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Hot Dry Rock Geothermal Energy Development Program

Annual Report
Fiscal Year 1983

MASTER

University of California

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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CONTENTS

	Page
ABSTRACT.....	1
EXECUTIVE SUMMARY.....	2
1.0. INTRODUCTION.....	9
1.1. The HDR Concept.....	9
1.2. Synopsis of the HDR Program Through FY82.....	9
1.3. FY83 Objectives.....	17
2.0. TECHNICAL ACTIVITIES.....	18
2.1. Fenton Hill Site Operations.....	18
2.1.1. Workover-Rig Operations.....	18
2.1.2. Workover Operations Review Committee.....	20
2.1.3. Environmental Surveillance.....	21
2.1.3.1. Water-Quality Monitoring.....	21
2.1.3.2. Federal and State Water Permit Activities.....	23
2.1.3.3. Seismic Activity.....	27
2.1.3.4. Biotic Monitoring.....	30
2.1.3.5. Vent Gases.....	30
2.1.4. Water Supply.....	30
2.2. Downhole Tools and Instrumentation.....	33
2.2.1. Slimline Detonator.....	33
2.2.2. Slimline Acoustic Detector (Geophone) Tool.....	33
2.2.3. Crosswell Acoustic Transceiver.....	37
2.2.4. Component Development.....	38
2.3. Reservoir Engineering.....	39
2.3.1. Geochemistry.....	39
2.3.2. Summary of Fracturing Experiments.....	42
2.3.3. Analysis of Fracture-Opening Pressures and Earth Stresses.....	46
2.3.4. Hydraulic-Fracturing Theory in Jointed Rock Masses.....	53
2.3.4.1. Correlating the Data with the Planar Fracturing Model.....	57
2.3.4.2. Correlating the Data with the Volumetric Fracturing Model.....	59

2.3.4.3.	Shape of Microseismic Zones.....	61
2.3.5.	Rock Mechanics.....	63
2.3.6.	Effects of Shut-ins During Hydraulic Fracturing.....	64
2.3.7.	Tracer Studies.....	67
2.3.8.	Insulating Geothermal Well Casings from Thermal Stress with Nitrogen Gas.....	73
2.3.8.1.	The Nitrogen Experiment.....	75
2.3.8.2.	Conclusion.....	78
2.4.	Technology Application	79
2.4.1.	Roosevelt Hot Springs.....	79
2.4.2.	Acord 1-26 Hot Dry Well.....	80
2.4.3.	Navopache HDR Project.....	81
2.4.4.	East Mesa Field Operations.....	81
2.4.5.	Beowawe Field Operations.....	82
3.0.	PROGRAM MANAGEMENT.....	83
3.1.	Organization.....	83
3.2.	Program Development Council.....	84
3.3.	International Steering Committee.....	85
3.3.1.	Sixth ISC Meeting.....	85
3.3.2.	Seventh ISC Meeting.....	87
ACKNOWLEDGMENTS		89
REFERENCES.....		89

HOT DRY ROCK GEOTHERMAL ENERGY DEVELOPMENT PROGRAM
ANNUAL REPORT
FISCAL YEAR 1983

Compiled and Edited by
M. C. Smith, G. J. Nunz, and M. G. Wilson

ABSTRACT

During Fiscal Year 1983, emphasis in the Hot Dry Rock Program was on hydraulic-fracturing experiments at depths around 3.5 km (11 473 ft) in the two inclined wells of the Phase II system at Fenton Hill, New Mexico; on improved facilities and techniques for mapping the source locations of acoustic signals generated by the fracturing events; on mathematical modeling of the fracture systems produced in these and earlier experiments; and on development of a family of "slimline" high-temperature downhole instruments that can be used within or through relatively small-diameter pressure tubing.

Hydraulic fracturing at a vertical depth of approximately 3500 m (11 500 ft) in well EE-2, the deeper well, produced fractures that, in acoustic maps, appear to occupy a large, roughly ellipsoidal volume whose major axis is directed to the north of the other well, EE-3. Hydraulic fracturing from EE-3 at a similar depth produced another set of fractures that appear to be approximately parallel to and centered about 180 m (600 ft) east of the earlier set. Subsequent fluid injections reduced the distance between the two sets, but no hydraulic connection between them was established. The "seismic clouds" produced by mapping the source locations of acoustic signals generated by fluid injection are broadly three dimensional. It appears, however, that the fracture sets actually consist of one or a very few roughly planar fractures, the more broadly distributed acoustic sources representing small shearing displacements along natural joints and fractures intersected by the hydraulic fractures and permeated by the fracturing fluid. Modeling the silica concentrations of fluid circulated through the earlier Phase I system indicates that this type of permeation also contributes significantly to heat extraction during system operation.

The precision and accuracy of locating the sources of acoustic signals detected during hydraulic-fracturing operations have been increased by improvements in equipment, drilling of another deep hole for geophone emplacement, and additional station calibrations. Analysis of the signals has also been improved and broadened.

Development of slimline downhole instruments has included a detonator tool used to fire small explosive charges for geophone calibration, a geophone package using high-temperature electronics and requiring no temperature protection, and final design of a high-temperature borehole acoustic televiwer. A "crosswell acoustic transceiver" has also been developed for investigating rock type and structure between wellbores.

These and other activities in the Hot Dry Rock Program are discussed in this Annual Report for Fiscal Year 1983.

EXECUTIVE SUMMARY

The overall objective of the Hot Dry Rock (HDR) Program is to develop and demonstrate the technology required for economical commercial production of thermal energy from naturally heated rock at accessible depths in the earth's crust, in locations where that rock does not contain enough natural steam or hot water to be a useful source of hydrothermal fluids. The method being developed initially is to produce a pressurized-water heat-extraction loop by drilling two holes into the hot rock and connecting them at depth through a system of large cracks produced by fluid pressure ("hydraulic fracturing"). Cool water injected through one hole is then heated as it circulates through the cracks and is recovered through the second hole as hot water under sufficient pressure to prevent boiling. Its useful heat is removed through heat exchangers at the surface, and the water is reinjected to recirculate and recover additional heat.

A prototype ("Phase I") HDR system of this kind was completed in 1977 at Fenton Hill, New Mexico, in granitic rock at depths around 2600 m (8500 ft), where the initial rock temperature was about 185°C. The system was enlarged in 1979 and was operated successfully for a total time of more than a year. Its operation was essentially trouble-free and had no detectable environmental effect. Part of the heat was used to operate a small, experimental, binary cycle power plant. However, neither fluid temperature nor rate of heat production was sufficient to support economical generation of electricity on a commercial scale.

To approach more nearly the requirements of a commercial power plant, construction of a larger, hotter, "Phase II" system was initiated at the same site in 1979. The two wells of this deeper system were drilled with the lower 1000 m (3000 ft) of each inclined at 35° to the vertical and left uncased. The deeper well, EE-2, reached a measured depth of 4660 m (15 289 ft), representing a vertical depth of 4389 m (14 400 ft), where the rock temperature was 320°C. In their inclined sections, the shallower well (EE-3) was 370 m (1215 ft) vertically above EE-2.

In a series of pumping operations, a total of 8820 m³ (2.33×10^6 gallons) of water was injected into the bottom 136 m (447 ft) of the deeper well. Formation breakdown — the initiation of hydraulic fractures — occurred at a wellhead pressure of 33 MPa (4800 psi). Maps of the source locations of the

acoustic signals that accompanied further fluid injection suggested growth of a series of inclined hydraulic fractures that passed below and beyond the bottom of the other well. This was accompanied by evolution from the reservoir rock of quite large volumes of carbon-dioxide gas containing a little hydrogen sulfide, which subsequently contributed to a long series of stress-corrosion-cracking failures of drill pipe and pressure tubing.

To isolate an open-hole section of well EE-2 at a depth where an inclined fracture was more likely to intersect the other well, EE-2 was filled with sand to a point 110 m (360 ft) below the bottom of the casing. A total of 950 m³ (250 000 gal) of water was then injected into this section, producing three fracture zones roughly 30 m (100 ft) apart along the wellbore. Acoustic mapping indicated growth of these hydraulic fractures within a roughly ellipsoidal volume whose major axis was directed considerably to the north of EE-3. It was evident that a much larger fluid injection would be required to extend this volume along its minor axis to an intersection with the other well, and this could not be attempted until pressure tubing more resistant to the aggressive downhole environment could be obtained.

At the beginning of FY83, pending procurement of that new tubing, one more injection experiment was attempted in EE-2. It was terminated by another tubing failure after an additional 3190 m³ (844 000 gal) of water had been pumped into the fractures, still without producing a hydraulic connection to EE-3.

The workover rig was then skidded to well EE-3, where a liner was cemented in to bypass a fluid-loss zone near the bottom of the casing. Injection of 579 m³ (153 000 gal) of water into an open-hole section 115 m (375 ft) long, between the bottom of the liner -- at 3472 m (11 390 ft) measured depth -- and the top of a sand plug, was terminated by a drill-pipe failure without producing a connection to the fractures previously created from the other well. Acoustic mapping suggested that the new set of fractures was approximately parallel to and centered about 180 m (600 ft) east of that earlier set.

Because it was intended to be the production well of the heat-extraction loop, the casing in EE-3 had been pretensioned to 400 000 kg (880 000 lb), about 80% of its yield strength -- so that, when superheated water was produced through it, its thermal expansion would be accommodated by relief of elastic strain rather than buckling of the pipe. Injection through it of

large amounts of cool water would therefore be expected to result in enough thermal contraction to pull the pipe in two. To avoid this, the water injected in the above fracturing experiment was preheated at the surface to about 65°C. However, it appeared possible that replacing water with nitrogen gas in the annulus between the tubing string and the casing would reduce the rate of heat transfer between them sufficiently so that cool water could be injected safely. An experimental determination of heat-transfer rate in the well showed that such a "nitrogen blanket" did reduce it significantly, but not enough to eliminate the necessity of preheating the water to a temperature of the order of 50°C.

Damage to the uncemented upper section of the liner in EE-3 during these experiments resulted in two difficult cutoff, fishing, and repair operations, and finally in postponement into FY84 of further fracturing experiments below the liner, pending acquisition of a specially designed casing packer to be used within the liner. In the meantime, two fracturing experiments were conducted in which water was pumped into the open-hole section of EE-3 above the liner (which, through the liner itself, was also directly connected to the open-hole section below the liner). The fluid-loss zone near the bottom of the casing was found to accept water freely at relatively low pumping pressures, and a significant fraction of this water returned when the well was vented. Maps of the source locations of acoustic signals recorded during fluid injection indicated that the distance between the fracture system produced from this well and from EE-2 had been reduced from about 180 m (600 ft) to about 80 m (260 ft).

Other operations at Fenton Hill during FY83 included downhole water sampling; repeated logging of both Phase II wells (particularly temperature logging subsequent to fluid injections, to locate fracture zones); detonation of small explosive charges downhole, for geophone calibration; and water-quality, seismic, biotic, and meteorological monitoring of the area. No environmental deterioration from Fenton Hill activities was detected beyond the previously reported accumulation of minor amounts of trace elements in the soil and vegetation in the canyon immediately downstream from the point at which there have been occasional discharges from a water-storage pond.

Fluid pressure required to open fractures at various depths in the Fenton Hill wells has been determined by direct measurements of instantaneous shut-in pressure (ISIP); by an extrapolation method of estimating ISIP; by

pressure-transient analysis; and by back-extrapolation of flow rate vs pressure curves to zero flow rate. On a plot of opening pressure versus depth, the points are fitted reasonably well by a line representing a "fracture gradient" of 0.0185 MPa/m (0.82 psi/ft) except in the depth interval 2600 to 3200 m (8500 to 10 500 ft) — occupied primarily by a biotite-granodiorite intrusive — where opening pressure is anomalously low.

Hydraulic fractures produced at Rosemanowes Quarry in Cornwall, at Falkenberg in West Germany, at Yakedake in Japan, and at Le Mayet de Montagne in France, have been mapped acoustically by methods generally similar to those used at Fenton Hill. In every case, the source locations of the acoustic signals recorded during fluid injection plot as a "seismic cloud" that occupies a roughly ellipsoidal volume of reservoir rock. This suggests that fluid pressure has reopened an array of pre-existing natural fractures to produce a three-dimensional fractured reservoir in which conduction paths should be short and heat extraction rapid and efficient. However, pressurization and flow experiments at Fenton Hill suggest instead that a small number of discrete, roughly planar fractures have been produced that simply are not well resolved individually in the microseismic maps.

To decide between these possibilities, correlations were sought between the volume of fluid injected and the dimensions of the seismic cloud. It was assumed that if the fracture system were a three-dimensional array, the volume of the seismic cloud (approximated as an ellipsoid) would increase linearly with the volume of fluid injected. However, if the planar-fracture model were correct, the linear relation would be between fracture area (approximated as an ellipse occupying the two greatest dimensions of the seismic cloud) and injected volume. Except for the Rosemanowes data, the better correlation was between area and injected volume, supporting the planar-fracture model. The fracture aperture derived from this relation was 1.0 mm, compared with estimated apertures of 1.7 to 4 mm from modal volumes and heat-transfer areas in the Fenton Hill Phase I system. Comparing this to injected volume suggests that, except at Rosemanowes, hydraulic fracturing generally produces about one to four principal, planar fractures in the reservoir formations considered here. Other calculations based on this planar-fracture model gave formation-permeability estimates that agreed well with field measurements.

If, as appears usually to be the case in these formations, hydraulic fracturing produces only one or a few planar fractures, then the broad

three-dimensional appearance of the seismic cloud is probably best explained primarily in terms of permeation by the fracturing fluid of natural joints and fractures intersected by the hydraulic fractures. Pressurized water entering these natural openings would reduce the effective stress normal to their surfaces and therefore facilitate shearing displacement along them, producing the microseismic signals whose source locations are plotted to produce the seismic map. Rock-mechanics studies of a jointed rock mass show that shearing displacements should occur along joints with a wide range of orientations before there is any physical opening of them (i.e., actual separation of their opposite surfaces). A joint or connected set of joints or microfractures with an aperture as small as 50 μm could permit fluid permeation to distance as great as 300 m (984 ft) from the main hydraulic fracture in a period of 10 hours, permitting the shearing displacements that produce acoustic signals to occur at locations quite remote from the main fracture. A very extensive array of source locations may, therefore, envelop one or a few localized hydraulic fractures, and the dimensions of the seismic cloud would be further increased by the uncertainties in mapping individual source locations.

Fluid permeation along natural joints and fractures apparently also contributes significantly to heat extraction from the reservoir rock. Modeling the silica concentrations of fluids circulated through the Phase I system indicates that at least 30% of the fluid moves slowly through the joints and microfractures surrounding the hydraulic fractures rather than through the main fractures. Although this fluid has a relatively long residence time in the reservoir, once its continuous circulation has been established, it removes heat from a much larger volume of rock than has previously been estimated from heat-transfer modeling and the residence-time distributions determined by tracer techniques.

Much of the modeling of the Phase I system has been based on the decrease in temperature of fluid entering the production well after circulating through the fracture system. Even after 9 months of essentially continuous circulation, this decrease was only 8°C and was not sufficient to permit confident estimation of the useful lifetime of the system. For the much larger Phase II system or a commercial-scale system elsewhere, the rate of temperature decrease of the produced fluid should be very much lower, making this method of predicting system lifetime impractical. Other means of doing so are therefore being investigated. One that appears particularly promising

is the use of reactive chemical tracers whose reaction rates vary significantly with temperature in the range of temperatures to be expected of a cooling HDR reservoir. A series of tests in which one or more such tracers flowed through the reservoir with the heat-extraction fluid would indicate progressive cooling of the reservoir rock by a progressive increase in the proportion of unreacted tracer detected in the produced fluid. However, a reverse-flow technique would be even more informative. One or more tracers would be added continuously to the fluid entering the injection well for a sufficient period to distribute it through much or all of the fractured reservoir. Injection would then stop, the well would be shut in for a time sufficient to permit considerable reaction to occur, and the fluid would be returned to the surface through the same well. Following the fluid stored in the well, the next fluid returned would be from the fractures nearest the well, where cooling was greatest and extent of chemical reaction least. Later returns would be from regions farther from the well where temperatures were higher and reaction more rapid. This method would provide an indication of cooling of the reservoir very early in its production history and, with other information concerning the volume and geometry of the fracture system, would permit construction of a rough map of rock temperature within the reservoir. A series of such measurements would allow an early estimate of when there would be significant cooling as far away as the vicinity of the production well.

Kinetic experiments in the laboratory show that ester-hydrolysis reactions are promising for measurements of this type.

A family of "slimline" (small-diameter), high-temperature, downhole instruments is being developed that can be used inside or through 11.4-cm (4.5-in.)-diameter pressure tubing. One of these developed during FY83 is a slimline detonator tool that fires small (2.66 g) explosive charges downhole to provide acoustic signals for calibrating geophones deployed in other wells. It has operated successfully in wellbores at temperatures above 300°C. Another new slimline tool is a triaxial geophone instrument in which all components are high-temperature devices so that thermal protection by dewars or heat sinks is not required.

Although it has not yet been fully protected against very high temperatures a crosswell acoustic transceiver has been designed and successfully tested at shallow depths in the Fenton Hill wells. In use, a

magnetostrictive transducer is raised and lowered in one well, producing acoustic signals that are received by a piezoceramic transducer stationed at various depths in the other well. Variations in the characteristics of the received signal provide information concerning the rock type and structure between the two wells.

Field personnel from the HDR Instrumentation Group participated in two experiments sponsored by the Geothermal Division of Phillips Petroleum Company at the Borchard Site near El Centro, California. In the first of these, pretensioned samples of several types of well-logging cables were suspended in the geothermal fluid in a hydrothermal well to investigate the effect of the aggressive downhole environment on various cable-armoring materials. A surprising result was that, in an 11-hour test, the Inconel wire used to suspend the samples was seriously embrittled. In the second experiment, vertical seismic profiles were run in two wells using a Los Alamos triaxial geophone instrument stationed at various depths to receive signals generated at the surface by a Vibroseis unit. Data were recorded throughout a total of 64 hours of downhole operation.

The triaxial geophone system was also used to record microseismic signals generated by acid-fracturing well-stimulation experiments at Beowawe, Nevada, conducted jointly by the U.S. Department of Energy (DOE), Republic Geothermal, and Chevron Geothermal, and to monitor an attempt to initiate flow from one of the wells by injecting nitrogen gas. Los Alamos temperature logs subsequently confirmed existence of a cool zone in the upper section of the well in which the stimulation treatment was conducted.

The Milford Valley in Utah, separated by a major fault from the Roosevelt Hot Springs hydrothermal field, is a particularly promising prospect area for HDR development. Waters from shallow wells in the alluvium overlying an essentially impermeable granite basement are of the sodium-chloride type with 1300 to more than 5000 ppm total dissolved solids (TDS), and are unsuitable for domestic use, stock watering, or irrigation. However, they are abundant and appear suitable for use in an HDR heat-extraction system.

