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Hot Dry Rock Geothermal Energy Development Program

Annual Report

Fiscal Year 1982

Compiled and Edited by

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HOT DRY ROCK GEOTHERMAL ENERGY DEVELOPMENT PROGRAM
ANNUAL REPORT
FISCAL YEAR 1982

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

ABSTRACT

During Fiscal 1982, emphasis in the Hot Dry Rock Program was on development of methods to produce the hydraulic fractures required to connect the deep, inclined wells of the Phase II system at Fenton Hill. Environmental surveillance, instrument development, laboratory and modeling studies, and other supporting activities were continued as well.

After two unsuccessful attempts to fracture hydraulically through inflatable packers, formation breakdown was produced in an uncased section near the bottom of well EE-2 by pumping water through a cemented-in steel liner. Breakdown occurred at a wellhead pressure of 33.1 MPa and a total of 8539 m³ of water was injected. Mapping of source locations of microseismic events indicated opening of an extensive set of planar features dipping about 40°W, striking about N20°W, and apparently passing beneath the bottom of well EE-3. An attempt was then made to fracture at a higher level where the relative positions of the two wells increased the probability that an inclined fracture would connect them. Pumping through a casing packer into an open-hole section between the casing shoe and a sand plug, breakdown was observed at a wellhead pressure of 31 MPa and 4128 m³ of water were injected. Acoustic mapping indicated opening of two inclined, roughly parallel fracture zones, followed by events distributed throughout a large, roughly ellipsoidal volume. Fault-plane solutions indicated normal faulting in this zone instead of the strike-slip motion that occurred at greater depth, representing a remarkable change in stress condition with depth.

Repeated failures of drill pipe, tubing, couplings, and packers terminated most pumping experiments prematurely. These failures are attributed primarily to stress-corrosion cracking by H₂S in the gases unexpectedly evolved when fracturing operations began. Pending procurement of tubular goods and equipment more resistant to the downhole environment, further attempts to connect the two wells were postponed into FY83.

Important advances were made in thermal protection of downhole instruments, real-time mapping of source locations of microseismic signals, modeling of heat and mass transport, and the mechanics of hydraulic fracturing.

These and other activities in the Hot Dry Rock Program are discussed in this Annual Report for Fiscal Year 1982.

EXECUTIVE SUMMARY

The overall objective of the Hot Dry Rock (HDR) Program is to develop and demonstrate the technology required for commercial-scale extraction of thermal energy from naturally heated crustal rock that contains insufficient free water or steam to be economically productive of usefully hot natural fluids. A method to accomplish this was proposed in 1970 at Los Alamos National Laboratory. It involves the use of hydraulic fracturing to connect two well-bores through the hot rock, and circulation of pressurized water through the resulting fractures to extract heat from the rock and bring it to the surface. Literature, laboratory, and field investigations during 1971 and 1972 indicated that the method was probably feasible and identified an area about 30 km (20 mi) west of Los Alamos that appeared suitable for development of such an energy system. Accordingly, a Hot Dry Rock Geothermal Energy Development Program was formally initiated by the Laboratory in 1973. It has since been sponsored principally by the U.S. Department of Energy (DOE) and its predecessor agencies, with supplementary support since 1980 by agencies of the Governments of Japan and the Federal Republic of Germany.

Under a Program Director at DOE Headquarters in Washington, D.C., the HDR Program is managed by a field office at Los Alamos. Programmatic responsibilities are shared by a Program Manager in the Earth and Space Sciences Division of the Laboratory and an Associate Program Manager in the Energy Technologies Division of the DOE Albuquerque Operations Office (DOE/ALO). Program review and guidance are provided by an International Steering Committee representing the United States, West Germany, and Japan, and by a National HDR Program Development Council composed of representatives of U.S. industry, universities, and government agencies.

