numerical and analytical studies of fluid flow in deformable joints, estimations of fracture apertures from hydraulic data and of fractured-reservoir size from the results of hydraulic-fracturing experiments, and modeling of thermal effects during a variety of pressure-transient tests.

Geochemical studies have included investigations of the degradation of sepiolite drilling muds at high temperatures, corrosion of cable-armour materials, cor-

rosion and calcite deposition in surface-system components, a variety of chemically reactive tracers, and the adsorption of such tracers on rock surfaces.

Routine support activities such as site maintenance, environmental monitoring, repeated well logging, examination of the four rock cores recovered during redrilling, and analysis of pressure-flow and microseismic data, all continued throughout FY85.

Finally, the Electric Power Research Institute has undertaken an independent study of the economic potential of commercial hot dry rock energy systems. The study will be available in 1986.

INTRODUCTION

The HDR Concept

The purpose of the HDR Program is to develop and demonstrate 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 FY84

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 that would 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 was 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 (FY84) by the Massive Hydraulic Fracture (MHF) from EE-2 during which 21 300 m³ (5.6×10^6 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).

FENTON HILL SITE OPERATIONS

Phase II Energy Extraction System

The primary objective for the HDR Project during FY85 was to complete the Phase II reservoir connection and to begin flow testing the resulting reservoir. This was accomplished. Progress was made toward developing a detailed understanding of the Phase II fractured region through a variety of reservoir interrogation methods, both before and during the drilling of wellbore EE-3A and during the subsequent series of planned reservoir flow tests.

At the outset of FY85, a Brinkerhoff Signal workover/drilling rig was at the Fenton Hill Test Site, first to repair the EE-2 wellbore and then, after the optimum redrilling trajectory had been selected, to initiate the directional drilling of EE-3A by kicking out of the present EE-3 wellbore at a depth of about 2835 m (9300 ft). These repair operations would re-establish pressure and flow continuity into the MHF zone

In March, a larger drilling rig was mobilized by the Big Chief Drilling Co. over EE-3A. In May, connection between the wells was completed at about 3660 m (12 000 ft). The drilling went quickly with drilling rates of more than 30 m (100 ft) per day—a record rate for

After completing EE-3A as the Phase II reservoir injection hole, a series of flow tests established the initial reservoir flow impedance, outlet temperature, and fluid geochemistry. A new open-hole packer designed to operate in the hottest sections of the wellbores was an important factor in successfully completing the connection between EE-3A and EE-2. Additional high-pressure injections into EE-3A during this time were conducted in an attempt to reduce the reservoir-inlet flow impedance.

Frequent periodic downhole measurements continue in the EE-2 and EE-3 wellbores, using Los Alamos instruments. Commercial logs conducted in FY85 were free-point determinations and 64-arm caliper, tracer, and cement bond logs.

The downhole measurements performed by Los Alamos included gamma logs, temperature surveys, caliper logs, USGS surveys, and microseismic mapping (during pressurization tests in all four Fenton Hill wells plus the Precambrian monitoring wells). Acoustic televiewer logs were conducted with the USGS instrument obtaining data over part of the open-hole region. Temperature logs monitored resulting dynamic changes in the reservoir during extended flow tests. The other logs used were static well-condition diagnostics.

The Zia Company and C.J.C., Inc., performed maintenance work and janitorial services at the Fenton Hill Test Site. They also supported workover/drilling operations and reservoir-stimulation experiments. Site preparation for the contract extension (and return) of the

Brinkerhoff Signal rig in October 1984, the rig's demobilization in February 1985, and the mobilization of the Big Chief Drilling Co. rig in March required extra effort in the fiscal year.

The on-site well, which produces at about 6 ℓ/s (100 gpm), was the basic water supply for domestic use and experimental work at Fenton Hill. The well permit issued by the New Mexico State Engineer's Office allows 3 acre feet (3700 m^3) of domestic use and 15 acre feet (18 500 m^3) of experimental use per year through calendar 1986. Requests have been submitted through the DOE for an extension of these permit quantities. A request has also been initiated to procure, by purchase if necessary, alternative water rights for the site operations. Currently, supplemental water is available on contract from C.J.C.; 715 m^3 (189 000 gallons) of water were hauled for drilling instrumentation hole PC-2. However, this source is dependent on the water rights of C.J.C., as adjudicated by the State Engineer.