In discussions with Pan American Energy Corporation during FY83, Los Alamos provided recommendations concerning exploration strategy in northeastern Arizona for that company's proposed Navopache HDR Project, existing geologic and geophysical information from Los Alamos work and other

sources, and a listing of the types of technical assistance that Los Alamos could provide if the project were to receive support from the U.S. DOE.

There were no changes in HDR program-management structure during FY83. Progress and plans of the Program were reviewed at one meeting of the Executive Committee of the National Hot Dry Rock Program Development Council and at two meetings of the International Steering Committee (ISC).

1.0. INTRODUCTION

1.1. The HDR Concept

The overall objective of the HDR Program is to develop and demonstrate the technology required for commercial extraction of thermal energy from naturally heated crustal rock in locations where the rock does not contain enough indigenous fluid to be an economical source of natural steam or hot water. The HDR heat-extraction concept conceived and now being developed by Los Alamos National Laboratory is illustrated conceptually in Fig. 1. It is based on closed-loop circulation of pressurized water through a man-made fracture system created by hydraulically fracturing hot rock (of low initial permeability) between two wellbores. The useful heat is recovered at the surface through heat exchangers and the water is reinjected to recirculate through the underground loop.

1.2. Synopsis of the HDR Program Through FY82

This HDR concept originated at Los Alamos National Laboratory in 1970. During 1971, background information was collected on the equipment and techniques required to create such a system and on the geology, hydrology, and terrestrial heat flow in the vicinity of the Valles Caldera just west of Los Alamos, an area of geologically recent silicic volcanism that appeared well suited for HDR field experiments. In 1972, a slim exploratory hole (GT-1) was drilled in Barley Canyon on the western volcanic apron of the caldera. It reached a depth of 785 m (2576 ft), a rock temperature of 100.4°C, and penetrated 143 m (469 ft) of Precambrian crystalline basement. Experiments in GT-1 during 1973 showed that the basement rock could be fractured hydraulically at moderate pressures, that its permeability was low enough to contain pressurized water with very little loss, and that the fractures produced were essentially vertical with an approximately northwest-southeast orientation.

Fig. 1.
HDR concept.

In 1974, a second exploratory hole (GT-2) was drilled at Fenton Hill, a more accessible and convenient location about 2.5 km (1.5 mi) south of GT-1. Final depth was 2929 m (9610 ft) in a granodiorite intrusive, where the rock temperature was 197°C. Experiments in GT-2 confirmed the results of similar experiments in GT-1 but at greater depth and higher temperature.

In 1975, well EE-1 was directionally drilled in an attempt to intersect a hydraulic fracture made from near the bottom of GT-2. It reached a final depth of 3064 m (10 053 ft) and a rock temperature of 205°C, but did not intersect that fracture. However, another hydraulic fracture made from EE-1 did permit enough flow through the rock between the two fractures to make useful experiments possible.

By 1977 there had been significant improvements in equipment, instrumentation, and wellbore- and fracture-mapping techniques, and the lower part of well GT-2 was directionally redrilled in an attempt to intersect the hydraulic fracture made from EE-1. Apparently it did so, but at a point too near the upper edge of the fracture, so that flow impedance between the two wells was still very high. Therefore GT-2 was again redrilled, along a lower trajectory, and a connection with reasonably low flow impedance was achieved. With the two wellheads connected at the surface through an air-cooled heat exchanger, this became the Fenton Hill "Phase I" (or "Research") HDR system.

The Phase I system was flow-tested for 4 days in FY78 and for 75 days in FY79 as a recirculating pressurized-water heat-extraction loop. Thermal energy was extracted from the rock at rates up to 5 MW(t), and both flow impedance and rate of water loss decreased with time. In a subsequent 38-day flow test, fluid pressure was increased throughout the underground system and a further decrease in flow impedance was observed.

This "high-back-pressure test" was terminated by deterioration of the cement around the EE-1 well casing. The cement was repaired in FY79 and the major entrances into the fracture system from that well were intentionally sealed. Then a pre-existing hydraulic fracture near the bottom of EE-1 was extended by fluid pressure. It grew upward into the fracture system through which water had previously been circulated. Thus enlarged, the Phase I system was flow-tested for 23 days early in FY80 at an average rate of heat extraction of 3 MW(t), and showed no decrease in temperature of the water entering the production well. Primarily to obtain an estimate of effective heat-transfer area in the fracture system, the Phase I system was then operated

again for 288 days, and over this period the fluid produced showed a temperature drawdown of about 8°C. Presumably because of thermal contraction of the reservoir rock, the volume of the fracture system increased by about 25% during the 9-month run. Effective heat-transfer area was estimated to be at least 90 000/m² (970 000 ft²), counting both surfaces of each fracture. System operation was essentially trouble-free and had no detectable environmental effect.

A small (60 kVA) experimental binary cycle power plant was operated for short periods on a bypass flow of the geothermally heated water. It used Freon (R-114) as the second fluid and worked well, although necessarily at low efficiency because of the relatively low temperature (132°C) of the primary fluid fed to it.

The Phase I system was convincing with regard to the feasibility of creating and operating an HDR heat-extraction loop and using the heat that it produced. However, while it could have heated several hundred homes, it did not produce heat at a temperature or rate that could support a commercial electrical power plant. To more nearly approach the requirements of that higher temperature application, a larger, hotter "Phase II" system has been planned and is now being developed at the same site. Its design was of course based on experience in constructing and operating the Phase I system.

Modeling the thermal behavior of the Phase I system indicated that heat extraction occurred primarily in the part of the fracture system best represented mathematically by a circular region between the locations at which water entered and left it. In that system, water was circulated between entrance and exit locations separated vertically by about 320 m (1050 ft), and an only slightly larger separation was planned for Phase II. However, because of the limited heat-transfer area provided by a circular region of this diameter, it was evident that several parallel fractures would be required for long-term heat extraction at the proposed rate of 35 ± 15 MW(t). Therefore, since substantially planar, vertical fractures with a consistent orientation were expected, the conceptual design shown in Fig. 2 was developed. It required that the lower sections of the two wellbores be inclined at 35° to the vertical to provide sufficient horizontal separation between successive parallel fractures to effectively isolate them thermally; and, to maximize the probability of fracture-wellbore intersection, the inclined sections of the

Fig. 2.
Phase II conceptual design.

two wells were to be directed toward the northeast—approximately normal, in plan view, to the expected orientation of the fractures.

To avoid the problems anticipated in accurately mapping a series of horizontally and vertically separated fractures and then directionally drilling through a specific point on each of them, it was decided to develop the Phase II system by drilling both holes and then extending the hydraulic fractures from one wellbore to the other.

The injection well, EE-2, was completed as planned in May 1980 at a vertical depth of 4389 m (14 400 ft) where the rock temperature was 320°C. (This was about 50°C hotter than had been predicted by extrapolating temperature gradients measured in the Phase I wells, presumably because the inclined section of EE-2 was drilled toward a magmatic heat source underlying the Valles Caldera.) The production well, EE-3, was completed in August 1981 at a vertical depth of 3977 m (13 049 ft) and in its inclined section is about 370 m (1215 ft) above EE-2. Approximately 1000 m (3000 ft) at the bottom of each well were left uncased. To compensate for thermal expansion when superheated water was produced through it, the casing of well EE-3 was pretensioned to 400 000 kg (880 000 lb), about 80% of its yield strength.

Pressure testing of the two wells showed that well EE-2 was very tight at wellhead pressures up to at least 14.3 MPa (2070 psi). However, in EE-3, a limited region just below the casing shoe broke down when wellhead pressure reached 10.2 MPa (1480 psi) and thereafter accepted water readily at pumping pressures above 9.6 MPa (1390 psi), and more slowly at lower pressure. Investigations of this water-loss zone during FY83 are discussed in the body of this report.

The first two hydraulic-fracturing attempts in the Phase II system were made by pumping water through inflatable open-hole packers set about 90 m (300 ft) off bottom in EE-2. In both cases the packers failed before there was evidence that a hydraulic fracture of significant size had been produced. Therefore a steel liner 11.4 cm (4.5 in.) in outside diameter, terminating at its upper end in a polished-bore receptacle (PBR), was cemented in place with its lower end 136 m (447 ft) off bottom (Fig. 3). With a sliding seal, at the end of drill pipe or pressure tubing, inserted into the PBR, water was pumped through the liner into the open-hole section below it. In five pumping operations, four of which were terminated by equipment problems, a total of 8820 m³ (2.33×10^6 gallons) of water was injected into this region. Formation breakdown was observed at a wellhead pressure of 33 MPa (4800 psi). Mapping the source locations of acoustic signals generated by subsequent fracturing events indicated growth of a set of large hydraulic fractures, initially as planar features sloping upward toward the east at about 45°. Thereafter the microseismic events were distributed throughout an oblate volume containing those planar features and having a similar strike and dip. The fracture system appeared to pass below and beyond the bottom of well EE-3,

Fig. 3.
Wellbore modifications
for various hydraulic-
fracturing experiments.

and made no hydraulic connection to it. Because it seemed unlikely that further pumping would produce a connection, the decision was made to make the next attempt higher in the hole, where the relative positions of the open-hole sections of the two wellbores increased the probability that an inclined fracture would intersect EE-3.

In addition to this unexpected fracturing behavior, which was quite different than that observed a few thousand feet higher in the Phase I wells, hydraulic fracturing resulted in the evolution of large quantities of gas from the reservoir formation. The gas is primarily CO_2 with a small content of H_2S and, between fracturing operations, its production rate diminishes with time. However, its presence has resulted in a long series of stress-corrosion-cracking failures of downhole tubular goods, and long and expensive fishing

jobs and programmatic delays. (The problem has since at least been mitigated by, so far as possible, replacing conventional high-strength steels with more resistant chromium-molybdenum low-alloy steels.)

To isolate an open-hole section higher in the EE-2 wellbore, a sand and gel plug was emplaced in it, initially to a well depth of 3638 m (11 935 ft). This left an uncased section about 110 m (360 ft) long between the top of the sand and the bottom of the casing. A packer was then set in the casing about 73 m (240 ft) above the casing shoe, to permit injection into this section through drill pipe or pressure tubing extending to the surface.

In the first hydraulic-fracturing operation in this open-hole section of EE-2, 905 m³ (239 000 gal) of water were injected and three fracture zones were created - about 30 m (100 ft) apart along the wellbore. Pumping was terminated by a drill-pipe failure, as were two subsequent pumping operations. In one of them, an additional 42.8 m³ (11 300 gal) of water were injected. After failures of a packer and then a coupling on the frac string, the next successful fluid injection was accomplished during the first week of FY83. It and subsequent experiments in the two wells are discussed later in this annual report.

Almost from its beginning, the HDR Program has operated at or beyond the limits of existing downhole technology with regard to equipment, instruments, and experimental techniques. It has therefore been necessary to work with industrial manufacturers, service companies, other laboratories, universities, or independently, to improve such things as high-temperature drilling, drill-guidance and well-completion equipment, borehole-surveying instruments, well-logging and downhole-monitoring tools, and the equipment and techniques for a variety of tests and innovative experiments. Many of these items are now finding useful applications outside of the HDR Program. Recent progress in several of these areas is described below.

Similarly, until recently, there has been little interest in analyzing and modeling the thermal, hydraulic, and mechanical behavior of fractured geothermal systems. There has also been important progress in this area in the HDR Program.

Because hot dry rock represents an essentially inexhaustible supply of thermal energy almost everywhere, the U.S. HDR Program has attracted international interest ever since it was first publicly announced. Parallel and complementary programs have since been initiated in several other countries,

notably in the Federal Republic of Germany, Japan, Great Britain, Sweden, and France. Under an International Energy Agency (IEA) Agreement, agencies of the Governments of West Germany and Japan (KFA-Jülich and NEDO) now participate directly in the Fenton Hill Project. This involves partial financial support, membership in its ISC, and long-term assignment of scientists and engineers from both countries to the HDR staff at Los Alamos. Under a bilateral agreement between the U.S. DOE and the Italian Energy Agency (ENEL), a close relation with geothermal programs in Italy has been maintained. There is continuing informal cooperation and information exchange with individuals and organizations in other countries.

1.3. FY83 Objectives

Pursuant to the Program status at the conclusion of FY82, the specific programmatic objectives for FY83 were as follows:

- Procure special stress-corrosion-resistant work strings and related hardware for fracturing in the chemically aggressive environment of the EE-2 and EE-3 open-wellbore regions.
- Complete the preliminary fracturing between the EE-2 and EE-3 wells, forming the Interim Engineering Reservoir (IER).
- Complete procurements for, and construction of, the interim surface system that is needed to flow test the IER for a sufficient duration to obtain a measurable thermal drawdown within the reservoir and meet the other technical objectives of the test.
- Begin the sequence of detailed planning, testing of special hydraulic-fracturing hardware, rig-specification and procurement procedure, and related operations preparatory to fracturing and completion of the Final Engineering Reservoir (FER).
- Begin the detail design of, and initiate major long-lead procurements for, the final surface system needed to flow test the FER.
- Continue careful surveillance for any significant environmental impacts, particularly seismic or hydrologic, of constructing and running an HDR thermal-energy-extraction loop.
- Continue the reservoir-engineering and analysis effort needed to (a) thermally and fluid-dynamically model, design and modify the multi-fracture reservoir; (b) reduce, analyze, and document data obtained

from its testing; and (c) provide requisite support to the hardware-development and operational efforts.

- Begin development of relatively rapid and reliable reservoir size-assessment technique(s) using chemical tracers.
- Obtain initial information concerning reservoir scaling/deposition problems under Phase II conditions, including development of any necessary remedial measures, and conduct geochemical studies of the CO₂ evolution and possible sand-pack alteration in the EE-2 well.
- Continue to provide both scheduled and unscheduled calibration and maintenance for the Phase II instrumentation and data acquisition systems, including periodic replacement of high-temperature logging cables.
- Continue to upgrade/modify existing downhole instruments and equipment as necessary to meet changing in situ conditions and/or programmatic requirements.
- Initiate design and construction, and subsequently conduct laboratory testing, of new downhole equipment and instruments essential to the creation and testing of the FER.
- Continue technology exchange with industry and other interested organizations.

2.0. TECHNICAL ACTIVITIES

2.1. Fenton Hill Site Operations

Fenton Hill site operations for FY83 constituted a continuation of Phase II system development with activities directed primarily toward completion of the geothermal reservoir.

2.1.1. Workover-Rig Operations. The workover-rig contract was let in FY82. The rig was active through that year, and completion operations in EE-2 continued at the start of FY83. With the workover rig operating at EE-2, the lower portion of the hole and cemented-in liner had been filled with sand. A casing packer-PBR-tubing system was being employed to allow pumping at high pressures into an open-hole section just below the casing shoe. EE-3 was cased to 3162 m (10 375 ft).

A brief summary of major rig-related activities and experiments in FY83 is listed below.

- 10-1 to 10-9-82 Experiment 2020. Pump into EE-2 terminated by pressure leak from frac string to annulus. The experiment was delayed by a fatal accident to a Dowell employee.
- 10-10 to 10-17-82 Fished and cleared EE-2. Rig placed on standby to allow planning and hardware procurement.
- 11-21 to 11-26-82 Skidded rig to EE-3 with plans to isolate low-pressure zone at casing shoe and fracture from lower open-hole section.
- 11-27 to 12-12-82 Cemented in liner and PBR.
- 12-12 to 12-15-82 Experiment 2025. Injected 575 m³ (152 000 gal) into lower section of EE-3; pump terminated by leak to annulus.
- 12-16 to 12-20-82 Recovered frac string (drill pipe) with split section. Placed rig on standby to procure new frac string of specially tailored alloy for Phase II service.
- 5-3 to 6-21-83 Discovered obstruction in 11.4-cm (4-1/2-in.) liner just above cement; fished; tried overshot connection; fished; finally reconnected to liner with downhole screw-in connection.
- Received 11.4-cm (4-1/2-in.) L-80 tubing for EE-3 and placed order for 14-cm (5-1/2-in.) C-90 tubing for EE-2 during the first week in May.
- 6-22 to 6-23-83 Tested effectiveness of nitrogen as annulus insulation during fracturing experiment in EE-3. Screwed-in connection failed; temperature tool left in hole.
- 6-24 to 7-8-83 Fished; furloughed rig with EE-3 tubing configuration of overshot PBR and a safety joint from liner to within casing.
- 7-9 to 9-30-83 Conducted several logs and small pumping experiments in EE-2 and EE-3 while waiting for 14-cm (5-1/2-in.) Hydril tubing (for EE-2 frac string). Rig still on standby at end of fiscal year; tubing expected to be delivered in October.

With the workover contract in force and the rig over EE-3 but on furlough, EE-3 stood protected but inoperable, pending delivery of a new overshot (patch) for connecting to the 11.4-cm (4.5-in.) liner at 3320 m (10 890 ft). EE-2 was open down to the sand above the cemented-in liner. Delivery of a casing packer and the special alloy string of fracturing tubing was expected within days. Figure 3 depicts the configuration of holes for subsequent fracturing experiments.

Fenton Hill site operations continued with the Laboratory's technicians preparing and conducting experiments supported by craftsmen from Zia Co. and on a contract basis by CJC, Inc.

Zia was modifying piping at the existing heat exchangers and circulation pump installation in preparation for the Phase II energy-extraction experiment in September and October of 1982. This work was terminated as downhole workover operations continued far beyond the expected schedule. Laboratory technicians reworked most of the heat-exchanger control system and valves.

The maintenance contractor was utilized for custodial work, minor craft-type repair work, snow removal, and road and site-grading maintenance.

2.1.2. Workover Operations Review Committee. A panel of industrially experienced experts was convened in September 1983 (during a period of workover-rig furlough) to review and make recommendations for planned program operations. In particular, they were asked to review the proposed plans for

- a) liner repair (i.e., the cemented-in liner below the casing shoe) in EE-3;
- b) a hydraulic-fracturing experiment in EE-3 to create a target for a proposed massive hydraulic fracturing (MHF) experiment; and
- c) the subsequent MHF experiment in EE-2.

The EE-3 liner problem has been alluded to previously and was a current item needing a solution. Fracturing experiments to date had not achieved the flow connection (reservoir) between boreholes EE-2 and EE-3. Recommendations were sought to enhance the chance of success in the next sequence of experiments.

Committee members were

Dr. Hirohide Hayamizu, Chief
Mining Machinery and Explosives Division
Mining and Safety Department
National Research Institute for Pollution and Resources
Ministry of International Trade and Industry
JAPAN

Dr. William Livesay, President
Livesay Consultants, Inc.
Cardiff-by-the-Sea, California

- Prof. Dr.-Ing. Claus Marx
Institut für Tiefbohrkunde
Clausthal-Zellerfeld
WEST GERMANY
- Mr. Del Pyle, Manager (Committee Chairman)
Drilling Operations
Union Geothermal Division
Union Oil Corp.
Los Angeles, California
- Dr. Ralph W. Veatch, Jr., Research Supervisor
Amoco Production Co.
Tulsa, Oklahoma

In general, the Committee concurred with Los Alamos planning and recommended that

- a) liner repairs in EE-3 should be sequenced relative to fracture experiments to allow flexibility in completion after the connection is accomplished;
- b) fracturing experiments should be thoroughly instrumented (microseismic-detection recording); and
- c) the MHF in EE-2 should be designed for both high flow rate and total volume, considering mechanical, site, and personnel limitations.