After much development of equipment, instruments, and techniques, the pioneering Phase I (Research) HDR System was completed in 1977 at Fenton Hill on the western flank of the Valles Caldera, about 56 km (35 mi) by highway west of Los Alamos. Two wells, EE-1 and GT-2, were connected at a depth of about 2650 m (8700 ft) through hydraulic fractures made in granodiorite at an initial temperature of about 185°C (365°F). After a series of flow tests in 1977 and 1978, the underground system was enlarged in 1979 by additional hydraulic fracturing and flow-tested again, the longest run lasting 9 months.

Heat was extracted from the rock at rates up to 5 MW(t) (17×10^6 Btu/h), most of which was dissipated to the atmosphere through air-cooled heat exchangers. However, a small (60 kVA) experimental binary-cycle electric power plant was also operated intermittently on part of the flow of pressurized hot water. Water quality remained good at less than 0.2% total dissolved solids, water-loss rate diminished with time to less than 8% of the flow rate through the system, and there was no detectable scaling or corrosion of carbon-steel surface equipment or environmental damage from system operation. Because of thermal contraction of the rock as heat was extracted from it, volume of the fracture system increased by about 25% during the 9-month run, with a corresponding increase in effective heat-transfer area.

If it had been located near an urban area, this system could have heated several hundred homes. However, it did not produce heat at a temperature or rate sufficient to support a commercial electrical power plant. To approach more nearly the energy requirements of such a plant, a larger, deeper, hotter Phase II (Engineering) System was designed for construction at Fenton Hill. From temperature gradients and fracturing behavior in the Phase I system, it was estimated that a rock temperature of about 275°C (525°F) would be reached at a vertical depth of 4400 m (14 400 ft) and that hydraulic fractures would be substantially vertical with a roughly northwest-southeast orientation. It was further estimated that, with this bottom-hole temperature, a fracture area of 10^6 m^2 ($11 \times 10^6 \text{ ft}^2$) would produce about 35 MW(t) (120×10^6 Btu/h) at temperatures above 200°C (390°F) for not less than 10 years. It was concluded that hydraulic fractures could be extended upward at least 360 m (1200 ft) from the wellbore. Accordingly, the injection well of the Phase II system, EE-2, was designed to reach 4400-m vertical depth with its bottom 1000 m (3280 ft) inclined at 35° to the vertical in a northeasterly direction — to provide horizontal space for up to about 14 thermally isolated vertical fractures. The production well, EE-3, was to be drilled about 50 m (165 ft) away from EE-2 at the surface and, in its inclined section, was to be about 360 m (1200 ft) vertically above the injection well.

Well EE-2 was completed substantially as planned in May 1980. However, presumably because it was directionally drilled toward a magmatic heat source underlying the Valles Caldera, its bottom-hole temperature was unexpectedly high — about 327°C (620°F). Well EE-3 was completed in August 1981; its inclined section was about 380 m (1250 ft) above EE-2. It was planned that,

during FY82, the two wells would be connected by approximately three parallel, vertical fractures, creating an "interim" system whose thermal output would not exceed the 20 MW(t) (68×10^6 Btu/h) heat-dissipation capacity of the existing Fenton Hill heat exchangers. When the behavior of this system had been thoroughly investigated, it was to be enlarged in FY83 to its final 35 MW(t) configuration by additional hydraulic fracturing.

In preparation for fracturing operations in well EE-2, a cleaning rig was mobilized in November 1981 to remove a coating of "black gunk" that had accumulated on the borehole walls below about 1500 m (5000 ft). It apparently was composed of thermal-degradation products of an organic lubricant added to the drilling fluid, plus entrained particles of rubber from drill-pipe protectors, rock cuttings, and metal particles. Two treatments with a commercial detergent followed by a Hydrojet wash with fresh water removed it and left a clean hole.