Well production for FY85 was 18.4 acre feet (22 700 m^3) for experimental use and 3.9 acre feet (4800 m^3) for domestic use. Domestic use includes supply to the Santa Fe National Forest's fire guard station.

An instrumentation well, PC-2, was completed in December of 1984. The well is about 0.7 km (one-half mile) west of the site, on Forest Service land, and was drilled to 1804 ft. The well is for emplacement of a third geophone in the "Precambrian net."

Environmental Monitoring

Fluid and solid samples were collected on and off the Fenton Hill geothermal site as part of a continuing program to determine the effect of geothermal operations on the surrounding area.¹⁻⁹ Twenty-nine stations adjacent to the site (Fig. 1) were monitored, as were on-site storage ponds and the water-supply well. Data from the 29 off-site stations indicate HDR Program activities had no effect to date on the water quality.

Solid or sludge samples were collected from the bottoms of the storage ponds while they were empty for cleaning. These samples have been analyzed and

EPA Hazardous Waste Number	Contaminant	Maximum Concentration (mg/ ℓ)
D004	Arsenic	5.0
D005	Barium	100.0
D006	Cadmium	1.0
D007	Chromium	5.0
D008	Lead	5.0
D009	Mercury	0.2
D010	Selenium	1.0
D011	Silver	5.0

were found not to exceed the threshold levels of the eight elements listed above.

A discharge plan now exists for the Fenton Hill operations.¹⁰ Under this plan, all fluid and solid waste will be contained if possible on the site using available storage facilities. For this reason, as well as to conserve water, the fluid from a small leak in the 21 600- m^3 (5.7-million-gallon) reservoir is now collected in a holding tank and pumped back into the reservoir. No further fluid discharge has occurred since this step was taken.

DOWNHOLE INSTRUMENTATION DEVELOPMENT

Los Alamos continued to make additional design modifications and improvements in the basic downhole instruments used in the Phase II wells.

Work continues on the prototype, thermally upgraded, digital borehole acoustic televiewer (BAT) tool being developed by the Laboratory in cooperation with the research institute Westfälische Berggewerkschaftskasse (WBK) of the Federal Republic of Germany. Los Alamos also designed and successfully used a new, high-temperature, combination temperature/spinner/pressure tool in FY85 and worked on a family of high-temperature explosively activated tools needed in both the Phase II reservoir completion and the interrogation operations continuing into FY86.

Borehole Acoustic Televiwer

The development of the Borehole Acoustic Televiwer (BAT) has progressed to the final fabrication and test stages. The downhole electronics and uphole data acquisition and display, provided by WBK of West Germany, has been interfaced to the acoustic sub-assembly and tested in the laboratory. The overall system performance meets all of the specifications as detailed in the Fiscal Year 1984 Hot Dry Rock Annual Report.¹¹ Field tests conducted at the Fenton Hill Test Site have proved the design of the pressure-balance system to successfully protect the TFE Teflon acoustic window from deformation as well as provide leak-tight seals throughout the downhole instrument package (Fig. 2).

Figure 2. Borehole acoustic televiwer (rotating assembly).

The software system that controls the downhole microprocessor significantly simplifies televiwer operations and will provide improved signal-to-noise transmission, resulting in obvious signal enhancement at the surface recording and display equipment.

Temperature/Spinner/Pressure Tool with Collar Locator

A new high-temperature combination temperature/spinner/pressure sonde was designed and fabricated for use in geothermal environments (Fig. 3). This instrument also includes a collar locator. The pressure transducer has been calibrated over the temperature range from ambient to 300°C. This strain-gage pressure transducer, Model 1009, has excellent thermal stability over the specified range (Fig. 4). The other components in the combination tool—temperature probe, fluid velocity (spinner) assembly, and collar locator—are proven “standard” devices used in Los Alamos high-temperature downhole instruments.

Figure 5 shows data recorded during a borehole survey in a flowing geothermal well using this instrument. The data from the spinner show the transition to two-phase flow from around 850 to 800 m (2790 to 2620 ft), which correlates with the temperature and pressure data.

String Shot/Detonator Explosive Tool

This tool, as configured in Fig. 6, is used in the HDR Program as an acoustic-signal source for calibration of an (existing) microseismic activity detection net. This net is located at the Fenton Hill test area with its deployment

Figure 3. Temperature/spinner/pressure tool with collar locator.

in nearby wellbores and surface stations.