The Committee also discussed directional redrilling (in the event that successful connection was not established with the EE-2 MHF) to a "known" fractured zone, as identified by the microseismic activity. Such an operation was suggested for the deeper (hotter) target regions even with a successful connection near the casing-shoe depths.

2.1.3. Environmental Surveillance. Continuous hydraulic, seismic, biotic, and meteorologic monitoring has been done at and around the Fenton Hill HDR site since 1974.¹⁻⁷ Early studies established baseline information, which may be found in previous HDR Annual Reports.

No liquid discharges into the environment occurred during FY83. Therefore, monitoring the on-site water supplies, the ground-water discharge plan, seismic developments, and vegetation and soil studies are emphasized in review of environmental activities.

2.1.3.1. Water-Quality Monitoring. The domestic water for Fenton Hill is supplied by a 137-m-deep (450-ft) well drilled in 1976 into a perched aquifer of limited size. Since its completion, this well has been monitored

for chemical content and drawdown/recharge characteristics.^{8,9} Results from this monitoring indicate that the level of the water has declined since production first started. As of December 1982, the drop was 2.7 m (8.9 ft) (Fig. 4). Data inspection indicates that an increase in the levels of a number of chemical constituents has occurred, possibly because of this water-level decline.⁹ Total dissolved solids (TDS), which increased only slightly from 1976 through 1980, went from 240 mg/l in 1980 to over 300 mg/l in 1981. Calcium showed the same general trend: a slight increase before 1980 with a jump from 34 mg/l to over 50 mg/l between 1980 and 1981 (Fig. 5). This was a result of yield from different beds within the aquifer. Since the beginning of 1983, samples of the well have been collected and analyzed on a regular basis (Table I). A decrease in heavy well production early in the year is evidenced by a slow decrease and stabilization of the calcium concentration.

Three major storage ponds exist at Fenton Hill. The 19 000-m³ (5-million-gal) storage pond contains well water (Table I) and water hauled from San Antonio Creek. The pond at GT-2 was used very little this year, and as a result, a slow "cleaning" occurred because of natural sedimentation and dilution from rain and snow melt (Table II). In October this pond was emptied and the water pumped into the third pond, at EE-1. The EE-1 pond has been the major source of water for the interim-system fracture operations. As such, it

Fig. 4.
Average monthly water levels in supply well 1981-1982.

Fig. 5.
Levels of calcium and total dissolved solids 1976-1982.

is highly mineralized and contains a number of organic additions used in the operations.

Fluctuation in the inorganic constituents (Table III) is due to the water's continued modification. This fluid is contained on the site, the pond originally being lined with heavy-gauge plastic to prevent seepage into the ground water. This lining however has since deteriorated in spots, though no evidence of contamination of ground water has been reported from the designated sampling stations (Fig. 6). The latest analyses (Tables IV and V) show no variation from previous findings outside normal seasonal fluctuations.^{1-7,9}

2.1.3.2. Federal and State Water Permit Activities. In January 1983, the New Mexico Oil Conservation Division (OCD) requested that a ground-water discharge plan be submitted for Fenton Hill. A ground-water discharge plan can be requested when the OCD believes that the potential exists that ground

TABLE I
FENTON HILL WELL SAMPLES

Analysis	3/17/83	5/26/83	6/29/83	8/1/83	9/1/83	10/3/83	Unit
As	-	-	-	-	-	-	ppm
B	0.15	0.18	0.17	0.24	0.12	0.21	ppm
Ba	0.08	0.08	0.04	0.08	0.12	0.10	ppm
Br	0.22	-	0.23	0.16	0.19	0.20	ppm
Ca	42	39	41	38.9	34.8	36.1	ppm
Cd	0.001	0.002	-	-	-	-	ppm
Ce	28	16	22.3	19.6	18.8	18.2	ppm
Cond	330	320	320	300	290	290	μmho/cm
Cr	0.002	0.002	0.001	0.003	0.003	0.002	ppm
Cu	-	0.002	-	0.005	0.021	0.017	ppm
F	0.08	0.13	0.09	0.11	0.08	0.09	ppm
Fe	-	-	-	0.27	0.04	-	ppm
HCO ₃	137	140	139	140	142	139	ppm
K	5.0	4.8	4	4	4	4.5	ppm
Li	0.03	0.08	-	-	-	-	ppm
Mg	4.8	4.2	4.6	4.2	3.7	3.9	ppm
Mn	-	-	-	-	-	-	ppm
Na	15	15	16	16	15	14	ppm
NO ₃	-	-	-	-	-	-	ppm
Pb	-	-	-	-	-	-	ppm
pH	7.69	7.86	7.53	7.68	7.74	7.88	pH
PO ₄	-	-	-	-	-	-	ppm
SiO ₂	70	65	70	72	71	71	ppm
SO ₄	10.4	7.7	9.3	8.5	9.1	18.2	ppm
Sr	0.19	0.14	0.14	0.14	0.15	0.17	ppm
Zn	0.04	0.11	0.14	0.21	0.28	0.25	ppm

water may be contaminated above certain specified levels at a point of present or potential future withdrawal for drinking water purposes. The ground-water discharge plan is a legally enforceable document that states what actions have been, or will be taken, to prevent contamination of ground water. In New Mexico, the OCD is responsible for the regulation of geothermal operations rather than the Environmental Improvement Division (EID).

A draft plan was prepared and submitted to the OCD on June 30, 1983. The draft plan relied on lined ponds and sealed shafts to prevent co-mingling of any underground fluids and fluids used as part of the HDR research operations. The general concept of the plan was reviewed with the Director of OCD and his staff before submission.

The OCD reviews the draft plan, suggests improvements, and finally indicates acceptance of the draft plan. A final plan is then submitted to the

TABLE II
GT-2 POND ANALYSIS

4/19/83 08:00			5/25/83 11:15			6/28/83 10:00			8/1/83			9/1/83 11:00			10/3/83 10:30		
Analysis	Result	Unit	Analysis	Result	Unit	Analysis	Result	Unit	Analysis	Result	Unit	Analysis	Result	Unit	Analysis	Result	Unit
As	-	ppm	As	-	ppm	Ag	-	ppm	Ag	-	ppm	Ag	-	ppm	Ag	-	ppm
B	3.50	ppm	As	0.1	ppm	Az	0.3	ppm	Az	0.3	ppm	Az	-	ppm	Az	-	ppm
Ba	0.09	ppm	B	2.13	ppm	As	-	ppm	As	-	ppm	As	-	ppm	As	-	ppm
Bact-SO ₄	NEGATIVE	-	Ba	0.07	ppm	B	2.09	ppm	B	2.09	ppm	B	1.66	ppm	B	1.30	ppm
Br	0.64	ppm	Bact-SO ₄	POSITIVE +	-	Ba	0.09	ppm	Ba	0.08	ppm	Ba	0.09	ppm	Ba	0.07	ppm
Ca	26	ppm	Br	0.34	ppm	Br	0.60	ppm	Bact-SO ₄	NEGATIVE -	-	Bact-SO ₄	POSITIVE +	-	Bact-SO ₄	POSITIVE +	-
Cd	0.002	ppm	Ca	26	ppm	Ca	31	ppm	Br	0.57	ppm	Br	0.47	ppm	Br	0.41	ppm
Ce	115	ppm	Cd	0.003	ppm	Cd	-	ppm	Ca	29.6	ppm	Ca	24.9	ppm	Ca	16.7	ppm
Co	-	ppm	Ce	81	ppm	Ce	91.4	ppm	Cd	-	ppm	Cd	-	ppm	Cd	-	ppm
CO ₃	0	ppm	Co	-	ppm	Co	-	ppm	Ce	89	ppm	Ce	72	ppm	Ce	54.9	ppm
Cond	810	umho/cm	CO ₃	0	ppm	CO ₃	13.8	ppm	Co	-	ppm	Co	-	ppm	Co	-	ppm
Cr	-	ppm	Cond	660	umho/cm	Cond	675	umho/cm	CO ₃	0	ppm	CO ₃	0.1	ppm	CO ₃	15.6	ppm
Cu	-	ppm	Cr	-	ppm	Cr	0.001	ppm	Cond	660	umho/cm	Cond	530	umho/cm	Cond	430	umho/cm
Eh	413	mV	Cu	-	ppm	Cu	-	ppm	Cr	0.001	ppm	Cr	-	ppm	Cr	0.003	ppm
F	0.76	ppm	Eh	380	mV	Eh	320	mV	Cu	-	ppm	Cu	-	ppm	Cu	0.003	ppm
Fe	0.1	ppm	F	0.62	ppm	F	0.62	ppm	Eh	375	mV	Eh	320	mV	Eh	375	mV
HCO ₃	200	ppm	Fe	-	ppm	Fe	0.10	ppm	F	0.69	ppm	F	0.55	ppm	F	0.48	ppm
K	12.9	ppm	HCO ₃	192	ppm	HCO ₃	167	ppm	Fe	0.05	ppm	Fe	0.04	ppm	Fe	0.11	ppm
Li	1.00	ppm	K	12.8	ppm	K	10	ppm	HCO ₃	198	ppm	HCO ₃	152	ppm	HCO ₃	106	ppm
Mg	3.1	ppm	Li	0.74	ppm	Li	0.79	ppm	Mg	-	ppm	Hg	-	ppm	Hg	-	ppm
Mn	0.25	ppm	Mg	3.1	ppm	Mg	3.7	ppm	K	11	ppm	K	7	ppm	K	7.9	ppm
Na	122	ppm	Mn	0.35	ppm	Mn	-	ppm	Li	0.73	ppm	Li	0.58	ppm	Li	0.45	ppm
NO ₂	-	ppm	Na	95	ppm	Na	96	ppm	Mg	3.5	ppm	Mg	2.9	ppm	Mg	2.0	ppm
NO ₃	0.2	ppm	NO ₂	-	ppm	Ni	-	ppm	Mn	0.01	ppm	Mn	0.01	ppm	Mn	0.01	ppm
Pb	-	ppm	NO ₃	-	ppm	NO ₂	-	ppm	Mo	-	ppm	Mo	-	ppm	Mo	-	ppm
pH	8.00	pH	Pb	-	ppm	NO ₃	0.23	ppm	Na	96	ppm	Na	71	ppm	Na	65	ppm
PO ₄	-	ppm	pH	7.68	pH	Pb	-	ppm	Ni	-	ppm	Ni	-	ppm	Ni	-	ppm
S	-	ppm	PO ₄	-	ppm	pH	8.63	pH	NO ₂	-	ppm	NO ₂	-	ppm	NO ₂	-	ppm
SiO ₂	30	ppm	Si	18.4	ppm	PO ₄	-	ppm	NO ₃	-	ppm	NO ₃	-	ppm	NO ₃	0.34	ppm
SO ₄	33	ppm	SiO ₂	40	ppm	Si	29.4	ppm	Pb	-	ppm	Pb	-	ppm	Pb	-	ppm
Sr	0.16	ppm	SO ₄	21	ppm	SiO ₂	46	ppm	pH	8.03	pH	pH	8.31	pH	pH	8.82	pH
Zn	0.02	ppm	Sr	0.13	ppm	SO ₄	25.0	ppm	PO ₄	-	ppm	PO ₄	-	ppm	PO ₄	-	ppm
			Zn	-	ppm	Sr	0.15	ppm	Sb	-	ppm	Rb	0.010	ppm	Rb	0.042	ppm
						Zn	-	ppm	Se	-	ppm	Sb	-	ppm	Sb	-	ppm
									Si	16.4	ppm	Se	-	ppm	Si	-	ppm
									SiO ₂	46	ppm	Si	14.0	ppm	SiO ₂	9.2	ppm
									SO ₄	24	ppm	SiO ₂	31	ppm	SO ₄	24	ppm
									Sr	0.14	ppm	SO ₄	22.2	ppm	SO ₄	20.6	ppm
									Zn	-	ppm	Sr	0.16	ppm	Sr	0.12	ppm
												U	-	ppm	Zn	0.03	ppm
												Zn	-	ppm			

TABLE III
EE-1 POND ANALYSIS

4/14/83 11:30			5/25/83 11:30			6/28/83 09:30			8/1/83			9/1/83 11:30			10/3/83 11:00		
Analysis	Result	Unit	Analysis	Result	Unit	Analysis	Result	Unit	Analysis	Result	Unit	Analysis	Result	Unit	Analysis	Result	Unit
As	2.5	ppm	As	-	ppm	Ag	-	ppm	Ag	-	ppm	Ag	-	ppm	Ag	-	ppm
B	50	ppm	As	1.1	ppm	Az	-	ppm	Az	0.2	ppm	Az	-	ppm	Az	-	ppm
Ba	0.62	ppm	B	49.7	ppm	As	1.9	ppm	As	1.62	ppm	As	1.0	ppm	As	1.1	ppm
Bact-SO ₄	POSITIVE +		Ba	0.55	ppm	B	47.3	ppm	B	45.5	ppm	B	43.8	ppm	B	35.1	ppm
Br	11.5	ppm	Bact-SO ₄	POSITIVE +		Ba	0.45	ppm	Ba	0.44	ppm	Ba	0.47	ppm	Ba	0.31	ppm
Ca	35	ppm	Br	9.3	ppm	Bact-SO ₄	POSITIVE +		Bact-SO ₄	POSITIVE +		Bact-SO ₄	POSITIVE +		Bact-SO ₄	NEGATIVE -	
Cd	0.003	ppm	Ca	33	ppm	Br	12.6	ppm	Br	11.9	ppm	Br	9.5	ppm	Br	8.1	ppm
Cz	1858	ppm	Cd	0.003	ppm	Ca	31	ppm	Ca	31.2	ppm	Ca	28.5	ppm	Ca	27.0	ppm
Co	-	ppm	Cz	1639	ppm	Cd	-	ppm	Cd	-	ppm	Cd	-	ppm	Cd	-	ppm
CO ₂	0	ppm	Co	-	ppm	Cz	1720	ppm	Cz	906	ppm	Cz	1402	ppm	Cz	1370	ppm
CoHd	8400	umho/cm	CO ₂	0	ppm	Co	-	ppm	Co	-	ppm	Co	-	ppm	Co	0.001	ppm
Cr	0.005	ppm	CoHd	8200	umho/cm	CO ₂	0	ppm	CO ₂	85	ppm	CO ₂	78	ppm	CO ₂	33.6	ppm
Cu	-	ppm	Cr	-	ppm	CoHd	7800	umho/cm	CoHd	7400	umho/cm	CoHd	6700	umho/cm	CoHd	6000	umho/cm
Eh	431	mV	Cu	-	ppm	Cr	0.001	ppm	Cr	0.004	ppm	Cr	0.003	ppm	Cr	0.006	ppm
F	6.9	ppm	Eh	25	mV	Cu	-	ppm	Cu	-	ppm	Cu	-	ppm	Cu	-	ppm
Fe	1.3	ppm	F	6.1	ppm	Eh	298	mV	Eh	307	mV	Eh	285	mV	Eh	260	mV
HCO ₃	1623	ppm	Fe	0.2	ppm	F	6.46	ppm	F	7.13	ppm	F	5.49	ppm	F	5.11	ppm
K	165	ppm	HCO ₃	1621	ppm	Fe	0.14	ppm	Fe	0.31	ppm	Fe	0.05	ppm	Fe	1.02	ppm
Li	19.5	ppm	K	151	ppm	HCO ₃	1620	ppm	HCO ₃	1464	ppm	HCO ₃	1296	ppm	HCO ₃	1172	ppm
Mg	2.2	ppm	Li	23.0	ppm	K	126	ppm	Hg	-	ppm	Hg	-	ppm	Hg	-	ppm
Mn	0.20	ppm	Mg	2.7	ppm	Li	19.5	ppm	K	132	ppm	K	124	ppm	K	108	ppm
Na	1480	ppm	Mn	0.18	ppm	Mg	3.5	ppm	Li	18.5	ppm	Li	16.6	ppm	Li	14.0	ppm
NO ₂	-	ppm	Na	1580	ppm	Mn	0.10	ppm	Mg	3.6	ppm	Mg	3.0	ppm	Mg	2.8	ppm
NO ₃	-	ppm	NO ₂	-	ppm	Na	1610	ppm	Mn	0.05	ppm	Mn	0.01	ppm	Mn	0.07	ppm
Pb	-	ppm	NO ₃	-	ppm	Ni	-	ppm	Mo	0.08	ppm	Mo	0.10	ppm	Mo	-	ppm
pH	7.77	pH	Pb ₃	-	ppm	NO ₂	-	ppm	Na	1560	ppm	Na	1370	ppm	Na	1180	ppm
PO ₄	-	ppm	pH	8.16	pH	NO ₃	-	ppm	Ni	-	ppm	Ni	-	ppm	Ni	-	ppm
S	0.42	ppm	PO ₄	-	ppm	O ₂ Dis	0.13	ppm	NO ₂	-	ppm	NO ₂	-	ppm	NO ₂	-	ppm
SiO ₂	110	ppm	Si ₄	46.2	ppm	Pb	-	ppm	NO ₃	-	ppm	NO ₃	-	ppm	NO ₃	-	ppm
SO ₄	180	ppm	SiO ₂	100	ppm	pH	8.14	pH	Pb ₃	-	ppm	O ₂ Dis	1.80	ppm	Pb ₃	-	ppm
Sr ⁴	0.85	ppm	SO ₄	128	ppm	PO ₄	-	ppm	pH	8.57	ppm	Pb	-	ppm	pH	8.48	ppm
Zn	0.04	ppm	Sr ⁴	0.83	ppm	Si ⁴	55.0	ppm	PO ₄	1.9	ppm	pH	8.65	pH	PO ₄	1.0	ppm
			Zn	-	ppm	SiO ₂	114	ppm	Sb	-	ppm	PO ₄	3.4	ppm	Rb ₄	1.24	ppm
						SO ₄	145	ppm	Se	-	ppm	Rb	1.28	ppm	Sb	-	ppm
						Sr ⁴	0.72	ppm	Si	47.3	ppm	Sb	-	ppm	Se	-	ppm
						Zn	-	ppm	SiO ₂	113	ppm	Se	-	ppm	Si	47	ppm
									SO ₄	134	ppm	Si	47.2	ppm	SiO ₂	102	ppm
									Sr ⁴	0.66	ppm	SiO ₂	106	ppm	SO ₄	112	ppm
									Zn	-	ppm	SO ₄	125	ppm	Sr ⁴	0.56	ppm
												Sr ⁴	0.73	ppm	Zn	0.6	ppm
												U	-	ppm			
												Zn	0.02	ppm

Fig. 6.
Locations of sampling stations.

OCD, who issues a public notice of pending approval. If sufficient public comment is received, a public hearing may be held.

To date the OCD has not formally responded to the June 30, 1983, submittal. The OCD continues its initial review process, which may last for a year or more, based on other case histories.

During the OCD review process, the Laboratory will implement milestones listed in the plan as they come due.