The tool's electronic firing system provides the energy necessary to fire the explosive charge at the front end of the tool and at the same time provides an electrical timing signal (T_o) at the moment of detonation. These signals (pressure wave, shear wave, arrival time, and T_o), when detected and recorded by the detection net, provide calibration information for comparison of experimentally originated microseismic activity in the

net area. Shock attenuators in the region of the main explosive charge prevent damage to the tool and allow reuse after each run by replacing the sacrificial detonator, detonator-cord housing, and main explosive charge (up to 200 g). The tool essentially is a reusable instrument and will operate in an environment of 250°C and 10 000 psi.

This tool is used before fracturing experiments at Fenton Hill to provide timing calibration signals.

RESERVOIR ENGINEERING

Achieving Hydraulic Communication

Precursor signs of an impending connection between the two Phase II boreholes appeared in May. Weak flows, 0.3 ℓ/s (4.8 gpm), into EE-3A developed when EE-2 was pressurized to 12 MPa (1700 psi). After drilling ahead, another flow developed, but this time the flow was much stronger and occurred at three joints intersecting EE-3A near 3.6-km (11 800-ft) depth. On May 20 the drill-rig pumps were used to inject water into EE-3A, and a sudden pressure rise occurred almost immediately in EE-2.

With these increasing portents of success, we decided to improve the hydraulic communication quality of the joints near 3.6 km (11 800 ft) by stimulating them with high pressure. We did this in Experiment 2059 on May 27 and 28 by setting a specially developed, high-temperature packer¹² at a depth of 3.52 km (11 500 ft) where the drill hole was reasonably smooth and then pumping water into the entire open-hole inter-

val between the packer and the bottom of the hole, which had been sanded up to a depth of 3.72 km (12 200 ft). The situation is depicted in Fig. 7. A volume of 1670 m^3 (441 000 gallons) of water was injected into EE-3A, primarily at rates of 15 to 27 ℓ/s (240 to 430 gpm) and at downhole pressures ranging from 66 to 75 MPa (9600 to 11 000 psi). Pressure rose rapidly at EE-2. Two hours after the start of pumping in EE-3A, the EE-2 wellhead valve was opened and water flowed out. At first the outflow rate was small, but by repetitively surging the well (i.e., by shutting it in for awhile, then quickly venting it), the outflow rate was steadily increased and attained a value of 10 ℓ/s (160 gpm) when testing stopped. The reservoir flow resistance was 3 GPa s/m^3 (30 psi/gpm). However, this is a transient value and should become less. Even now, this impedance is only two times the low-back-pressure impedance observed for the Phase I reservoir after several months of operation and several episodes of high-pressure stimulation.

A post-connection temperature survey taken in EE-3A on May 30 showed that several new joints had been stimulated and also served as flow entries from EE-3A to the reservoir. Figure 7 portrays the potential flow paths. Although they appear short in this elevation view, EE-2 and EE-3A are horizontally separated by 150 m (500 ft) at the depth where the two wells appear to intersect.

Following the successful connection, we extended the redrilled well and conducted two additional stimulations in it with open-hole packers. The first stimulation, Experiment 2061 (June 29 to July 2), conducted at a depth from 3.83 km (12 600 ft) to 4.02 km (13 182 ft) failed to result in significant communication. The second stimulation, Experiment 2062 (July 18-20), attempted at a depth about midway between the first successful and the second unsuccessful points of stimulation [i.e., 3.65 km (11 976 ft) to 3.84 km (12 600 ft)] achieved another hydraulic connection.

Figure 4. Graph of transducer calibration curves.

Seismic Results

During the early phases of redrilling EE-3A, water was injected into the wellbores of both EE-3A and EE-2. Seismicity was monitored almost continuously for six weeks. Figure 8 shows the locations of many of the seismic events determined by the Precambrian seismic network, which consisted of four stations: EE-1, PC-1, PC-2, and GT-1. The large scatter in the seismicity is due largely to the fact that many different zones were pumped into during this phase. Most important is the result that seismicity accompanying injections into EE-2 generally occurred at depths shallower than 3 km (9800 ft) and well to the north of the borehole.

Experiment 2061 was accompanied by a high level of microseismicity. Many events were large enough to be detected at the surface. Figure 9 shows locations of events determined during Experiment 2061 using the Precambrian seismic network. Later in the experiment, event locations migrated downward in a manner that was similar to movement in Experiment 2042. The dense cluster of events shown in the upper portion of the seismic cloud is nearly coincident with the dense cluster of events that occurred during Experiment 2032, the main hydraulic fracturing experiment in wellbore EE-2 (December 1983).

Experiment 2062 was accompanied by a moderate level of seismicity. A much smaller number of events were observed at the surface during this experiment than during Experiment 2061. Figure 10 shows locations of events accompanying this experiment.¹⁰

Most of the seismic waveforms have large S- to P-wave amplitude ratios, spectra similar to tectonic (shear) events that occur throughout the world, and fault-plane solutions consistent with shear slip along faults. This evidence suggests that most of the microseismicity accompanying hydraulic fracturing is associated with shear slip along natural joints. Most hydraulic-fracturing mod-

Figure 5. Pressure, spinner (flow-rate), and temperature logs of a flowing hydrothermal well.

Figure 6. String shot/detonator explosive tool.

Figure 7. Elevation view of acoustically mapped fractured reservoir, looking north, showing location of open-hole packer. Flow paths, indicated by curved lines, are inferred from flow entries detected in well EE-3A.

els predict that a tensile failure of the rock occurs to accommodate the injected water.^{13,14}

Seismologists working at volcanoes have long known of the existence of long-period earthquakes with waveforms distinct from the waveforms of tectonic events. Volcanologists often consider the origin of the long-period waveforms to be tensile fracturing caused by the injection or movement of magma beneath the volcano. In order to determine if long-period earthquakes may also accompany HDR hydraulic fracturing, a careful study analyzed microseismic data collected during the early portions of five hydraulic-fracturing experiments. Long-period waveforms were found to accompany the experiments studied. These long-period earthquakes are very small and can only be detected by careful inspection of the seismic records. Models of long-period earthquakes are currently being evaluated. Their applicability to the events detected at Fenton Hill will be tested.

Initial Reservoir Testing

The presence of an expensive drill rig over one well did not permit extensive flow testing this fiscal year. Nevertheless, some preliminary tests were conducted. Their results are summarized here.

Nonreactive tracer experiments conducted during hydraulic fracturing provided estimates of the volumes of the newly created fracture systems and identified possible short-circuiting flow paths. In two experiments, sodium fluorescein dye, sodium bromide, and sodium nitrate were injected at various times: 1) initially, before any flow communication existed between the wells; 2) shortly after a flow connection was achieved; and 3) after the outlet flow had increased to its steady-state value. An idealized flow model consisting of a combination of main fracture flow paths and fluid leakoff into secondary joints explains the different tracer response curves for the three cases and allows prediction of the fracture volume of the main paths. This volume is roughly 300 m³ (80 000 gallons), which is larger than the largest fracture system previously created at Fenton Hill.

Although these tracer results imply a large reservoir, the ultimate heat-extraction capability of the reservoir also depends on the produced fluid temperature. To establish this temperature, a modeling effort was undertaken with the wellbore-heat-transfer code WBHT. This effort was necessary because damage to the EE-2 production wellbore precluded temperature logging to depth. Shallow [to 0.75 km (2500 ft)] Kuster gauge temperature data were used to calibrate the code. The model results are shown in Fig. 11. The agreement is reasonable, with the modeled results being 5°C lower than the Kuster gauge data. The results indicate that the bottom-hole temperature is at least 230°C, in good agreement with earlier estimates of the equilibrium geothermal temperature at a depth of 3.53 km (11 578 ft), the depth at the bottom of the casing in EE-2. Using the model, projected production temperatures are shown in Fig. 12.

They indicate that at 6.3 ℓ/s (100 gpm) it would take 400 days to reach a surface production temperature of 190°C.

The silica and Na-K-Ca geothermometers for the vent fluid were usually in good agreement with the expected depths at which fluid was being produced and thus augmented the data from temperature logs. The transient response of the dissolved ion concentrations during the vents suggests that at the beginning, large quantities of the indigenous pore fluid are being produced, after which time the proportion of pore fluid declines.