2.1.3.3. Seismic Activity. Two classes of seismic activity are observed near Fenton Hill: natural and induced. The natural seismicity in the area is mostly confined to a band beneath the Nacimiento Mountains to the west of Fenton Hill. This activity is fairly extensive in a north-south direction from near Dulce, New Mexico, to south of Jemez Springs, at which point the zone turns to the southwest toward Grants. The Fenton Hill HDR site lies along the eastern edge of this relatively active zone. Therefore, any earthquakes occurring at or near the HDR site are not necessarily the result of geothermal experiments.

TABLE IV
GROUND WATER QUALITY, 1982
(mg/l)

Station	Location	Date 1982	SiO ₂	Ca	Mg	K	Na	CO ₃	HCO ₃	SO ₄	Cl	F	NO ₃	TDS	Total Hard	As	B	Cd	Li	Spec Cond (μmho)	pH	Temp °C
JS 2,3	Jemez Village (Spr)	6-28	66	20	4	3	18	0	84	9	5	0.6	1.9	194	66	0.012	0.1	0.003	0.02	180	7.0	21
JS 4,5	Jemez Village (Spr)	6-28	69	21	3	4	17	0	84	8	5	0.3	2.1	194	66	0.013	0.1	<0.001	0.02	190	7.0	21
FH 1	Fenton Hill (Well)	6-28	66	52	5	3	16	0	120	12	40	0.3	1.1	326	152	0.020	0.5	0.002	0.03	360	7.2	22
JF 1	Jemez Canyon (Hot Spr)	6-28	40	90	16	48	345	0	360	33	540	1.9	1.2	1568	292	0.016	4.5	<0.001	3.5	2540	6.9	20
JF 5	Jemez Canyon (Hot Spr)	6-28	37	324	29	200	855	0	736	49	1450	4.1	1.0	3964	930	2.57	6.6	0.007	10.8	6140	6.2	46
RV 2	San Antonio (Hot Spr)	6-28	70	5	1	2	25	0	48	7	4	0.9	2.6	130	16	0.006	0.1	<0.001	0.03	125	7.4	41
RV 4	Spence (Hot Spr)	6-29	60	7	2	<1	53	0	112	22	8	0.9	5.7	218	28	0.064	0.3	0.003	0.56	270	7.4	42
RV 5	McCauley (Hot Spr)	6-29	43	10	6	<1	19	0	72	7	4	1.0	1.4	142	48	0.025	0.2	0.001	0.24	165	7.5	33
Loc. 2	Redondo Campground (Well)	6-28	56	50	11	3	14	0	148	18	25	0.5	0.6	252	170	0.010	0.1	0.003	0.03	400	7.3	14
Loc. 3	San Antonio Campground (Well)	6-28	51	34	4	7	48	0	160	21	8	0.6	0.8	260	100	0.004	0.3	0.003	0.04	395	6.5	18
Loc. 4	La Cueva (Well)	6-28	70	13	2	<1	33	0	72	6	4	0.3	1.3	154	42	0.002	0.1	0.003	0.02	160	7.0	25
Loc. 6	La Cueva (Spr)	6-28	62	16	4	2	28	0	84	6	4	0.6	1.6	168	58	0.027	0.1	0.002	0.02	205	6.7	22
Loc. 31	Lake Fork (Spr)	6-28	42	16	3	2	16	0	64	4	4	1.5	1.3	154	52	0.022	0.1	0.010	0.02	160	6.9	10
Loc. 39	Lake Fork (Tank)	6-28	18	13	3	2	6	0	40	15	2	0.3	1.1	66	46	0.009	0.2	0.002	0.01	95	6.1	6
Loc. 42	La Cueva (Well)	6-28	68	13	7	1	18	0	76	5	4	0.4	<0.2	182	60	0.004	0.1	<0.001	0.01	170	6.2	20
Loc. 47	La Cueva (Well)	6-28	22	7	3	4	200	0	520	26	4	3.5	0.5	628	32	0.008	0.4	0.025	0.12	1070	8.0	20
Loc. 48	La Cueva (Well)	6-28	55	23	5	2	21	0	88	16	8	0.9	1.4	174	78	0.002	0.1	0.014	0.03	230	6.5	19
Loc. 53	Sulphur (Well)	6-28	62	46	6	3	25	0	156	12	4	0.6	2.4	272	110	0.010	0.1	0.003	0.03	340	6.6	20
Loc. 54	Sulphur (Well)	6-28	59	55	7	3	48	0	228	21	5	0.5	3.2	322	166	0.010	<0.1	0.003	0.05	490	6.6	15

TABLE V
SURFACE WATER QUALITY, 1982
(mg/l)

Station	Location	Date 1982	SiO ₂	Ca	Mg	K	Na	CO ₃	HCO ₃	SO ₄	Cl	F	NO ₃	TDS	Total Hard	As	B	Cd	Li	Spec Cond (μmho)	pH	Temp °C
F	Sulphur Creek	6-25	26	16	3	3	11	0	28	31	14	0.3	0.5	106	52	0.001	0.1	0.002	0.04	160	7.1	16
J	Jemez River	6-25	47	14	3	3	16	0	68	8	6	0.9	0.7	140	48	0.018	0.2	0.002	0.06	150	7.9	20
N	San Antonio Creek	6-15	51	18	3	2	21	0	72	10	3	0.9	0.6	130	56	0.002	0.2	<0.001	0.03	170	8.3	--
Q	Rio Guadalupe	6-28	26	50	6	4	14	0	156	9	4	0.8	0.7	216	152	0.010	0.1	<0.001	0.03	315	7.6	20
R	Jemez River	6-28	42	45	6	13	88	0	172	15	110	1.4	0.7	464	138	0.015	1.1	0.002	0.89	730	7.9	27
S	Jemez River	6-28	47	44	6	14	97	0	180	17	135	1.7	0.9	514	136	0.098	1.3	0.001	1.1	810	8.0	25
T	Rio Cebolla	6-28	39	18	3	2	13	0	68	5	2	0.8	1.1	138	58	0.010	0.1	0.002	0.01	145	7.0	20
U	Redondo Creek	6-28	18	14	2	1	11	0	32	8	13	0.3	0.7	86	44	0.002	0.1	<0.001	0.05	120	7.7	15
V	Sulphur Creek	6-28	42	59	10	8	22	0	0	280	3	0.6	0.9	430	190	0.004	0.1	<0.001	0.05	620	3.6	13
LF-2	Lake Fork (7285)	6-28	13	20	3	2	26	0	84	3	6	1.8	0.5	200	62	0.016	0.3	0.001	0.02	195	6.7	24
LF-3	Lake Fork (8500)	6-28	46	14	3	2	14	0	60	5	4	1.5	1.5	130	50	0.012	0.3	0.003	0.01	135	6.6	10
LF-4	Lake Fork (9420)	6-28	46	17	3	2	17	0	72	5	7	1.4	0.8	146	54	0.008	0.3	0.001	0.01	155	7.1	10
GTP-1	Pond Fenton Hill	6-28	130	25	6	216	1395	0	2200	112	1188	4.7	2.2	5430	88	6.56	40.0	0.003	9.6	7300	8.2	36
GTP-2	Pond Fenton Hill	6-28	144	47	13	92	495	0	600	89	520	3.9	0.3	2238	172	3.13	13.0	0.003	4.0	2800	7.7	20

Induced microquakes occur as a result of the introduction of fluids under pressure into the granitic rock of the geothermal reservoir. To date, no microquake has been induced of magnitude one or greater. Although several hundred events have been observed, all have been well below the threshold of normal perception, producing amplitudes of ground motion more than three orders of magnitude below the level at which minor damage could be expected.

2.1.3.4. Biotic Monitoring. Results from vegetation and soil analysis from the canyon below the GT-2 pond indicate accumulation of some elements in the soil or vegetation. Only boron and lithium have reached potentially toxic levels in the vegetation.⁹ Samples were collected at 100, 200, 400 and 1000 m below the GT-2 pond discharge point. An additional sample was collected at the junction of this canyon with Lake Fork Canyon. The more recent analyses are in Table VI. (For more background, see Ref. 9). The vegetation (grass and aspen) looks healthy, although there are traces of oily discharge from the pond.

The storage ponds and the domestic well were also checked for the presence of sulfate-reducing bacteria that have caused drilling and safety problems in the past. This anaerobe, which produces H_2S , exists in the GT-2 and EE-1 ponds. The EE-1 pond has the highest population because of the presence of organic substrates and sulfate. Aeration during the summer months kept the bacteria in the EE-1 pond restricted to the lower sediment layers. This aeration could also have encouraged aerobic bacteria growth, possibly breaking down the organics in the pond. The elevation of pH that accompanied the aeration, however, inhibited such growth.

2.1.3.5. Vent Gases. Gas or air samples were collected from various site locations when there was concern about the gases present (Table VII). Occasionally, high concentrations of H_2S were found at the source, but the gas dispersed quickly. H_2S detectors have been installed with an alarm system. In March and April, NO and NO_2 gases were released from EE-3, the result of an additives decomposition. Gas released from GT-2 and EE-1 ponds was not evident.

2.1.4. Water Supply. A contract with CJC, Inc., a local general contractor, was extended for another year to provide auxiliary water to the Fenton Hill site. The additional water hauled to the site totaled 11 880 m³ (3 138 600 gal) in FY83.

TABLE VI
VEGETATION AND SOIL
(ppm)

Location	ARSENIC	CADMIUM		BORON			FLUORIDE		LITHIUM
	Fall 1981	Fall 1981	Spring 1982	Fall 1981	Spring 1982	Fall 1982	Fall 1981	Spring 1982	Fall 1981
Roots (bank)									
100 m	3.75	180	--	42	7	29	45	7.5	23.4
200 m	2.18	100	--	29	12	37	28	12.0	19.1
400 m	2.87	170	--	28	17	30	59	2.5	19.9
1000 m	5.72	--	--	35	10	34	46	10.1	3.7
Roots (channel)									
100 m	13.3	200	--	73	63	114	92	10.9	43.0
200 m	5.69	530	--	140	102	139	96	15.4	15.8
400 m	6.47	260	--	61	45	130	70	15.0	6.0
1000 m	1.93	330	--	36	7	30	52	7.1	4.5
Lower Canyon	1.06	320	--	21	11	32	34	28.9	3.6
Foliage (bank)									
100 m	0.11	--	--	15	19	11	6.7	2.1	1.22
200 m	0.08	--	--	14	18	13	1.8	1.6	0.86
400 m	0.35	--	--	20	17	32	6.0	1.9	2.10
1000 m	<0.06	--	--	12	10	9	3.8	2.0	0.75
Foliage (channel)									
100 m	<0.11	--	--	210	670	188	19.0	2.1	51.7
200 m	0.09	--	--	110	700	434	2.7	2.1	32.0
400 m	0.45	--	--	130	108	110	11.0	2.6	19.2
1000 m	0.24	--	--	13	33	12	6.0	1.2	--
Lower Canyon	0.30	--	--	15	10	13	5.2	1.1	4.3
Soil (bank)									
100 m	2.8	130	120	16	14	14	90	80	29.7
200 m	3.3	170	170	16	16	23	150	130	30.3
400 m	4.2	110	160	15	19	17	130	200	29.3
1000 m	3.6	160	110	15	21	31	140	220	25.9
Soil (channel)									
100 m	4.9	160	280	38	38	49	350	240	44.5
200 m	3.7	170	180	51	42	104	250	200	35.3
400 m	3.8	150	110	17	18	54	170	150	31.6
1000 m	2.5	130	110	15	21	18	160	190	30.6
Lower Canyon	3.4	140	150	19	18	15	180	200	39.7

TABLE VII
GAS ANALYSES

<u>Location</u>	<u>Collected</u>	<u>Analysis</u>	<u>Result</u>	<u>Unit</u>
EE-3 Vent Sample Gas Only	2/10/83 14:30	H ₂ S	-	ppm
EE-3 Vent Sample Gas Only	2/18/83 09:15	H ₂ S	-	ppm
EE-3 Vent Sample Gas Only	2/25/83 14:00	H ₂ S	-	ppm
EE-3 Vent Sample Gas Only	3/14/83 14:00	H ₂ S	-	ppm
EE-3 Vent Frontside Gas Only	3/14/83 14:00	H ₂ S	18	ppm
EE-3 Vent Backside-Inner Gas Only	3/22/83	H ₂ S	-	ppm
EE-3 Vent Backside-Outer Gas Only	3/22/83	H ₂ S	-	ppm
EE-3 Vent Frontside Gas Only	3/22/83	H ₂ S	18	ppm
EE-3 Backside Before 3 Hr Venting	3/24/83 11:00	H ₂ S	-	ppm
		NOX	200	ppm
EE-3 Backside After 3 Hr Venting	3/24/83 14:00	H ₂ S	-	ppm
EE-3 Frontside Vent	4/11/83 13:30	H ₂ S	240	ppm
EE-3 Vent Frontside Gas Only	4/18/83 15:30	H ₂ S	20	ppm
EE-3 Vent Frontside Gas Only	4/20/83 14:00	H ₂ S	18	ppm
EE-3 Vent Backside Gas Only	4/22/83 15:00	H ₂ S	-	ppm
		NOX	2	ppm
EE-3 Vent Frontside Gas Only	4/26/83 10:00	H ₂ S	24	ppm
EE-2 Wellbore	10/03/83 13:20	C ₂ H ₆	0.02	%
		CH ₄	0.04	%
		CO ₂	95	%
		H ₂	-	%
		H ₂ S	200	ppm
		N ₂	2.57	%
		O ₂	1.51	%
EE-2 Wellbore	10/06/83 14:30	C ₂ H ₆	0.03	%
		CH ₄	0.06	%
		CO ₂	97	%
		H ₂	-	%
		H ₂ S	180	ppm
		N ₂	2.34	%
		O ₂	0.31	%
EE-2 Vent Line Exit	10/11/83 14:00	C ₂ H ₆	0.01	%
		CH ₄	0.06	%
		CO ₂	61	%
		H ₂	-	%
		H ₂ S	125	ppm
		N ₂	30.2	%
		O ₂	7.8	%

The 6.3- ℓ /sec (100-gpm) water-supply well continued to be a dependable source of water for both the Laboratory site and the adjacent Forest Service camp.

The large, approximately 19 000 m³ (5-million-gal), water-storage pond, completed in FY82, was used to store the hauled water plus the experimental allocation from the water-supply well. Water storage was accumulated during FY83 in preparation for the MHF in early FY84.

This large pond liner, of reinforced (polyester and nylon) rubber, developed a leak that varied up to 0.174 ℓ /sec (2.75 gpm) as the volume of storage increased. The water was collected in the drain system in the sand bed under the pond and continually monitored. Water leaked from this pond in FY83 totaled 4833 m³ (1 276 800 gal). Repair or correction of this leak is planned in the summer of 1984 when the pond should be emptied by experimental use.

2.2. Downhole Tools and Instrumentation

2.2.1. Slimline Detonator. A new slimline detonator tool was designed to run in the 4.5-in. (11.4-cm) tubing installed in the EE-3 borehole. The high-temperature downhole detonator sonde is used to provide acoustic signals from a known fixed location deep in the EE-3 wellbore. The acoustic signals generated by the firing of the detonators are used to calibrate the high-temperature triaxial geophone packages deployed in adjacent wells. The downhole sonde is modular in design and currently is used to fire two detonators (Fig. 7). Each detonator contains 2.66 g (two pellets) of hexanitrostilbene (HNS) explosive. The detonator is a modified version of the Reynolds Industries RP-84 slapper initiator used in other Los Alamos National Laboratory high-temperature explosive devices.¹⁰ The detonator is initiated by a downhole capacitive-discharge firing unit, which is controlled through the armored instrumentation cable from the surface control unit.¹¹

The detonator tool incorporates a collar locator used to locate the casing shoe in order to correct cable-depth measurements for better depth control. The detonator tool also incorporates a high-temperature geophone (Mark Products L-15TW-HT30HZ) to obtain a time-zero firing signal. This firing circuit and detonator system has operated successfully in wellbores where the temperature exceeded 270°C.

2.2.2. Slimline Acoustic Detector (Geophone) Tool. A slimline acoustic detection system (geophone tool) was designed to run in the 4.5-in. (11.4-cm)

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Fig. 7.
Slimline detonator.

tubing in the EE-3 wellbore. This downhole tool was designed to operate in the high-temperature and high-pressure borehole environment without the use of dewars or heat sinks normally used for thermal protection of electronics and instruments. All components used in the design and fabrication of this slimline tool are high-temperature devices. The acoustic detectors (geophones) are Mark Products 30-Hz phones (the same as those used in the detonator tool) and are virtually insensitive to tilt for angles up to 60° from the vertical axis. The geophones are arranged in a triaxial orthogonal array clamped in a nonmetallic (Vespel I) cradle (Fig. 8).

Line-driving amplifiers are manufactured by Harris Semiconductor Corporation (Model No. HA-2600-1). They are configured with differential inputs and rated at 260°C. The amplifiers and associated passive components

Fig. 8.
Slimline geophone.

are mounted on a high-temperature printed circuit board made of Polyemit G.I.N. Spec 13949F, which is manufactured by Howe Industries. The fabricated printed circuit boards were tested at 300°C and exhibited no material degradation. Power to the amplifiers is supplied from the surface to downhole, high-temperature, voltage regulators made by White Technology. Figure 9 shows a schematic of the downhole electronics.

The geophone package is deployed in the wellbore on a seven-conductor TFE Teflon-insulated wireline. Signal inputs, power common, and signal common

Fig. 9.
Schematic high-temperature geophone system.

must be carefully isolated to minimize crosstalk and improve signal-to-noise ratio.

2.2.3. Crosswell Acoustic Transceiver. A new high-temperature acoustic transceiver has been designed, and a prototype system (without full thermal protection) was successfully tested at shallow depths in the boreholes at Fenton Hill. Figure 10 illustrates the essential downhole components of the transmitter and separate receiver modules. The transmitter utilizes a magnetostrictive transducer that yields a 2-J, 10-kHz, acoustic source. A piezoceramic-crystal transducer comprises the receiver. To maximize signal strength, transmitted and received, acoustic coupling is enhanced by filling the transducer cavity with oil. A thin metal window separates oil and borehole fluids and offers good acoustic transmissibility. Upper and lower centralizers made of Nitronic 40 center the tool within the borehole. The new design incorporates features that significantly increase tool reliability in the very high temperature geothermal environments. A simple assembly procedure to improve field reliability was foremost in the design criteria. A major additional improvement in the tool design is a "floating" TFE Teflon acoustic window. Problems encountered when using Teflon acoustic

Fig. 10.
Acoustic transceiver.

windows for high-temperature environments included mechanical distortion, sealing against the high-pressure fluids, and special premachine heat-soak cycling of the material. The new, proven, floating-window design will allow thermal expansion of the TFE Teflon without stressing the elastomeric material and will eliminate the heat-soak cycles. The high-pressure sealing capability is not affected by temperature or displacement. Another significant improvement incorporates the use of free-rotating acoustically isolated centralizers.