Earth Stresses

Using the methods outlined below, the minimum principal compressive earth stress was determined from pressurization records obtained during fracturing experiments in the newly redrilled well EE-3A. These new measurements complement earlier measurements, so we now have 30 independent estimates of minimum earth stress at depths varying from 0.6 to 4.3 km (2000 to 14 000 ft). These measurements are important not only because of their bearing on the HDR Program but also because Fenton Hill lies at the transition of the Colorado Plateau and the Basin and Range tectonic provinces. In such transitions earth stresses are highly variable, so measurements, usually few in number, are highly prized by the scientific community studying the earth's crust.

In all tests pressure records showed no evidence of rock breakdown, indicating injection into pre-existing joints. A typical pressure response consisted of an early wellbore storage period followed by linear fracture flow, which then evolved into a steady-pressure, fracture-extension mode. A sharp pressure drop followed by a more gradual decay characterized shut-in behavior.

The minimum principal earth stress was deduced from the following:

1. Extrapolations of hydraulic-fracture extension pressures to zero injection flow rate, yielding true fracture-open-

ing pressures.

2. Instantaneous Shut-In Pressures (ISIP).
3. Differential strain analysis of core specimens. (See discussion below and Ref. 15).

The directions of the principal stresses were determined from fault-plane solutions obtained from first motions of fracturing-induced microearthquakes that were recorded on 11 surface seismometers.¹⁶ Measured earth stresses are summarized in Fig. 13. A general linear trend appears with depth; the min-

Figure 8. Hypocentral locations in microearthquakes induced by fluid injection in well EE-2. Upper left is plan view, looking down. Lower right is elevation view, looking west. Lower left is elevation view, looking north.

Figure 9. Hypocentral locations of microearthquakes induced by fluid injection in the deepest section of well EE-3A.

imum stress increases with a gradient of 18 MPa/km (0.80 psi/ft). However, a low stress anomaly occurs from 2.6 to 3.1 km (8500 to 10 000 ft) where the minimum stresses are 28 MPa (4000 psi) lower. The lithology is just slightly different in this low stress region (consisting of biotite granodiorite, rather than the gneisses, granites, and schists above and below), and the measured differences in physical properties are insignificant. Furthermore, the biotite granodiorite was intruded so long ago (about 1.6 billion years) that stress contrasts at intrusion, if any, should have been dissipated by creep processes. Hence these measurements are in sharp contrast to the experience of the petroleum industry where abrupt changes in stress are generally associated with marked changes in lithological and formation properties.

During EE-3A redrilling, four oriented core samples were cut that show fracture orientations substantially different in the Phase I and Phase II systems. The Phase I system contains predominantly near-vertical fractures striking in a wide range of directions. In contrast, the Phase II system is dominated by fractures inclined 30 to 60°.

Differential strain analysis (DSA) of the cores gives information on the *in situ* earth stresses that supplements the above results. A sufficient number of oriented strain gages mounted on core samples completely determine the strain tensor. The sample is compressed in a hydrostatic pressure vessel until all the microcracks in it are squeezed shut. Analysis of the strain measurements gives the volumes and orientations of the cracks. These values are directly related to the *in situ* stresses and stress directions.

The first core from the Phase II redrilling came from a depth equal to the bottom of the Phase I reservoir region. DSA results from this core give stresses and stress directions in good agreement with those determined from pressurization records. The maximum compression is vertical; the minimum compression is horizontal and along the east-west direction. However, as one descends through the Phase II reservoir, the maximum compression rotates away from vertical until it is essentially horizontal along the northwest-southeast direction.

These results are in generally good agreement with seismic fault-plane solutions. For example, at about 3.5-km (11 500-ft) depth, DSA shows the maximum compression to be inclined roughly 45° from vertical and consistent with normal faulting along a near-vertical, north-south-striking plane. Fault-plane solutions from seismic events from Experiment 2020 and many seismic events from Experiment 2032 show this same result. At about 3.75-km (12 300-ft) depth, DSA shows a stress state consistent with strike-slip faulting. Seismic events from 4- to 4.3-km (13 000- to 14 000-ft) depth during Experiments 2012 and 2016 show this strike-slip behavior, although the azimuth of the stress directions differs from the DSA results. These strike-slip events also occur at 3- to 4-km (9800- to 13 000-ft)

depth during Experiment 2032, and their locations are intermixed with those of normal faulting events.

Reservoir-Engineering Support

Reservoir engineering work supports future experiments at Fenton Hill, particularly the longer-term reservoir-evaluation tests that will be conducted to assess reservoir size and ultimate heat capacity.

Studies of the possibility of using temperature-sensitive, chemically reactive tracers to measure reservoir temperatures continued, both in laboratory experiments and theoretical work. The kinetics of several new reactions have been measured at various temperatures, and all of the tracers examined so far have also been tested for either adsorption or catalytic effects. A new laboratory technique for measuring the kinetics of reactions more rapidly has also been developed. The temperature-programmed reaction method appears to be a viable technique for determining the same kinetic information in one or two experiments that previously required seven or eight.

The recently acquired MASSCOMP seismic digital data acquisition system is now operable. Our goal was to develop a system that could digitize data from all downhole and surface stations and store data only when seismic events occurred. The system has a typical throughput of 50 000 samples per second for each of 4 channels (3 triaxial geophones plus a time code), 5000 samples per second for 6 channels, and 500 samples per second for 16 channels (surface network). Figure 14 shows a flow diagram for data flow through the digital seismic-event detection and recording system.

The Finite Element Heat and Mass (FEHM) computer code underwent significant modifications during FY85. These modifications dealt with the speed and storage of the solution scheme and were motivated by the need for 3-D models of reservoir-stimulation tests.

An incomplete factorization scheme was implemented with an orthominimization iterative acceleration. Incom-

plete factorization is achieved by taking only a few steps of the Gauss elimination scheme in the solution of the matrix equations that arise in the finite element discretization of the reservoir equations. By performing only several steps, the filled-in nodes can be accounted for directly instead of saving the whole band in the usual direct-solution algorithms. On heat and mass transfer problems with bandwidths of 100 (about average), savings of 90% in storage were achieved.

The algorithm works only on the non-zero entries of the solution matrix. On all but the smaller problems, computer time is saved compared with working on all entries in the band, even with the extra expense of the conditional statements that skip over the zeros.

To accelerate the iteration process, the orthogonalization minimization al-

Figure 10. Hypocentral locations of microearthquakes induced by fluid injection at intermediate depth in well EE-3A.

gorithm ORTHOMIN is used. This algorithm is similar to conjugate gradient methods except that ORTHOMIN is applicable to nonsymmetric matrices. The algorithm tries to reduce the condition number of the solution matrix by making successive iterations orthogonal to one another. For practical considerations only several iterations are orthogonalized before restarting the process. The algorithm has greatly accelerated the incomplete factorization scheme and increases in speed of one to two orders of magnitude have been realized over standard banded Gauss elimination. For more details, see Refs. 17 and 18.

TECHNOLOGY TRANSFER

The purpose of the HDR Program is to develop and demonstrate the technology required for the large-scale extraction of thermal energy from naturally heated rock at accessible depths in the earth's crust. However, the Program's ultimate goal is to transfer a mature technology with economic promise to the private sector so that industry can pro-

ceed with further development and application of hot dry rock energy systems. Toward this end, technology transfer has been and is an essential element of the HDR Program.

Complementary Programs

Industry and government agencies in countries other than the U.S. have expressed strong interest in hot dry rock energy systems. However, the remaining uncertainties about such systems – particularly concerning completion costs and useful lifetimes – have so far discouraged international investment in their commercial development. To this time, therefore, most information on the hot dry rock concept and the Los Alamos experience in developing it has been transferred principally to government organizations in countries with energy resources more limited than those of the U.S. This has led to excellent background research, resource evaluations, and field experiments in several countries, notably in the Federal Republic of Germany, Japan, the United Kingdom, and France. The HDR Program maintains good information exchange with all of these complementary programs. This cooperative international effort will contribute to and hasten a convincing demonstration of the commercial viability of hot dry rock energy systems.

Presentations and Publications

Program staff regularly presents technical developments, experimental results, scientific analyses, and program reviews at appropriate scientific and engineering meetings and publishes technical information as promptly as possible in technical journals, meeting transactions, and Los Alamos reports. To keep the general public informed of the nature and status of the HDR Program, less technical talks are presented and articles are written when a suitable opportunity

Figure 11. Temperatures in EE-2 at 3000-m depth during venting period of Experiment 2062, as modeled (continuous curve) and as measured with a Kuster gauge (circles).

for them appears. The Laboratory produced a movie describing the HDR concept and program that has been widely distributed and shown. HDR Program staff and facilities are always available to newspaper, radio, and television reporters. This ready access to information about hot dry rock has resulted in much favorable publicity not only in New Mexico but also nationally and internationally.