2.2.4. Component Development. Several advancements in high-temperature component development were achieved in FY83. Tests of dewar flasks supplied from three manufacturers were conducted and results evaluated to determine best usage for our downhole instrumentation systems. National K Works (NKW), Inc. and PDA Engineering are relatively new companies that specialize in dewars used primarily for logging tools in geothermal environments. The NKW and PDA dewars that were tested at Los Alamos proved to be superior for downhole thermal protection compared to the dewars now in common use. Several very desirable features can be incorporated into these custom-made dewars during the manufacturing process that enhance downhole tool lifetime. Such features as multiple-layer radiation shields, custom-fit heat sinks and heat pipes, and cable routing through protected end pieces can be built into the dewar design. A hybrid dewar is also available that uses, as the pressure housing, an outer wall made of nonmagnetic stainless steel with yield strengths of over 138 MPa (20 000 psi) at 315°C.

A series of pressure-temperature tests was performed on several types of O-rings designed for use in downhole instrument packages. The tests were initiated by the development of a new O-ring material under contract to Brookhaven National Laboratory and were run for comparison with the L'Garde EPDM-Y267 compound. Included in the series of tests were O-rings purchased from Parker Seal Company to whom the L'Garde technology was transferred as part of the technology transfer program. The testing program included temperature and pressure cycling of the O-rings set in a cablehead test fixture to determine the operating characteristics at 300°C and 69 MPa (10 000 psi). Test results led to the conclusion that the L'Garde Y267 and Parker E-692-75 (based on the L'Garde formula) were well within test specifications, but the new material did not meet the performance criteria.

A significant improvement in electrical connectors for downhole instrument packages was made by Reynolds Corporation under contract to the Laboratory. The new connectors are configured like the standard Amphenol but use a ceramic insert. The ceramic insert is unique in that it is made from a molded material that is machinable during the curing process. This insert will accept the crimped pins that are readily inserted and removed from the ceramic feedthroughs. This feature allows the connector to be reused many times. The connectors have been tested at 350°C with no observable degradation. Each 10-pin connector pair (mating connectors) presently costs \$350 in small quantities.

Extensive frequency-response tests were conducted on the new seven-conductor TFE Teflon insulated armored cable. Tests conducted over 6100 m (20 000 ft) of the cable show a corner-frequency response of greater than 10 kHz, which is a factor of 10 better than either the standard Tefzel or the PFA Teflon-insulated logging cables. The data also show that the response is down only 20 dB at 100 kHz. Frequency-response enhancement may be achieved by careful selection of particular conductors for signal lines, coupled with proper cable-termination impedance.

2.3 Reservoir Engineering

2.3.1. Geochemistry. Preliminary modeling of the Phase I system fluid geochemistry indicated that roughly 5% of the fluid produced at GT-2 was actually "pore fluid," which was initially present in the fractured reservoir rock.^{12,13} The pore-fluid-displacement model incorporated two parallel flow paths: the first consisted of a main-fracture flow path, which was characterized by the tracer studies and by the heat-extraction performance of the system, and the second consisted of the connected microfractures, which surrounded the main-fracture flow path. Modeling of the behavior of the silica in the production fluid was accomplished this fiscal year.

Modeling of the silica concentration accounted for the rate of dissolution of quartz in the main-fracture flow path. The rate of dissolution is given by Eq. (1).

$$\frac{dC}{dt} = k a^* (C^{sat} - C), \quad (1)$$

where C is the local silica concentration, C^{sat} is the local saturation concentration, k is the reaction rate constant and a^* is the ratio of the total

quartz surface area to the total fluid volume. Both C^{sat} and k are exponential functions of temperature.

$$k = A \exp (-E_{act}/RT). \quad (2)$$

$$C^{sat} = \beta \exp (-\Delta H_{diss}/RT). \quad (3)$$

Equation 2 is an Arrhenius expression where A is the pre-exponential factor, ($\sim 3-6m/s$) E_{act} is the activation energy (~ 80 KJ/mole), and R is the gas constant. Equation 3 is the integrated form of the condition of phase equilibrium between quartz and water where ΔH_{diss} is the enthalpy change of dissolution, and β is a constant which is related to the saturation concentration at some reference temperature. Experimental observations of quartz-water equilibrium give values of $\log (-\Delta H/R) = 1309$ Kelvin and $\log \beta = -5.19$.

Because k and C^{sat} vary with temperature, which varies with position in the reservoir, a heat-transfer model is used to calculate the temperature distribution in the reservoir at each time. The silica concentration in the reservoir at a particular time is described by the convective diffusion equation with a reaction term.

$$u \frac{\partial C}{\partial x} - D \frac{\partial^2 C}{\partial x^2} = k a^* (C^{sat} - C), \quad (4)$$

where u is the fluid velocity, D is a dispersion coefficient, and x is the distance along the fracture. In dimensionless coordinates, Eq. (4) is written as:

$$\frac{\partial C}{\partial \zeta} - \frac{1}{Pe} \frac{\partial^2 C}{\partial \zeta^2} = k \tau a^* (C^{sat} - C), \quad (5)$$

where ζ is the dimensionless distance along the fracture. Pe is the Peclet number (which indicates the degree of dispersion of the fluid), and τ is the mean residence time. Pe and τ are known from tracer experiments.

After the temperatures are calculated, the local values of k and C^{sat} can be calculated, and Eq. (5) (in finite difference form) can then be solved for C . After correcting for the silica concentration in the pore fluid (estimated as the quartz saturation concentration at the initial reservoir temperature),

we arrive at the calculated silica concentration in the production fluid. A comparison of the calculated and the experimentally observed silica concentrations for Run Segment 5 is given in Fig. 11. For this calculation, the initial rock temperature was assumed constant at 200°C (higher than the actual reservoir temperature), the flow rate was assumed constant at 6.3 l/s (100 gpm), and the inlet silica concentration was taken to be 212 ppm (average for the experiment). The calculated outlet silica concentration was only 215 ppm compared to the actual outlet concentration of 230 ppm. Furthermore, the silica concentration did not change significantly with heat extraction -- suggesting that the residence time of the fluid in the reservoir is not sufficient at these temperatures for the reaction to approach equilibrium. (Note: the decline in produced silica concentration during the final 100 days of the experiment is due to a lower injection concentration of silica rather than to a decline in the quartz dissolution rate in the reservoir.)

A simple mass balance calculation shows that if the silica concentration exiting the main-fracture flow path is 215 ppm (compared to an input concentration of 212 ppm), then at least 30% of the produced fluid must be saturated with respect to quartz at 200°C rather than the 5% that is estimated from pore-fluid displacement. There are two important conclusions from this result:

Fig. 11.

Comparison of model with field data for quartz dissolution using kinetic rate parameters for pure quartz.

1. At least 30% of the production fluid comes to thermal equilibrium at the initial rock temperature ($\sim 200^{\circ}\text{C}$) and with sufficiently long residence time to also saturate with silica (with respect to quartz) at 200°C (approximately 5 days).
2. At least some breakthrough of fluid has occurred in the secondary flow paths.

These conclusions suggest that the Phase I system was significantly larger than previous estimates based on heat-transfer modeling and residence-time distributions alone.

2.3.2. Summary of Fracturing Experiments. Five major fracturing experiments (2020, 2023, 2025, 2028, and 2033) were conducted in the Phase II wells during FY83. The key parameters of the experiments are listed in Table VIII. The corresponding wellbore configurations are shown schematically in Fig. 12.

Another attempt to connect the fracture from just below the casing shoe of EE-2 to EE-3, Experiment 2020, was conducted on October 6 and 7, 1982. Two successful detonator shots were fired before pumping was started for geophone calibration. Pressurization began at 4:22 p.m., and pumping continued through the night at a rate of approximately 90 ℓ/s (34 bpm) at a pressure of 46 MPa (6700 psi). Pumping was terminated at 7:15 a.m. on October 7 after 3190 m^3 (844 000 gal) had been injected, when an annulus leak of 1.3 ℓ/s (1/2 bpm) occurred. The seismic data indicated many events close to the EE-3 wellbore, but no fracture connection was achieved. Figures 13 and 14 show the pressure and flow-rate history in the wellbore and annulus, respectively. A recent summary of the microseismic locations is reported in Ref. 14.

Seismic data obtained in Experiment 2020 indicated that very large volumes of injected water would be required to achieve fracture communication between EE-2 and EE-3. To reduce this water volume, a series of fracture stimulations was planned at EE-3. The first experiment, 2023, was carried out to investigate the nature of a water-loss zone near the casing shoe in EE-3, and to determine the difficulties associated with pumping heated water into EE-3. After a lost-circulation-material treatment at the leak-off zone was finished, we started Experiment 2024 using a modified Lynes packer, which failed soon after the pumping was started. Then a cemented liner and PBR assembly were set, and Experiment 2025 was conducted.

TABLE VIII
SUMMARY OF FY83 HYDRAULIC-FRACTURING/PUMPING EXPERIMENTS

Experiment No.	Well	Date	Zone Isolation Method	Vertical Depth (km)	Pressure (MPa)	Rate (ℓ/s)	Injected Volume (m^3)
2020	EE-2	10-6-82	Otis packer (9-5/8-in. casing) and sand plug	3.46 - 3.59	48.3	90	3190
2023	EE-3	11-8-82	Open hole	3.09 - 3.98	13.8	17.2	148
2025	EE-3	12-14-82	Cemented liner/PBR and sand plug	3.35 - 3.44	45.5	66	579
2028	EE-3	6-22-83	Cemented liner/PBR and sand plug	3.35 - 3.44	41.4	21.2	152
2033	EE-3	9-27-83	Open hole above cemented liner/PBR	3.09 - 3.26	17.8	25.2	713

Expt. 2020

Expt. 2023

Expt. 2025
2028

Expt. 2033

Fig. 12.

Wellbore configurations for the five major fracturing experiments conducted during FY83.

Experiment 2023 was conducted on November 8, 1982. Full open-hole pumping of EE-3 was started at 7:40 p.m. with the flow rate of 1.3 ℓ/s (0.5 bpm), which was gradually increased to 17 ℓ/s (6.5 bpm) (Fig. 15). At the constant flow rate of $\sim 17 \ell/s$, the wellbore pressure slowly decreased and then was almost constant at 12.6 MPa (1820 psi). Finally the pressure increased to 13.8 MPa (2000 psi). When the injected-water volume reached about 148 m^3 (39 000 gal), the experiment was terminated and EE-3 was shut-in. Further details can be found in Ref. 15.

Experiment 2025 was conducted on December 13 and 14, 1982. First pumping attempts between the cemented liner and the sand plug began at 2:00 p.m., December 13. When the borehole pressure of EE-3 reached ~ 18 MPa (~ 2600 psi), the backside pressure started to rise. After remedial attempts failed, the pumping was stopped.

Fig. 13.
Wellhead pressure and injection rate, Experiment 2020 in EE-2.

The second fracturing attempt began at 11:24 a.m., December 14. The flow of hot water was gradually stepped up from 5.3 to 53 ℓ/s (2 to 20 bpm), and the wellhead pressure attained 45.5 MPa (6600 psi) (Fig. 16). During the early stage of pumping there was no clear breakdown, but a slight pressure plateau at 32.4 MPa (4700 psi) was observed. At 2:54 p.m., when approximately 579 m^3 (153 000 gal) of hot water had been injected, the borehole and annulus pressure equalized, indicating frac-string failure. Then pumping was terminated and venting was started. Further details can be found in Refs. 16 and 17. Subsequent injection of 152 m^3 (40 000 gal) of water in Experiment 2028 (the Nitrogen Experiment described below) did not enlarge the fracture system significantly.

Experiment 2033 was conducted on September 27, 1983, in the open-hole region above the cemented-in liner in EE-3. The primary objectives were to test apparent lithologic boundaries and to observe the venting behavior of the

Fig. 14.
Annulus pressure and injection rate, Experiment 2020 in EE-2.

upper EE-3 zone. An additional objective was to test existing elements of the so-called Precambrian seismic net.

Some 713 m³ (188 000 gal) of water were pumped, with the pressure and flow profiles given in Figs. 17 and 18. The major results of Experiment 2033 were:

- One of the apparent boundaries was penetrated. The separation distance between EE-2 and upper EE-3 seismic clouds decreased from ~180 to ~80 m (~590 to ~260 ft).
- Significant volume of fluid was produced during venting of the system. Venting occurred at ~3.2 l/s (~50 gpm) with the wellhead at atmospheric pressure.

2.3.3. Analysis of Fracture-Opening Pressures and Earth Stresses.

Fracturing operations in the Phase II system at Fenton Hill have been conducted over different intervals in both EE-2 and EE-3. Initial operations

Fig. 15.

Wellhead pressure and injection rate, Experiment 2023 in EE-3. Full open-hole pressurization.

in EE-2 (Experiments 2011, 2012, and 2016) were conducted near the bottom of the hole, below a cemented-in liner at 4.25 to 4.36 km (13 943 to 14 308 ft) true vertical depth (TVD). For later experiments (2018, 2019, and 2020), a sand plug was placed at about 3.59 km (11 765 ft) TVD, and fracturing was conducted in the open interval below the casing shoe at 3.46 km (11 365 ft) TVD. Temperature surveys following experiments in the upper EE-2 interval showed at least three distinct fracture inlets at vertical depths of about 3.47, 3.50, and 3.53 km (11 369, 11 473, and 11 582 ft) TVD. Initial EE-3 pumping (Experiments 2006, 2007, and 2023) was conducted over the entire open-hole interval, 3.09 to 3.98 km (10 134 to 13 046 ft) TVD. However, temperature surveys indicated that all the flow was entering fracture inlets at approximately 3.09, 3.13, and 3.15 km (10 144, 10 253, and 10 345 ft). A liner was cemented into EE-3 for Experiment 2025 and the hole was plugged back with sand. Fracturing of the open interval at 3.35 to 3.44 km (10 985 to 11 296 ft) TVD resulted in fracture inlets at about 3.39, 3.41, and 3.43 km (11 146, 11 190, and 11 243 ft) TVD.

Fig. 16.

Wellhead pressure and injection rate, Experiment 2025 in EE-3. PBR liner-unit assembly and sand plug.

Fig. 17.

Pressure profile, Experiment 2033 in EE-3.

Fig. 18.
Flow profile, Experiment 2033 in EE-3.

During these experiments, different methods have been used to determine fracture-opening pressures. The pressure required to extend a large planar fracture is only slightly greater than the normal earth stress, but because of wellbore pressure-drop and fracture-entrance impedance, the surface pumping pressure plus the weight of the water column may be significantly greater than the earth stress.

If, however, pumping is stopped and the well shut-in so that no flow occurs into or out of the fracture, the pressure should decrease quickly to the value just required to hold the fracture open, and then decay slowly as water permeates away from the fracture and the fracture closes. This region of almost constant pressure, if observed, is called the instantaneous shut-in pressure, or ISIP, and is a good measure of the stress normal to the fracture face. If no pressure plateau exists, special techniques may be used to identify the ISIP value.¹⁸ Unfortunately, the data do not always work well with the standard ISIP method, nor to the extrapolation of ISIP, therefore an attempt was made to determine fracture-opening pressures using simple

fracture-flow models, P vs Q^n , where P is the downhole injection pressure minus the fracture-opening pressure, $P_f - P_o$, and Q is the flow rate. Reasonable fits to the data were obtained using a laminar flow model, P vs $Q^{0.25}$, and a turbulent flow model, P vs $Q^{0.5}$. Examples are shown in Figs. 19 and 20 for the EE-2 lower zone. Once the data are fit, the true fracture-opening pressure, analogous to the ISIP, is determined by extrapolating the data-fit back to zero flow rate. Fracture-opening pressures from these models and from the ISIP and extrapolated ISIP are given in Table IX.

A compendium of fracture-opening pressures for Phase I and Phase II experiments was compiled, and the results are given in Table X. The pressures are categorized by the method of determination.

Fracture-opening pressures versus depth were then plotted for the Phase II and previous Phase I experiments. It was found that a fracture gradient of 0.0185 MPa/m (0.82 psi/ft) fit the data fairly well (Fig. 21) with the exception of an anomalous region from 2.6 to 3.2 km (8500 to 10 500 ft) where fracture-opening pressures were 12 to 20 MPa (1740 to 2900 psi) lower than

Fig. 19.

Laminar flow model. Fenton Hill Phase II lower zone experiments in wellbore EE-2.

TABLE IX
FRACTURE INTERVALS AND FRACTURE-OPENING PRESSURES
FENTON HILL PHASE II

Experiment	Fracture-Opening Pressures (MPa)				Depth Interval (TVD)	Fracture Inlets By Zone (TVD)
	Laminar Flow Model	Turbulent Flow Model	ISIP	Extrapolated ISIP		
EE-2 Lower Zone						
2011 (5/30/82)			80.2	80.3	4.25-4.36 km	Undetermined
2012 (6/4/82)	74.5	78.9	80.2	80.3	(13 943-14 308 ft)	
2016 (6/4/82)	73.0	78.5	81.2	81.3		
Combined fit (Expts. 2011, 2012, and 2016)	73.0	78.2				
EE-2 Upper Zone						
2018 (7/19/82)	58.3	65.2	62.7	75.0	3.46-3.59 km	3.47 km (11 369 ft)
2020 (10/6/82)	63.1	69.1	67.7-73.9	70.0-74.2	(11 365-11 765 ft)	3.50 km (11 473 ft)
Combined fit (Expts. 2018, 2019, and 2020)	62.1	68.4				3.53 km (11 582 ft)
EE-3 Upper Zone						
2006 (1/19/82)				38.1	3.09-3.98 km	3.09 km (10 144 ft)
2007 (2/17/82)	33.7	36.0		38.4	(10 134-13 046 ft)	3.13 km (10 253 ft)
2023 (11/8/82)	34.2	37.7	38.6	42.5		3.15 km (10 345 ft)
Combined fit (Expts. 2006, 2007, and 2023)	33.1	36.5				
EE-3 Lower Zone						
2025 (12/14/82)	43.9	55.5			3.35-3.44 km	3.40 km (11 146 ft)
					(10 985-11 296 ft)	3.41 km (11 190 ft)
						3.43 km (11 243 ft)

TABLE X
FENTON HILL FRACTURE-OPENING PRESSURES

<u>Well/Experiment No.</u>	<u>Depth (km)</u>	<u>Fracture-Opening Pressure (MPa)</u>	<u>Method of Determination</u>
GT-1	0.745	13.7-14.8	ISIP
GT-2	2.0	33.5-34.9	Extrapolated ISIP
	2.93	36.6-37.3	Fracture Extension
EE-1	1.96	30.6-31.5	Fracture Extension
	2.93	37.5	Fracture Extension Pressure from PTA ^a
EE-2/2018 (7/19/82)	3.46-3.59	58.3	P vs Q ^{0.25} Extrapolation
		65.2	P vs Q ^{0.5} Extrapolation
		62.7	ISIP
		75.0	Extrapolated ISIP
EE-2/2020 (10/6/82)	3.46-3.59	63.1	P vs Q ^{0.25} Extrapolation
		69.1	P vs Q ^{0.5} Extrapolation
		67.7-73.9	ISIP (4 measurements)
		70.0-74.2	Extrapolated ISIP (3)
EE-2/2011 (5/30/82)	4.25-4.36	59.2	P vs Q ^{0.25} Extrapolation
		69.9	P vs Q ^{0.5} Extrapolation
		80.2	ISIP
		80.3	Extrapolated ISIP
EE-2/2012 (6/4/82)	4.25-4.36	74.5	P vs Q ^{0.25} Extrapolation
		78.9	P vs Q ^{0.5} Extrapolation
		80.2	ISIP
		80.3	Extrapolated ISIP
EE-2/2016 (6/19/82)	4.25-4.36	73.0	P vs Q ^{0.25} Extrapolation
		78.5	P vs Q ^{0.5} Extrapolation
		81.2	ISIP
		81.3	Extrapolated ISIP
EE-3/2006 (1/19/82)	3.09-3.15	38.1	Extrapolated ISIP
EE-3/2007 (2/17/82)	3.09-3.15	33.7	P vs Q ^{0.25} Extrapolation
		36.0	P vs Q ^{0.5} Extrapolation
		38.4	Extrapolated ISIP
EE-3/2023 (11/8/82)	3.09-3.15	34.2	P vs Q ^{0.25} Extrapolation
		37.7	P vs Q ^{0.5} Extrapolation
		38.6	ISIP
		42.5	Extrapolated ISIP
EE-3/2025 (12/14/82)	3.35-3.44	43.9	P vs Q ^{0.25} Extrapolation
		55.5	P vs Q ^{0.5} Extrapolation

^aPressure-transient analysis.