An appendix to this annual report lists technical information published or presented in FY85.

Equipment, Instruments, Techniques, and Analyses

The stringent requirements of the HDR Program have necessitated development of a wide variety of downhole equipment and instruments, investigative techniques, and analytical and computer analyses. Many of these have broad applications in other programs and industrial operations. Of special interest during FY85 has been the development of successful high-temperature open-hole packers, an innovative acoustic borehole televiewer, and reactive chemical tracers for predicting reservoir lifetime. Information on these and other developments appears earlier in this report. Details concerning all of them for which the HDR Program has had primary responsibility are available to anyone interested, in the U.S. as well as in other countries.

Economic Study

A competitive unit cost of energy is essential for successful commercial development of hot dry rock energy systems. Therefore, the Electric Power Research Institute (EPRI) is making an independent study of the economics of such systems to evaluate their commercial potential. The study was initiated in FY85 and will be published early in FY86.

Field Support of Other Programs

When commercial capabilities do not exist or are not available for investigating high-temperature geothermal wells or for implementing field experiments, the specially equipped HDR Program logging trucks, downhole instruments, and field crews are made available on a cooperative or cost-recovery basis to industrial organizations or other development programs. Most recently, the Laboratory sent its field-support equipment and personnel to Costa Rica. Several very hot hydrothermal wells there were logged for the Costa Rican Government, both to provide information urgently needed for field development and – particularly – to educate local operators concerning the equipment, techniques, and analyses needed to acquire that information.

Spin-Off Companies

Two former staff members in the HDR Program have formed spin-off companies. One company manufactures and

Figure 12. Simulated temperature at 25-m depth in well EE-2 during continuous production of fluid at 6.3 l/s (100 gpm).

Figure 19. Measured earth stresses as a function of depth at Fenton Hill.

markets high-temperature downhole instruments; the other provides technical information and assistance to potential developers of commercial hot dry rock energy systems.

Although commercial production of energy from the worldwide hot dry rock energy resource is still in the future, the Laboratory is pursuing an aggressive program of technology transfer now. Its

efforts in this area will hasten transfer of technology to the private sector and, in the meantime, contribute substantially to many other development programs and industrial operations.

PROGRAM MANAGEMENT

Program Organization

During FY85 some organizational and personnel changes occurred in the management structure of the HDR Program. P. R. Franke is now Fenton Hill Project Manager for Planning, Administration, and Fiscal Control.

Figure 15 depicts the present programmatic organizational structure. As indicated, the HDR Program continues to be field managed jointly by Los Alamos and the Energy Technologies Division of the DOE Albuquerque Operations Office (ALOO-ET) with support from the Los Alamos Area Office (LAAO), under the overall purview of the HDR Program Director in the DOE Division of Geothermal and Hydropower Technologies (DGHT).

The HDR Program Development Council (PDC) conducts an annual review of the Program. The PDC is an advisory body to Los Alamos with a membership comprising representatives of industry, academia, and the USGS. According to its charter, the PDC provides guidance to Program management in the development of a commercializable technology.

The International Energy Agency's (IEA) HDR International Steering Committee (ISC) also reviews the Program's progress, has jurisdiction over resolution of major programmatic problems, and approves proposed changes with significant schedule and/or fiscal impact.

Program Development Council

The 10th annual meeting of the PDC Executive Committee was held in Albuquerque, New Mexico, on October 24, 1985. Present were the following Committee members:

S. K. Bazant (Plains Cooperative),
 R. Greider (Geothermal Resources International),
 G. V. Keller (Colorado School of Mines),
 P. Mathusa (New York ERDA),
 S. Oba (National Research Institute for Pollution and Resources),
 and
 D. Yueh (Stone and Webster).

Others attending included ex-officio members from Los Alamos and the DOE and visitors from the Sandia National

Laboratory, West Germany, and Japan.

Los Alamos staff members presented an overview of technical progress since the last meeting of the PDC. They reported on redrilling operations at EE-3A, packer development, seismic results in EE-3A flow testing, and reservoir size assessments as well as surface system design and instrumentation developments.