Fig. 20.

Turbulent flow model. Fenton Hill Phase II lower zone experiments in EE-2.

estimated with the above gradient. This anomaly coincides with a biotite-granodiorite intrusive emplaced into a heterogeneous, jointed, metamorphic complex comprised of gneisses, amphibolite and metavolcanic rocks.

2.3.4. Hydraulic-Fracturing Theory in Jointed Rock Masses. Hydraulic fracturing is used to create HDR reservoirs. The formations are dense competent rocks, which have pre-existing fractures, i.e., natural joints. Consequently questions arise about the applicability of conventional fracturing theory, which is based upon homogeneous elastic solids, to heterogeneous and discontinuous geological media. For several years we have been struck by the dual nature of the fracture systems created. The microearthquake hypocenters located during the fracturing experiments are distributed in three-dimensional space, often described as microseismic "clouds," and suggest that huge volumetric regions of rock are opened by fracturing. This model of the reservoir, an optimistic one regarding the amount of heat to be recovered, is called the volumetric fracturing model (Fig. 22). However, pressurization and flow experiments conducted after the fracturing operations suggest that

reservoirs consist of a discrete number of planar fractures. These discrete fractures are the main water conduits, but some interfracture communication is afforded by natural joints. The natural joints are more tightly closed than the main fractures and so are high-flow-resistance paths. This reservoir model, a more pessimistic one because the heat must be transported to the few fractures primarily by conduction over relatively large distances, is referred to as the planar model (Fig. 23).

Natural joints opened
by pressurization.

Fig. 22.
Volumetric fracturing model.

To examine which of these models is more appropriate, correlations were sought between injection volume and the dimensions of the fractured rock volume determined by microearthquake mapping at several HDR reservoirs. If a truly volumetric reservoir were to be created, then the volume of the fractured region should scale linearly with injection volume. However, for a planar fracturing model, the area should scale with injection volume.

Data from six HDR reservoirs were reviewed, including fracturing experiments in both the Phase I and Phase II Fenton Hill reservoirs, the Phase II Rosemanowes reservoir in Cornwall, England,¹⁹ Falkenberg in West Germany,²⁰ Le Mayet de Montagne in France,²¹ and Yakedake, Japan.* The formations involved consist primarily of hard crystalline rocks like granite, but the Yakedake formation consists of slate and very competent sandstone, with 1 to

*Information provided by I. Matsunaga and M. Kuriyagawa, National Research Institute for Pollution and Resources, Ministry of International Trade and Industry, Tsukuba, Japan.

Natural joints, still mostly closed,
show diffusive permeation losses.

Discrete number
main hydraulic fractures
opened by pressurization.

Fig. 23.
Planar fracturing model.

2% porosity. Reservoir depths range from 200 to 4250 m (650 to 13 900 ft), fracturing pressures vary from 4 to 48 MPa (580 to 7000 psi) as measured at the wellhead, and injection volumes range from 5 to 40 000 m³ (1300 to 10.6 million gal). Ordinary water was used as the fracturing fluid with the exception of Le Mayet, where a sand and gelled-water mixture was used.

All fracture dimensions were taken from microseismic maps of the hypocenters determined for each experiment. Some degree of judgment is required in defining dimensions from the microseismic "cloud." Occasionally several hypocenters fall outside the main clustering, and in these cases the outlying hypocenters were excluded. Because of the subjectiveness involved, it is estimated that each seismic dimension has an uncertainty of $\pm 25\%$. Despite the volumetric nature of the "clouds," none is actually spherical. All can be characterized as ellipsoidal, with three axes: major, intermediate, and minor. With the exception of Fenton Hill fracturing Experiments 2012 and 2016, the width is a horizontal dimension. The other two axes are referred to as the down-dip and along-strike dimensions. The microseismic maps of

Experiments 2012 and 2016 suggest fracture zones dipping at 45° ; however, all other fracture experiments exhibited microseismic clouds with at least one axis, either the major or the intermediate one, which is approximately vertical. At Fenton Hill, the strike bearing has been generally north.

In both Fenton Hill reservoirs, the down-dip dimension ranges from 50 to 100% of the along-strike dimension (averaging 60%), with the notable exceptions being the 45° zones of Experiments 2012 and 2016, where the dip dimension is roughly twice the strike dimension. The width at Fenton Hill has typically been one-half the strike dimension.

During the Rosemanowes fracturing experiments in Cornwall, it was observed that the fractures grew preferentially downward, extending about 1 km (3300 ft) below the injection well and only 0.4 km (1300 ft) above it. Consequently the down-dip (vertical) dimension at Rosemanowes is typically twice the along-strike dimension. The width is about half the strike dimension and the strike bearing is N 50° W, which is nearly perpendicular to the measured direction of the minimum compressive earth stress and 15 to 30° west of the orientation of a major set of natural vertical joints.

At Falkenberg and Yakedake, the dip and strike dimensions are roughly equal and the width is again roughly half the strike dimension.

2.3.4.1 Correlating the Data with the Planar Fracturing Model. Figure 24 is a log-log plot of injection volume versus seismic area. The area of the

Fig. 24.
Correlation of seismic area with injection volume.

seismic zone was computed as that of an ellipse, $\pi/4$ times the product of the two largest axes, the down-dip and along-strike dimensions. A linear correlation, as required for the planar fracturing model, should result in a straight line with unit slope, and the intercept of this line is related to b , the water injected per unit fracture area. Apart from the Rosemanowes data, which will be discussed later, a linear correlation does exist, and the dashed lines that encompass the remaining data suggest that b ranges from 4 to 20 mm. To determine if this range of values is in reasonable accord with expected values, we examine the separate components of b , that part due to the fracture aperture itself, then the part due to permeation.

Geertsma and de Klerk²² determined for a circular fracture of radius R , that the aperture δ was:

$$\delta = \left[\frac{\mu q R}{G} \right]^{0.25}, \quad (6)$$

where μ is fluid viscosity, q is injection flow rate, and G is the rock shear modulus, which can be approximated as 30 GPa. At a typical injection temperature, 50°C, the viscosity of water is 5×10^{-4} Pa·s. A typical injection rate during fracturing is 50 ℓ/s (19 bpm), so that taking $R = 400$ m (a typical interwell spacing for HDR reservoirs), δ is 1.0 mm. Fracture apertures derived from measurements of modal volumes and heat-transfer area in the Fenton Hill Phase I reservoir have ranged from 1.7 to 4 mm.²³ In view of the uncertainties in deriving the value $\delta = 4$ mm from the minimum value of b in Fig. 24, the number of fractures must be regarded as rather speculative, but it appears that only one to, at most, four main fractures were propagated.

Equation (6) indicates that the average fracture aperture varies mildly with the fracture radius, i.e., δ scales with $R^{0.25}$. Approximating R as $\sqrt{\text{area}/\pi}$, then δ scales as $(\text{area})^{1/8}$, and the injection volume should actually scale as $(\text{area})^{9/8}$ rather than linearly. A detailed examination of Fig. 24 indicates that there is enough scatter in the data to support this scaling law; therefore the planar fracturing model is not invalidated. Furthermore, this slight correction is required only for that part of b directly responsible for the fracture aperture, δ . The remainder of b is due to permeation, which does result in linear injection volume-area scaling.

The remainder of b is attributable to fluid losses caused by permeation of the rock surrounding the main fracture(s). Using Darcy's law it can be shown that:

$$b - \delta = \Delta P \sqrt{\frac{\pi k \beta t}{\mu}}, \quad (7)$$

where k is permeability, ΔP is the downhole pressure change, t is fracturing duration, and β is the compressibility taken as $2.7 \times 10^{-11} \text{ Pa}^{-1}$, which is a reasonable estimate for all the HDR reservoirs. Using the appropriate values, the permeability was computed for each experiment. The Fenton Hill reservoirs have computed formation permeability on the order of $1 \text{ } \mu\text{D}$; Rosemanowes is between 0.3 to 0.5 mD , and the Falkenberg reservoir is about 3 mD . The values at Le Mayet, 6 mD , and Yakedake, $10 \text{ } \mu\text{D}$, must be considered as much more speculative because of the assumptions required regarding the viscosity of the fluid used (Le Mayet) and the formation compressibility (Yakedake). Much of the permeability variation is probably due to depth differences, i.e., the natural joints that account for almost all of the permeability in dense rocks are more tightly closed at greater depths and pressures.

For comparison purposes, Fisher and Tester²³ found from flow testing and thermal drawdown that the permeability of the Fenton Hill Phase I reservoir ranged from 0.1 to $1 \text{ } \mu\text{D}$, in very good agreement with the value derived here.

Pulse-injection hydraulic tests at the very shallow Falkenberg reservoir²⁴ showed that when depth intervals were isolated which excluded natural joints, then k was as low as 0.1 to $1 \text{ } \mu\text{D}$, but when joints were present, k was 3 mD . Fracturing creates a large surface area, which is likely to intersect many joints. So, as expected, the present value agrees well with the values for intervals with joints.

2.3.4.2. Correlating the Data with the Volumetric Fracturing Model.

Figure 25 is a log-log plot of injection volume, V_{inj} , versus seismic volume, V_s . The seismic volume was computed as that of an ellipsoid, which is the area of the previous section times two-thirds the width. Assuming that the injected water is stored within the seismic volume, the volumetric fracturing model requires a linear correlation. Such a correlation results in a straight

Fig. 25.
Correlation of seismic and injection volumes.

line with unit slope, and the intercept of the line is related to the total porosity, ϕ , as

$$V_{inj} = \phi V_s \quad (8)$$

The data in Fig. 25 are too scattered, requiring a variation in ϕ of two orders of magnitude, to support a single linear correlation for all experiments. However, the data for Rosemanowes and the Fenton Hill upper Phase II reservoir Experiments 2018 and 2020 could be forced on individual linear correlations as indicated by the bold lines in Fig. 25. The inferred total porosity for Rosemanowes is 9×10^{-4} , in good agreement with the value expected from pressurization of the natural porosity. The value of ϕ for Experiments 2018 and 2020 is 2×10^{-4} , a factor of five lower than $\beta \Delta P$, so the

injected volume could have been absorbed by the natural porosity in these experiments also. Evaluating these experiments according to a volumetric fracturing model is still supported to a degree by the fact that the pertinent seismic clouds do not show any obvious planar features.

The seismic clouds for the Fenton Hill Experiments 203, 195, 2012, 2016 and Falkenberg 790CT17 do show one or more preferred planes upon which the hypocenters are arranged. Referring to Fig. 25, there does appear to be a nonlinear correlation for these latter experiments as suggested by the dashed line:

$$V_{inj} \propto V_s^{2/3}, \quad (9)$$

where $\propto$ is the indication for proportionality. As V_s was defined earlier as the seismic area, A , times two-thirds of the width of the seismic zone, W , and because we showed earlier that $A \propto V_{inj}$, Eq. (8) implies that

$$W \propto V_{inj}^{0.5}. \quad (10)$$

For much of the data in Fig. 25, the fracturing injection rate was very roughly constant, so Eq. (10) simply implies that the seismic width is proportional to $\sqrt{\text{time}}$. This is the diffusional relationship, so the correlation given by the dashed-line fit to the data confirms the planar fracturing model developed earlier.

2.3.4.3. Shape of Microseismic Zones. Despite the volumetric appearance of the microseismic zones, it was shown that fracturing usually results in the formation of a single, or at most, a few discrete, planar hydraulic fractures. Why then the appearance of microearthquakes in large extended volumetric zones? The best explanation appears to be from Pearson,²⁵ who argues that the permeation of fracturing fluid away from the main fractures, along existing, but still tightly closed natural joints, results in a pore-pressure increase in these joints. Using the usual Mohr circle analysis with a Coulomb-Mohr shear-failure criterion, the pore pressure reduces the effective stress normal to the joints until a localized failure occurs. Numerical calculations²⁶ show that natural joints, which are not aligned with the principal earth stress directions, are most prone to failure, resulting in a local shear-slip micro-earthquake, with dimensions comparable to the joint spacing. This local

failure is consistent with the microearthquake spectra, which indicate rupture radii of one to a few meters.

Failure cannot occur at distances from the main fractures that are greater than the distance to which the pore pressure diffuses, so the microseismic migration is limited to the diffusion distance:

$$l = 2 \sqrt{\kappa t}, \quad (11)$$

where κ is the hydraulic diffusivity, $k/(\mu\beta)$. Using the Fenton Hill values previously determined ($k = 1\mu\text{D}$, $\mu = 1.2 \times 10^{-4} \text{ Pa}\cdot\text{s}$, and $\beta = 2.7 \times 10^{-11} \text{ Pa}^{-1}$), a 10-hour experiment results in $l \approx 10 \text{ m}$, and a 100-hour experiment yields $l \approx 30 \text{ m}$. However, these estimates are considerably less than seismic widths. The explanation for this discrepancy lies in the statistical nature of the joints. When a spectrum of joints with various apertures is present, the water loss from a fracture is given by the sum of the permeabilities of all the joints. Thus the permeabilities derived earlier represent the average permeability:

$$k = \frac{\langle a^3 \rangle}{6s}, \quad (12)$$

where $\langle a^3 \rangle$ is the average of the cubes of all joint apertures, and s is the joint spacing.

The diffusion of fracturing fluid along an individual joint will be in accordance with the permeability of that particular joint, not the average joint. Consequently, the outer limits of the microseismic zone are controlled in large degree by the joints with the larger apertures. The distribution of joint apertures, which is usually log-normal,²⁷ accounts for the unusual temporal distribution of microearthquakes. One often observes early in an experiment that some microearthquakes occur far from the injection point, presumably along joints with large apertures, and later some events occur much closer, along joints more tightly closed.

To illustrate the point more quantitatively, assume that s is 10 m. Then if all joints had constant a , and $k = 1\mu\text{D}$, as at Fenton Hill, then from Eq. (12), a must be only 5 μm , which is extremely small. Many joints must have apertures many times greater. Suppose several joints are ten times as large, then the individual permeability of such joints would be 1000 times greater,

and from Eq. (11) the diffusion distance would be 30 times greater, so that a 10-hour experiment would result in $\lambda = 300$ m. Notice that these larger joints would have apertures of 50 μm , which would still be considered quite small, particularly in comparison to the main-fracture apertures.

Somewhere within the microseismic zones are hidden the main fracture(s). They are hidden because they are aseismic, or at least no more seismically active than the microearthquakes triggered by pore-pressure diffusion. An obvious explanation for the aseismicity is that the main fractures are caused primarily by tensile rather than shear failure. From typical seismic dimensions and durations, it can be shown that the average fracture propagation velocity is of the order of 0.01 m/s, negligibly small compared to the Rayleigh or sound velocities, so the failure process is not an energetic one. It is quite likely that the process may be an episodic one, i.e., a sudden, short propagation with velocity comparable to the Rayleigh velocity, followed by a quiescent period while the fluid catches up and repressurizes the fracture, but the energy in each episode is evidently no more pronounced than in the nearby shear failures. Furthermore, the propagation referred to here is probably not true tensile rupture of virgin rock but merely the opening of those natural joints with planes most nearly perpendicular to the minimum earth stress. In other words, hydraulic "fracturing" in this case is the preferential stimulation (i.e., opening) of those joints, more or less continuous, which are most nearly perpendicular to S_3 . The opening of these joints, along which exist significantly smaller components of shear stress, would indeed be expected to be quiet compared to the joints inclined to the earth stresses, which, when partially stimulated by a pore-pressure increase, slip in shear, creating the microearthquakes.

2.3.5. Rock Mechanics. Work this fiscal year focused on hydraulic stimulation of a jointed rock mass and the importance of shear slippage on many planes. Simple Mohr-circle analysis shows that slip should occur on a wide range of joint orientations before any joint opening occurs. Analysis by Hayashi and Abe²⁸ indicates that the stress gradients at Fenton Hill are such that stimulated regions should grow symmetrically up and down. Because the stress state at Fenton Hill is poorly known, we are attempting a new determination from strain relaxations observed during a core-slicing experiment.

Numerical calculations with a finite-element code show that simultaneous stimulation of both wells should aid in making a hydraulic connection between

the wells. It is assumed that there are enough joints in enough orientations that the shear strength of the rock mass is nearly isotropic. The highly stimulated regions around the wells can then be modeled as a plastic region with a pressure-dependent yield stress. Potential for growth of these regions is examined by explicitly putting joints into the mesh at the edge of this region. Simultaneous stimulation results in lower injection pressures causing joint slippage, and preference for the regions to grow toward each other when compared to stimulating only one hole at a time.

Questions remain. What are the effects of our previous stimulation attempts? Can a more technically feasible stimulation schedule, stimulating one well immediately after the other, give the same benefits as simultaneous stimulation?

2.3.6. Effects of Shut-ins During Hydraulic Fracturing. If the injection well is shut-in for a time during a hydraulic-fracturing operation, there is a doubly deleterious effect: one must "make up" not only the volume of fluid that would have been injected during the shut-in time, but an additional component of loss is due to permeation of previously injected water into the rock contiguous to the propagated fractures. It can be shown that much of the water injected during Fenton Hill fracturing is lost through permeation.²⁹

The area, A , of the propagated fracture is given as³⁰

$$A = \frac{\dot{Q}}{\pi c} \sqrt{t}, \quad (13)$$

where $\dot{Q}$ is the injection rate (assumed constant), and t is injection time. The quantity c is related to the permeability, k , and compressibility, β , of the rock, the change in downhole pressure, ΔP , and the viscosity, μ , of the injected fluid:

$$c = \Delta P \sqrt{k\beta/\pi\mu}. \quad (14)$$

If fracturing is stopped (the well shut-in, but not vented) at time t_s , the area during the shut-in time is provided by superposition as

$$A = \frac{\dot{Q}}{\pi c} (\sqrt{t} - \sqrt{t - t_s}); \quad t > t_s. \quad (15)$$

Note that Eq. (15) predicts that the fracture area decreases during the shut-in. Obviously, if virgin rock has been fractured, it cannot be mended

again; what Eq. (15) actually implies is that, since fluid is no longer injected to satisfy the permeation requirement, pressure cannot be maintained at a level to hold the entire fracture open in a dilated state. During shut-in, some of the dilated fracture area must close up. To resume fracturing, this deflated area must be repressurized and reinflated.