Committee members expressed concern over the condition of wellbore EE-2 resulting from the MHF experiments. They discussed various options for repair and recommended that repairs be made.

Considerable discussion centered on industrial participation in the planned Closed Loop Flow Test of the Phase II system at Fenton Hill. The PDC recommended industry involvement in the planning and in the actual flow tests, particularly in the Long Term Flow Test (LTFT). Industry participation would help to assure that the experiments and the data obtained would be applicable to industry needs.

Figure 14. Microseismic data acquisition system.

Figure 15. HDR Program organization chart.

The Committee emphasized the value of the foreign participation in the HDR Program under the IEA Agreement and encouraged further efforts to assure this continued participation. (Note: since this meeting, the Federal Republic of

Germany has ended its participation in the HDR Project, effective September 30, 1985.)

International Steering Committee

The ISC met twice during 1985, in June and again in November (actually a month after the end of the U.S. fiscal year). Committee members present at both meetings were

J. Bresee (DOE), Chairman,
J. Rannels (DOE),
G. Tennyson (DOE),
K. Kodama (NEDO), and
W. Schloemer (KFA).

The 10th regular ISC meeting was held in Santa Fe, New Mexico, on June 5-6, 1985. Program staff members briefed the committee on EE-2 workover operations, EE-3A redrilling operations, open-hole packer modifications, the Phase II reservoir connection, reservoir and seismic analyses, developments in instrumentation, and options for well completion and the surface system. Other topics discussed included future plans and the transfer of hot dry rock technology.

The 11th meeting of the ISC was held in Los Alamos, New Mexico, on November 14-15, 1985. Los Alamos reported on EE-3A redrilling, reservoir stress stud-

ies, size assessment, and geochemistry; EE-3A flow testing; and packer development. Discussion of future plans focused on technology transfer, industrial participation, financial reports, and operating plans. There was also considerable discussion surrounding parameters, plans, and projections for the Initial Closed Loop Flow Test. Dr. Kodama of NEDO reported on the Japanese Hot Dry Rock Program. Also at this meeting, Dr. Schloemer announced that West Germany would not continue to participate in the Fenton Hill Project after the end of FY85.

Plans for FY86

We deferred completing EE-3A as well as final flow testing the wellbore's lower section from FY85 to the early part of FY86. (Note: The drilling/workover rig remained on standby status until November of 1985.)

Immediately upon completion of EE-3A work (expected in January of FY86), preparatory site work will begin for locating and installing the Phase II surface system. Procurements for the major new components and the installation contract will be issued in FY86. A 10-month total construction period is anticipated, including a 1-month period to conduct the Initial Closed Loop Flow Test.

We will conduct the flow test in the closed-loop mode with a surface configuration thermohydraulically representative of the completed loop but with

some temporary installations and rental equipment. This test will provide vital preliminary data on flow impedance, water loss, and geofluid chemistry that are needed to finalize the configuration and operating parameters of a completed flow loop.

Surface-system installation will then resume. As soon as the surface system has been completed, instrumented, and tested, we will initiate an Extended Flow Test to investigate the thermal, mechanical, and chemical behavior of the system and to permit estimation of useful lifetime and economic viability. During this long-term test, we will operate the existing small, experimental, binary-cycle electrical-generating unit to evaluate improved efficiency (relative to the lower-temperature, geothermally heated feed water produced by the Phase I system) and to investigate possible corrosion, scaling, fouling, and maintenance problems associated with the deeper reservoir.

The essential reservoir-engineering, environment-surveillance, and instrumentation-development efforts will continue as needed to support Phase II. In addition, we will intensify efforts to assess interest by private operators or third-party entrepreneurs in the construction of a 5- to 10-MWe electrical power plant at Fenton Hill, for operation at the conclusion of the reservoir flow tests, and to provide up-to-date technical information to other interested organizations.

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APPENDIX:

PUBLICATIONS AND PRESENTATIONS

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"Information Extraction from Noisy Televiewer Logs of Inclined Wellbores in Hard Rock," K. L. Burns.

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"Characteristics of Microearthquakes Accompanying Hydraulic Fracturing as Determined from Studies of Spectra of Seismic Waveforms," M. Fehler and D. Bame.

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