When injection is resumed at the same rate, $\dot{Q}$, the area recovers, in accordance with another application of superposition, as

$$A = \frac{\dot{Q}}{\pi c} \left\{ \sqrt{t} - \sqrt{t - t_s} + \sqrt{t - t_s - \theta_s} \right\}; t > t_s + \theta_s, \quad (16)$$

where θ_s is the shut-in duration (t_s is when shut-in starts, θ_s is how long it lasts).

The clearest way to explain the effect of shut-in is to compare the resulting area, with shut-in, to the same area that would have been achieved had there been no shut-in. If a fracture is conducted nonstop for the intended duration, t_f , then from Eq. (13) the final area is

$$A_f = \frac{\dot{Q}}{\pi c} \sqrt{t_f}. \quad (17)$$

The normalized area growth versus time, without shut-in, is

$$\frac{A}{A_f} = \sqrt{\frac{t}{t_f}}. \quad (18)$$

The normalized area, with a shut-in, is

$$\frac{A}{A_f} = \sqrt{t'} - \sqrt{t' - t'_s} + \sqrt{t' - t'_s - \theta'_s}, \quad (19)$$

where the primed times are the normalized values, i.e., those divided by t_f (e.g., $t' = t/t_f$).

To quantitatively examine the shut-in effect, consider the upcoming Experiment 2032, in which up to 22,700 m³ (6 million gal) will be injected at a rate expected to be in the vicinity of 130 μ /s (50 bpm). Such an experiment will require about 50 hours. If the shut-in time is 2-1/2 hours, a typical value to change a pumping truck or conduct a minor repair, then $\theta'_s = 0.05$.

Figure 26 shows the effect of such a shut-in if it occurs at times of 1/4, 1/2, or 3/4 of t_f . The earlier the shut-in, the less extra injection

Fig. 26.
Effect of shut-ins on fracture-area growth.

time is required to achieve the same final fracture area had no shut-in occurred. For example, if the shut-in occurs at $t'_s = 1/4$, then to achieve $A/A_f = 1.0$ requires a total normalized time t' of 1.06. The extra normalized injection time, 0.06, is just slightly greater than the normalized shut-in time, 0.05, so nearly full recovery is accomplished just by making up the injection time lost during shut-in. However, if the shut-in occurs at $t'_s = 3/4$, then a total time of 1.08 is required, so that one must replace the fluid lost during shut-in on a 1.6 for 1 basis.

A simple rule for quantifying the extra pumping time required can be derived by requiring the normalized area of Eq. (17) to be one, and making use of the fact that θ'_s is usually much less than one. Then it can be shown that the ratio of the extra pumping time θ_p to the shut-in time θ_s is a factor always greater than 1:

$$\frac{\theta_p}{\theta_s} = \frac{1}{\sqrt{1-t_s/t_f}} \quad (20)$$

Despite the approximations, Eq. (20) yields good results even at high values of t_s/t_f . For example, for $t_s/t_f = 0.8$, Eq. (20) predicts $\theta_p/\theta_s = 2.2$, whereas the correct result is 2.0.

2.3.7. Tracer Studies. Preliminary research is being conducted to develop temperature-sensitive, chemically reactive tracers to estimate reservoir size and effective heat-transfer surface area. The productive lifetime of future HDR geothermal reservoirs needs to be evaluated, while minimizing the duration of energy-extraction experiments. In the past, produced-fluid thermal-drawdown measurements were used to size the small, prototype reservoirs operated during Phase I. The Phase II system will be a larger reservoir, which will demonstrate the feasibility of the HDR concept on a commercial, rather than pilot-plant, scale. Produced-fluid temperature decline is not expected (nor desired) for several years in these larger systems. Thus, the achievement of this programmatic goal will leave us without our most reliable reservoir diagnostic technique, produced-fluid thermal-drawdown measurements. Chemically reactive tracers could alleviate this problem by providing a measure of the rate of thermal drawdown between the wellbores in advance of actual produced-fluid temperature decline.

The kinetics of most chemical reactions is extremely temperature sensitive. For reactions carried out in a batch reactor, the following form of the rate equation is often applicable:

$$\frac{dC}{dt} = kC^n, \quad (21)$$

where C is the concentration of the reacting species, t is time, and n is the order of the reaction (assumed to be 1 in this discussion). The rate constant k is the variable that contains the temperature sensitivity. It can usually be described by the following equation:

$$k = A_r \exp(-E_a/RT), \quad (22)$$

where A_r is the pre-exponential factor, E_a is the activation energy of the reaction, R is the universal gas constant, and T is temperature. For typical reactions in solution, k will vary over several orders of magnitude over the range of temperatures encountered in an HDR reservoir undergoing extensive energy extraction.

Two methods of operation are currently being considered for the reacting-tracer experiments: (1) the flow-through method and (2) the reverse-flush technique. In the flow-through mode, the reacting tracer is injected in the inlet fluid either as a slug of limited duration, or continuously. The extent of chemical reaction is measured as a function of time in the produced fluid. A series of these experiments during long-term energy extraction should show a decline in the extent of reaction (an increase in the concentration of the reactant) because of thermal drawdown in the inlet region of the reservoir. The reverse-flush technique is designed to measure this drawdown directly. A steady stream of reacting tracer is injected for a time τ_{inj} . Next, the reservoir is shut-in for a time τ_{SI} , during which time the tracer will react at the local reservoir temperature. Finally, the flow is reversed, and the concentration-versus-time behavior is monitored during the flowback.

The transient response of either of these reacting tracer experiments will be governed by both the temperature field and the dispersive nature of the fluid flow. For preliminary scoping calculations, we assume here that the tracer behavior may be modeled using the one-dimensional axial-dispersion equation:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - \bar{u} \frac{\partial C}{\partial x} - kC \quad (23)$$

where x is the flow direction, $\bar{u}$ is the mean velocity in the x -direction, D is the effective dispersivity, and $(-kC)$ is the instantaneous rate of reaction of tracer, assuming a first-order reaction. Equation 21 can be rewritten in nondimensional form as:

$$\frac{\partial C}{\partial \theta} = \frac{1}{Pe} \frac{\partial^2 C}{\partial \zeta^2} - k\tau C, \quad (24)$$

where θ is dimensionless time, t/τ ; ζ is dimensionless distance along the fracture, x/L ; τ is the mean residence time; L is the length of the fracture; and Pe , the Peclet number, is the dimensionless group $(\bar{u}L/D)$ that characterizes the dispersion. A small value for Pe indicates a low degree of dispersion, while a large value indicates significant dispersion. A Peclet number of 40 was chosen in the following examples because it is typical of the level of dispersion encountered in the fractured geothermal reservoirs tested to date at Fenton Hill. The rate constant k is a function of fluid

temperature and thus varies with position in the reservoir. The temperature field was calculated assuming conduction-limited energy extraction from a single rectangular fracture. Figure 27 is a plot of reservoir-fluid temperature profiles during long-term operation for a fracture of $300\,000\text{ m}^2$ ($3.23 \times 10^6\text{ ft}^2$) and flow rate of 13 l/s (200 gpm).

For a reservoir of the size assumed in Fig. 27, it can be shown that 5 years of operation would be required to achieve 10°C of thermal drawdown of the produced fluid ($x/L=1$.) Figure 28 shows that the time required to detect significant cooling of the reservoir may be reduced considerably using reactive tracers. A series of tracer experiments over a period of 2 years results in enough of a change in outlet concentration to estimate reservoir size in advance of production-fluid temperature decline.

In modeling the reverse-flush experiment, we assume that the dispersion equation holds during both the forward- and reverse-flow portions of the operation, and that the Peclet number is the same in both directions. Also, during the shut-in period there is no migration of fluid, and thus it reacts at a rate corresponding to the local reservoir temperature at the time of the experiment. Figure 29 is a plot of a series of reverse-flush tracer experiments for the same-size reservoir as was just considered in the flow-through experiment modeling. The most striking result of these simulations is that the reverse-flush technique is capable of providing an estimate of reservoir

Fig. 27.

Reservoir temperature profiles during long-term energy extraction. Conduction-limited heat transfer assuming plug flow through a single rectangular fracture.

Fig. 28.

Chemically reactive tracer-response curves at various times during long-term energy extraction. Overall rate of reaction declines as reservoir cooldown occurs.

Fig. 29.

Reverse-flush chemically reactive tracer-response curves at various times during long-term energy extraction. Extent of cooled region grows during reservoir cooldown, as measured by tracer-response curves.

size much sooner than the flow-through experiment. This is true because the mode of operation ensures that the first tracer recovered encounters only the cooled region of interest, rather than passing entirely through the system. Furthermore, the shape of the outlet-response curve is directly related to the internal temperature pattern of the reservoir. Dispersion distorts the curve somewhat, but this effect could be accounted for by measuring the fluid dispersion using an inert tracer. The reverse-flush technique appears to be a very promising method for early determination of reservoir-drawdown rate.

Although the one-dimensional axial-dispersion model is convenient for parameter studies to show the feasibility of the reactive tracer concept, the fluid flow in an actual reservoir will certainly be more complicated. Our current concept of the nature of energy extraction in fractured reservoirs is that the short residence-time flow paths are low-impedance conduits that thermally deplete faster than the higher impedance secondary paths. A transient, chemically reactive tracer experiment will measure the drawdown rate of fractures of different impedance, thereby increasing our understanding of the internal flow field. To describe this behavior, we are developing the theories of residence-time and reaction-time distributions with the goal of extracting the maximum amount of unequivocal (model-independent) information from a tracer experiment. The results may then be incorporated directly into finite-element computer codes, which are being modified to simulate reactive-tracer behavior, for the final deterministic description of the system.

Up to now, it has been assumed that a chemically reactive tracer test involves only a single chemical reaction. It is also conceivable that a suite of reactions could be carried out at the same time. For example, several different tracers could be injected simultaneously, and the extents of reaction could be followed at the outlet of the reservoir. If this could be done, more information could be obtained than from a single tracer test.

As an example, consider a group of substances undergoing first-order reactions in a particle of fluid traveling along a particular flow path. The particle spends a time t traveling from the injection well to the production well within an HDR reservoir, encountering different temperatures along its path. The final concentration of component i , C_{if} , in the particle as it

emerges into the production is given by:

$$\frac{1}{A_r \tau} \ln \left(\frac{C_{if}}{C_{io}} \right) = - \int_{T_{\min}}^{T_{\max}} \exp(-E_a/RT) \eta(T) dT. \quad (25)$$

The term $\eta(T)dT$ is the fraction of the time t that the particle of fluid has spent between the temperatures T and $T + dT$.

In this equation, the kernel under the integral is a function of both E_a and T , and the distribution function η depends on T alone. This is a Fredholm integral equation of the first kind. If a suite of reactions with different activation energies is used and the emerging fluid analyzed for the conversions of the various reactions, the equation can be solved approximately for the distribution function $\eta(T)$. A series of analyses at different times can provide the bivariate distribution function $\Phi(t, T)$, which will give the fraction of the time a particular element of fluid with a residence time t will have spent at any temperature T .

The bivariate distribution function $\Phi(t, T)$ characterizes the temperatures encountered and the time duration of the individual encounters. It can be combined with a residence-time distribution, acquired from nonreactive tracer experiments, to yield a picture of the temperature profiles within the reservoir. In other words, such an analysis would give the probable sequence of temperatures encountered by all particles of fluid as they pass through the reservoir, and the entire geometric temperature pattern of the reservoir would be obtained. The possibility of gaining such a detailed picture of the temperatures within the HDR reservoir by multiple-reaction tracer experiments is being pursued.

Laboratory kinetic experiments are also being carried out to find a suitable reactive tracer for the Phase II reservoir. The reaction rate parameters (A_r and E_a) must be such that the "half-life" of reaction is on the order of several hours between 200-300°C. We will also test for compatibility with the reservoir rock and the effect of fluid geochemistry on the rate parameters. Finally, the sensitivity of chemical analysis is a crucial issue in the search for a chemical reaction because of the necessity to measure low concentrations accurately. Ester-hydrolysis reactions appear to be a

promising class of reactions for this purpose. Results of these kinetic studies will be presented in future HDR publications.

2.3.8. Insulating Geothermal Well Casings from Thermal Stress with Nitrogen Gas. The production casing in EE-3 was cemented in two stages and then tensioned to 401 000 kg (885 000 lb),³¹ as indicated in Fig. 30.

EE-3 PRODUCTION WELL

Fig. 30.

Completion of HDR geothermal well EE-3, which was originally intended and pretensioned to serve as a production well for hot water.

Calculations were run to determine the allowable cooldown of the casing to avoid overstressing it in the uncemented interval from 0 to 1615 m (5300 ft). Three criteria for allowable stress were examined: (1) the Uniaxial Maximum Stress Theory, (2) the von Mises Biaxial Stress Theory, and (3) the Maximum Energy of Distortion Theory. All results were based upon 80% of the published maximum yield strength, or 441 MPa (64 000 psi). Results of the calculation are plotted in Fig. 31. The design point was chosen as the best compromise of the three criteria and results in a maximum cooling of 11°C and a maximum internal pressure of 24.1 MPa (3500 psi).

The average static temperature of the top, uncemented 1615 m (5300 ft) of the 24.4-cm (9-5/8-in.) o.d. casing is 78°C. To prevent excessive cooling of the casing, initial fracturing operations used water heated to 65°C. Later, when 3975-7950 m³ (25 000- to 50 000-bbl) fracturing treatments were proposed, heating of the water was no longer considered feasible, so two alternatives

Fig. 31.
Allowable casing-temperature decrease and allowable pressure based upon allowable yield strength of 64 000 psi — 80% of actual yield — for upper joints of L-80 casing.

were investigated. Releasing the casing tension was considered, at least initially, to be too risky and expensive. The use of high-pressure nitrogen gas or nitrogen foam in the annulus between the 11.4-cm (4-1/2-in.) o.d. tubing and the casing to insulate the casing from unheated water appeared to be a low-risk, less expensive alternative. In the case of insulating with nitrogen gas, high pressure was required to exert adequate backside pressure on the seal assembly in the PBR to prevent "corkscrewing" of the 11.4-cm (4-1/2-in.) o.d. L-80 tubing (Fig. 30).

Initial simulations using a wellbore heat-transfer computer code appeared promising, but the heat-transfer coefficient used was then based on enclosed air spaces between parallel vertical walls at 60°C and 0.1 MPa (14.7 psi). No data were found for free convection in annuli with large temperature differences between inner and outer radii at the high pressures required for this application. Consequently, in situ borehole tests were conducted in EE-3 to determine actual heat-transfer coefficients and the net effectiveness of insulating with gas or foam.

2.3.8.1. The Nitrogen Experiment. To provide centralization of the tubing inside the casing, four-bladed 21-cm (8-1/4-in.) o.d. rigid centralizers were constructed and placed at intervals of approximately 37 m (120 ft). Nitrogen gas was displaced into the tubing/casing annulus by temporarily unstinging the tubing from the PBR at the top of the liner-hanger assembly (Fig. 30). The nitrogen was pumped into the annulus at 57 m³ (2000 SCF) per minute with reverse circulation. The annulus was pressurized to 18.6 MPa (2700 psi) with a total of 6800 m³ (240 000 SCF) of nitrogen, and the fluid level was found at 1676 m (5500 ft) using an echo meter. A background temperature log was run to 1980 m (6500 ft), and then the temperature sonde was positioned at 1219 m (4000 ft) for most of the heat-transfer experiment. Injection at 2.6 ℓ /s (1 bpm) for 1-1/2 hours was followed by a 1-1/2-hour shut-in, and a 1-3/4-hour injection at 21.2 ℓ /s (8 bpm). The average heat-transfer coefficient was estimated by modeling the measured temperature rise of water as it traveled down the inside of the tubing. Figure 32 shows the measured temperature at 1219 m (4000 ft) compared with a computer-generated temperature history. The match shown was achieved using the convective heat-transfer correlation of El Sherbiny et al. (1982).³² The correlation was given by:

$$Nu = \max (1, 0.061 Ra^{1/3}), \quad (26)$$

Fig. 32.

Comparison of measured and predicted temperatures in the tubing at 1219-m (4000-ft) depth during nitrogen-gas insulation experiment. Predictions are based upon gas, natural convection, heat-transfer correlation.

where Nu is the Nusselt number and is equal to the larger of the two values unity or $0.061 Ra^{1/3}$, where Ra is the Rayleigh number. The heat-transfer coefficient is related to the Nusselt number by the formula $h = Nu k/s$, where k is the nitrogen thermal conductivity and s is the annular gap dimension. Ra is related to the Grashof and Prandtl numbers by $Ra = GrPr$ where

$$Gr = g \rho^2 \beta s^3 \Delta T / \mu^2, \quad (27)$$

in which g is the gravitational constant, ρ is the nitrogen density, β is its thermal-expansion coefficient, ΔT is the temperature difference across the annular gap, and μ is the viscosity; $Pr = \mu c/k$ where c is heat capacity. In addition to the convective heat-transfer coefficient of the nitrogen, a fouling-factor coefficient of $500 \text{ W}/(\text{m}^2 \text{ } ^\circ\text{C})$ was assumed for the tubing and casing surfaces.

Figure 33 illustrates the variation of Grashof number and the nitrogen-gas heat-transfer coefficient with time. Both quantities were computed at a depth of 1219 m (4000 ft), where the temperature was measured. Estimated

Fig. 33.

Variation of Grashof number and convective heat-transfer coefficient at 1200-m (4000 ft) during nitrogen-gas insulation experiment. Variations shown result from the changing temperature difference across nitrogen-filled annulus induced by injection down tubing. Injection history shown in Fig. 32.

h -values vary from 20 to 60 $W/(m^2 \text{ } ^\circ C)$. The major cause of variation in both quantities was due to the changing temperature with continuing cold water injection.

During the experiment, the Grashof number varied from 3×10^8 to 8×10^9 . These values are one to two orders of magnitude higher than those attained experimentally by El Sherbiny et al. and higher than any others attained, to the best of our knowledge. The fact that the results were reasonably modeled with the El Sherbiny correlation suggests that its extrapolation may be valid up to this range of Grashof numbers.

To put the results in perspective, it is noted that if the annulus had been filled with water instead of nitrogen, the heat-transfer coefficient would have been seven times higher. However, before it is concluded that nitrogen results in a system only one-seventh as conductive, we point out that wellbore heat-transfer systems are complex: heat is transferred from rock to

casing, through the annulus to the tubing, and then to the flowing water in the tubing. At each interface there are contact or fluid-film heat-transfer resistances, distributed resistances over the casing and pipe-wall thicknesses, and then a resistance in the surrounding rock formations. This latter resistance increases with time as the thermal boundary-layer penetrates deeper into the rock. For comparison purposes, the effective heat-transfer coefficient across the casing and tubing is about $3000 \text{ W/(m}^2 \text{ }^\circ\text{C)}$, and the coefficient for the water inside the tubing (which is in a state of forced, or pumped, convection) is $500\text{--}1500 \text{ W/(m}^2 \text{ }^\circ\text{C)}$. Their reciprocals, the heat-transfer resistances, are negligible compared to that of the nitrogen in the annulus. However, the rock resistance, because of rock's low thermal conductivity, is comparable to the nitrogen resistance after a period of several hours to perhaps a day, at which time the annulus insulation is no longer effectively shielding the casing from the injected cold water.

2.3.8.2. Conclusion. It had been hoped that use of nitrogen gas in the annulus would result in low enough heat transfer that resumption of fracturing in EE-3 might be possible without heating the injected water or releasing the casing tension. To avoid overstressing the casing, the casing cooling was restricted to 11°C or less over its uncemented length from 0 to 1615 m (5300 ft). Unfortunately, we have demonstrated coefficients only as low as $20 \text{ W/(m}^2 \text{ }^\circ\text{C)}$ for nitrogen, and unless further experimentation is carried out or better centralization is achieved, it is unlikely that one can avoid heating of the injected water or release of the tension.

Another consideration, but one not available to us with the present well completion, is to use very low-pressure nitrogen in the annulus. Examination of the Nusselt number correlation, (1), indicates that h varies with $\rho^{2/3}$. The density, ρ , varies markedly with pressure, whereas k , μ and c are relatively insensitive, so a 10-fold or 100-fold pressure reduction could reduce h 5-fold or 25-fold (subject, of course, to $Nu \geq 1$). Such a low-pressure approach could only be used where tubulars are "overdesigned" for the additional stresses that would result from lack of balancing hydrostatic pressure in the annulus.

While some reasonable success has been attained in modeling the experimental results, a true predictive capability must still be demonstrated. We have much to learn in our understanding of these experiments. Complicating matters are the effects of forced convection and possible natural convection.

Even if these experiments were performed under well-controlled conditions in the laboratory, considerable additional effort would be required.

2.4. Technology Application

2.4.1. Roosevelt Hot Springs. Roosevelt Hot Springs is located in Beaver County, southwestern Utah. In the past, this area was known as a small resort, but since the 1970s geothermal exploration has resulted in the discovery of a hydrothermal reservoir of commercial size. Now a 20-MW(e) geothermal power plant is planned to be in operation by the middle of 1984. On the western edge of the geothermal field, separated from the hydrothermal area by a fault, several hot-but-dry wells have been drilled. The Laboratory studied two of these wells for HDR development, and considers the area to be a good candidate site for a future HDR system. A thick alluvium sequence overlies the granitic basement rocks and contains an important aquifer recharged from the nearby mountains. This aquifer is more-or-less contaminated by geothermal fluids leaking out of the hydrothermal reservoir, and the chemical composition of the water is unsuitable for water supply or irrigation uses throughout an area of about 220 km^2 (85 mi^2). However, this water would be convenient for industrial use, such as injection into an HDR energy-extraction system.

A detailed geochemical investigation of 21 waters (thermal and cold, mineralized and dilute) was performed, mostly samples from the alluvium aquifer in the contaminated area. All of these ground waters have temperatures above the yearly surface average. The geothermal fluid and its surface manifestation (Roosevelt seep) have essentially a Na-Cl type of chemical composition, these two ions exceeding 85% of the total mineralization. The well waters issuing from the alluvium display various degrees of mixing between dilute, cold, shallow ground water and mineralized, hot, geothermal fluid, having 10 to >60% of the latter type. The contaminated alluvium aquifer is significantly enriched in SiO_2 and minor and trace elements such as lithium, boron, barium, manganese, and arsenic. Oxygen-18 and deuterium results confirm that mixing occurs with geothermal fluids and that the recharge area of this portion of the alluvium aquifer has its origin in the Mineral Mountains. Tritium results reveal the presence of a relatively slow circulation within the alluvium aquifer and therefore a long underground residence time of the water. In the HDR zone, the alluvium ground water has

indirect evaluation; the geothermal fluids of the deep hydrothermal reservoir have also the same minimum underground residence time.

Thermodynamic computations on the reaction states of numerous mineral phases show that the majority of the waters studied are saturated relative to a fair number of primary and secondary silicates as well as carbonates and fluorite. Chemical equilibria were also computed for a range of temperatures between 25 and 250°C, temperatures at which the water will be injected and produced in an HDR energy-extraction system. At low temperatures the selected water samples display saturation or oversaturation with respect to the majority of the primary and secondary minerals encountered in the deep HDR zone. On the contrary, most minerals are undersaturated at 250°C, and the more-or-less dilute waters injected in the artificial fractures will dissolve minerals from the reservoir rocks. A pressurized closed loop will prevent precipitation in the surface pipes until the last cooling stage of heat extraction. At this point, the water can be vented into a pond before reinjection or some other demineralizing process can be incorporated.

A pumping test carried out in an existing shallow stock well in the HDR zone, with a maximum yield of 0.87 m³/min (230 gpm) revealed a relatively low transmissivity (130 m²/d) for a well specific capacity of 0.14 m³/min·m. The permeability has been estimated to be in the range of 1 to 10 md, which corresponds to silty sand. These values may be valid only locally due to lithologic variations within the aquifer. Although the water level of the aquifer has strongly declined elsewhere in the Milford area over the past 20 years due to intensive irrigation, the alluvium aquifer has remained stable in the HDR zone. Under heavy pumping, the geochemical characteristics of the water, which contains a certain amount of geothermal fluid, will probably reach steady-state conditions after a few months.

The alluvium aquifer located west of the geothermal field seems to meet the requirements for the make-up water in an HDR energy-extraction system. A future 50 MW(e) HDR power plant would need a continuous supply of about 2 m³/min (500 gpm), which could easily be pumped from one or two 60-m-deep (200 ft) wells with a casing diameter of 30.5 cm (12 in.). The location of these wells will determine the chemical composition of the water, which may have a total mineralization varying from 1300 to more than 5000 mg/l.

2.4.2. Acord 1-26 Hot Dry Well. The Acord 1-26 well is a hot, dry well peripheral to the Roosevelt Hot Springs known geothermal resource area (KGRA)

in southwestern Utah. The bottom-hole temperature in this 3854-m-deep (12 645-ft) well is 230°C, and the thermal gradient is 54°C/km. The basal 685 m (2247 ft), comprised of biotite monzonite and quartz schist and gneiss, is a likely HDR prospect. The hole was drilled in a structural low within the Milford Valley graben and is separated from the Roosevelt KGRA to the east by the Opal Mound Fault and other basin faults. An interpretation of seismic data approximates the subsurface structure around the well using the lithology in the Acord 1-26 well. The hole was drilled with a minimum of difficulty, and casing was set at 2411 m (7910 ft). From drilling and geophysical logs, it is deduced that the subsurface blocks of crystalline rock in the vicinity of the Acord 1-26 well are tight, dry, shallow, essentially impermeable, and very hot. A hydraulic-fracture test of the crystalline rocks below 3170 m (10 400 ft) is recommended. Various downhole tools and techniques could be tested in promising HDR regimes within the Acord 1-26 well.

2.4.3. Navopache HDR Project. During FY83, there were several meetings and telephone conversations with E. L. Kaufman, President of the Pan American Energy Corporation, concerning the proposed Navopache HDR project. Site selection for the project is in progress in northeastern Arizona near the town of Springerville. Recommendations for exploration strategy and geologic data sources were made to help Pan American prepare a proposal for the Department of Energy. A list of technical assistance that Los Alamos could furnish emphasized geologic support such as evaluation of existing data, gradient measurements, examination of cores and cuttings, and in situ stress measurements. We are now waiting for the go-ahead from Pan American, Navopache, and the DOE to begin this work.

2.4.4. East Mesa Field Operations. Field personnel participated in a unique geothermal borehole experiment from July 27 to August 10, 1983. The field tests were performed for Phillips Petroleum Geothermal Division at the Borchard Site near El Centro, California. The field operations were entirely funded by Phillips Petroleum, and DOE/Los Alamos proprietary information policies were waived in favor of Phillips.

The field operations consisted of two separate tests. The first test concerned the effects of the borehole fluids encountered in the sour wells drilled in the Imperial Valley on various armor materials used to manufacture well-logging cables. Several samples of armored well-logging cables using different metal alloys were provided by the Rochester Cable Corporation. The

samples were installed in a borehole test fixture that allowed the test samples to be tensioned and exposed to the Borchard well fluids. The cable-test fixture was lowered into the well and stationed at a depth of 2380 m (7800 ft) for 11 hours. The test fixture was lowered on a "slickline" made of Inconel wire. One surprising observation was the effect of the borehole fluid on the Inconel wireline: it became very brittle and broke whenever subjected to a bending stress.

In the second test, extensive vertical seismic-profile work was conducted in two wells using the high-temperature triaxial geophone package positioned at numerous locations in the boreholes. A Vibroseis system was used for the source. Data were recorded for a total of 65 hours of downhole operation in the geothermal boreholes.

2.4.5. Beowawe Field Operations. Los Alamos participated in a well-stimulation experiment conducted as a joint effort by the DOE, Republic Geothermal, Chevron Geothermal, and the Laboratory. The stimulation experiment was conducted in the ROSSI Well 21-19 in Beowawe, Nevada. Personnel from ESS-Division were involved in making downhole acoustic measurements, using our triaxial geophone package deployed in the adjacent GINN 1-13 borehole.

A dual-channel FFT analyzer, Nicolet Model 660A, was interfaced to an HP9845B computer. The software driver for this interface includes data transfer, disc storage, and graphics plots of the following functions: dual-channel time domain, single-channel power spectrum, dual-channel power spectrum, cross spectrum, and cross correlation.

Microseismic data were recorded during several acid pumps in the ROSSI well on August 21-22. Microseismic data were also recorded in the GINN well on August 26 during a large nitrogen injection in the ROSSI well in an attempt to lift the well.

The well-stimulation experiment failed to produce the ROSSI well. Personnel from Republic Geothermal and Chevron suspected that a cold-fluid zone in the upper part of the well was "killing" the production. We then ran our temperature tool in the well and completed two successful temperature logs that confirmed the cool zone in the upper section of the well.

3.0. PROGRAM MANAGEMENT

3.1. Organization

In FY83, the HDR Program's management structure continued unchanged from FY82. At the Los Alamos National Laboratory, the HDR Program is placed under the Chemistry, Earth and Life Sciences (CEL) Directorate, headed by its Associate Director, J. H. Birely. Within the CEL Directorate, the Program is managed from the Earth and Space Sciences (ESS) Division, as shown in Fig. 34. J. T. Whetten was the HDR Program Manager (as well as Deputy Division Leader for Earth Sciences of the ESS Division).

The FY83 programmatic organizational structure is depicted in Fig. 35. As indicated, the HDR Program continued to be field-managed jointly by Los Alamos, as described above, and the Energy Technologies Division (ET) of the DOE Albuquerque Operations Office (ALO), under the overall purview of the HDR Program Director in the DOE Division of Geothermal and Hydropower Technologies (DGHT). Progress of the Program is reviewed by the 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.

Fig. 34.
Los Alamos Directorate for Chemistry, Earth and Life Sciences.

Fig. 35.
HDR programmatic organizational structure.

3.2. Program Development Council

The eighth meeting of the Executive Committee of the National Hot Dry Rock Program Development Council was held in Albuquerque, New Mexico, on March 3, 1983. Present were Committee members

- S. K. Bazant (Plains Electric Generation and Transmission Cooperative, Inc.)
- W. E. Brigham (Stanford University)
- R. Greider (Geothermal Resources International, Inc.)
- G. V. Keller (Colorado School of Mines), Chairman
- L. J. P. Muffler (U.S. Geological Survey),

ex-officio members

J. C. Bresee (DOE/DGHT)
W. P. Grace (DOE/ALO-ET)
M. C. Smith (Los Alamos), Secretary
J. T. Whetten (Los Alamos),

and others, chiefly HDR staff members from Los Alamos.

After presentations concerning the financial and political situation of the HDR Program in Washington, Albuquerque, and Los Alamos, the Los Alamos staff reviewed recent progress and problems of the Program and plans for its near-term and long-term future. These were discussed in depth and commented on at length by the Committee, whose members had many useful suggestions concerning materials, equipment, instruments, techniques, experimental approaches, and analysis of results. The Committee also reached and expressed a consensus on the following broader issues.

- (1) All items listed in the Program budget presented to the Committee (which, in general, are the activities described in this Annual Report) were considered essential to continued progress of the HDR Program.
- (2) While early completion of a hydraulic connection between the two deep wells of the Phase II system is of prime importance, it is essential that we go on to create and demonstrate a multiply fractured final system.
- (3) Termination of the Fenton Hill Project at the end of FY86 and closing out of the HDR Program in FY87, as outlined in current Program plans, are realistic if no connection between the two wells has been achieved by then. However, the Committee felt that this result was most unlikely.
- (4) The option must be kept open to extend a successful HDR Program considerably beyond FY86, in particular to provide for extended operation of the final Phase II heat-extraction loop, or for experiments at a second site, or both.

3.3. International Steering Committee

3.3.1. Sixth ISC Meeting. The sixth meeting of the ISC was held at the Sheraton Airport Inn, San Diego, California, on October 15, 1982. Present at

this meeting were the official representatives of the Contracting Parties,

J. C. Bresee (DOE), Chairman

W. P. Grace (DOE)

W. Schloemer (KFA)

Y. Yamashita (NEDO)

and their advisors. Bresee opened the meeting with a statement of the DOE's continued commitment to support the Program, subject to Office of Management and Budget support and congressional appropriations. He reviewed the status of the FY83 budget process. The Project was then operating under a continuing resolution at the FY82 budget level (\$10 million). He expected eventual passage of a budget bill at a probable level of about \$7.5 million.

Minutes of the fifth ISC meeting were approved without modification. G. Nunz (Los Alamos) presented an accounting report for FY82. The Committee requested additional detail on Fenton Hill Project costs, and this was provided.

J. Whetten introduced himself as the Laboratory's new HDR Program Manager; his predecessor, R. Olwin, had recently assumed other duties. Whetten also introduced his Project co-managers: G. Nunz for planning and administration and D. Brown for technical direction. In addition, Whetten informed the Committee about an unfortunate fatal accident at Fenton Hill on October 4, 1982. The accident involved an employee of Dowell, the pumping subcontractor, using Dowell equipment and procedures. The accident was not due to any DOE/Los Alamos deficiency or failure of HDR technology. Operations at Fenton Hill ceased for 2 days while several investigations were conducted. A DOE report on the incident is available.

J. Hill (Los Alamos) presented a review of workover operations at Fenton Hill since the last ISC meeting. The various problems uncovered while attempting to create the interim system were discussed, and possible solutions were identified. Surface-system installation, including the water-storage pond, was essentially complete. I. Matsunaga (NEDO) gave a thorough discussion of the many pressurization experiments that had been conducted. H. Keppler (KFA) presented seismic data collected during those experiments. Keppler cited the close cooperation among Japanese, German, and U.S. scientists in helping to develop a processing technique for locating the acoustic signals. G. Nunz summarized the preliminary operating plan for FY83.

The remainder of the meeting was devoted to discussion of possible extension of the IEA Agreement through FY86 or FY87.

The NEDO delegation believed that the DOE policy statement presented by Bresee would be very helpful to Japan in conducting internal discussions about future cooperation. Both delegations welcomed the DOE statement, and both expressed their intention to consider extending the Agreement.

3.3.2. Seventh ISC Meeting. The seventh meeting of the ISC was convened on July 14, 1983, at the Classic Hotel, Albuquerque, New Mexico. Present were the official members, representing the Contracting Parties,

J. Bresee (DOE), Chairman

K. Esaki (Exec. Director, NEDO, representing Y. Yamashita)

W. P. Grace (DOE)

W. Schloemer (KFA)

and their advisors.

In his opening remarks, Bresee discussed plans for an independent technical review of workover operations at Fenton Hill. He thanked the Contracting Parties for their cooperation with the review: experts from each Contracting Party would be asked to participate.

The proposed agenda was adopted and the minutes of the sixth ISC meeting were approved without modification. Bresee took the opportunity to point out the considerable improvement in the DOE's position on HDR research since the last meeting. The DOE had affirmed its commitment to complete the HDR Program and meet the objectives of the IEA Implementing Agreement. The U.S. Congress had indeed authorized \$7.5 million for HDR research in FY84, and Bresee was confident that an appropriations bill would be signed into law before the end of the fiscal year funding HDR research at the \$7.5 million level.

J. Whetten presented a summary of activities and problems at Fenton Hill since the last meeting. These included repeated pipe failures in EE-2 and EE-3, collapsed liner in EE-3, and problems in repairing the liner. He announced that operations at Fenton Hill had been suspended while plans were formulated to make EE-3 serviceable again. In the meantime, an independent panel of experts was being convened to review plans for repairing EE-3 and completing interim fracture operations. D. Brown elaborated on Whetten's remarks with additional details about activities at Fenton Hill. He emphasized the unexpected behavior of the Phase II reservoir. G. Cocks, Los Alamos, discussed problems created by the large volumes of gas evolving from the Phase II reservoir.

H. Keppler presented the latest analyses of microseismic data from previous fracture experiments. He identified two fracture models: (1) a planar fracture model and (2) a volumetric fracture model. Keppler's results, which included data from HDR experiments in Germany, France, Japan, and the United Kingdom, suggest that most extant HDR reservoirs fit the planar model. Only the Phase II upper reservoir seems to conform to the volumetric model.

I. Matsunaga used a hydrodynamic model to present pressure-flow rate analyses for previous fracturing experiments.

D. Brown reviewed the present condition of EE-3. A scheme for repairing the liner with a cemented-in patch was presented.

P. Franke, Los Alamos, gave the cost-accounting report for FY83 and the projected budget plan for FY84. He pointed to cash-flow problems that had arisen in previous years and are expected to recur in the future. G. Nunz then offered the rationale for continuation and completion of the Project, and concluded with a multiyear plan that would meet the Project's objectives.

Presentation of the plan for future work stimulated discussion about extending the IEA Implementing Agreement. Expiration date of the original Agreement is September 30, 1983. The position of each Contracting Party has been established through previous discussions: (1) DOE proposed a 3-year extension with no change to the main body of the agreement; (2) NEDO favored the DOE proposal but could not yet make a commitment; (3) KFA desired a 2-year extension, all other provisions remaining unchanged.

All parties recognized that the current Project plan would require at least 4 more years to accomplish. But in view of each party's position, they agreed to a formal extension of 2 years. An additional year of cooperative research would be considered in the second year of the extension (i.e., Spring 1985). A statement incorporating these ideas was drafted and circulated at the meeting. The statement was judged acceptable as a basis for further negotiations.

The representatives from both KFA and NEDO requested assurances that their organizations would continue to receive information on the Project after the extended Agreement has terminated. Bresee, speaking for the DOE, indicated that such information would be made available routinely to both parties.

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