To measure formation permeability and examine the uncased sections of the two wellbores for open natural fractures, pressurization tests were run in both holes during January and February 1982. Well EE-2 was found to be extremely tight. In 2.5 h at wellhead pressures up to 14.3 MPa (2070 psi), it lost only about 110 $\pm$ (30 gallons) of water to the reservoir formation. However, when EE-3 was pressurized, some natural feature opened and accepted water readily when wellhead pressure reached 10.2 MPa (1480 psi). No classical breakdown occurred. Repumping and temperature logging indicated that a pre-existing fracture had been reopened against an earth stress of about 36.2 to 41.0 MPa (5250 to 5940 psi), and that it extended downward along the wellbore as much as 73 m (240 ft) from a point about 6 m (20 ft) below the shoe of the well casing. To avoid excessive water loss during operation of a pressurized heat-extraction loop, it will probably be necessary eventually to either plug or bypass this zone.

In April 1982 a large workover drilling rig was mobilized over well EE-2. Its first task was an attempt to recover a Laboratory logging tool that had been left stuck in the hole at 4316 m (14 160 ft) during the January experiments. This was unsuccessful. However, the logging cable was recovered and the tool itself dropped out of the way into the fill at the bottom of the hole. The hole was rabbitted and logged, and lubricity tests were run. Then, in preparation for a hydraulic-fracturing attempt near the bottom of the well, a notch was cut in the borehole wall at a depth of 4611 m (15 128 ft, measured

along its inclined length) using a Hydrojet tool and an abrasive slurry containing 20 to 40 mesh sand. (However, there was no evidence in later experiments that this notch localized or helped to initiate fracturing.)

In the first hydraulic-fracturing attempt in well EE-2, an inflatable packer was set in the open-hole section about 50 m (164 ft) off bottom. After a pumping pressure of 18.6 to 19.3 MPa (2700 to 2800 psi) had been reached, pressure was reduced to 15.5 MPa (2250 psi) to permit replacement of an injection-pressure transducer. During the holding period at that pressure the packer elastomer blew out. A second, similar packer set 2.4 m (8 ft) lower in the hole also blew out, at a pumping pressure of 29.0 MPa (4200 psi), with no clear evidence of fracture initiation, and attempts to fracture through an inflatable packer at this depth and temperature were discontinued. Instead, a 4.5-in.-diam steel liner was inserted approximately 150 m (490 ft) off bottom. At its upper end it terminated in a polished-bore receptacle (PBR) into which a sliding seal, at the end of drill pipe or pressure tubing, could be inserted.

Cement formulations considered suitable for cementing the liner in place were proposed by two service companies and were tested at simulated downhole conditions in a Laboratory autoclave. It was found that the kinetics of setting and curing were sensitive not only to temperature at the time of emplacement but also to the profile of temperature recovery after emplacement. The cement formulation that appeared to behave best under the predicted downhole conditions was based on Class H cement with 40% silica flour. It was further tested by mixing a small batch and pumping it down to the appropriate depth in well EE-2, where it was retained in a section of pipe and allowed to set and cure. Its pumping behavior was satisfactory and, when returned to the surface, its properties were found to be good. This formulation was then used successfully to cement the liner in place.

Pumping water through the liner into the open-hole section below it at 0.90 ℓ /s (14.2 gpm) caused formation breakdown at a pumping pressure of 33.1 MPa (4800 psi). After about 525 m^3 (139 000 gallons) of water had been injected, the experiment was terminated by problems with the commercial pumping equipment. In two more attempts to extend the hydraulic fractures to an intersection with well EE-3, an additional 8014 m^3 (2.117×10^6 gallons) of water were pumped down through the liner, but no connection was achieved. Attempts to complete a connection at this depth were then discontinued because

mapping of the source locations of acoustic signals produced by the fracturing events indicated that the fractures being extended were by-passing well EE-3.

Microseismic signals produced by the hydraulic-fracturing events were detected by a Los Alamos triaxial geophone system stationed at 2926-m (9600-ft) depth in Fenton Hill well EE-1. However, during some periods, information from this unit was supplemented by data from a new accelerometer system stationed at greater depth in well EE-3. Because of electronic and temperature-protection problems with the new instrument package, data collected by it were limited -- but did greatly increase confidence in the source locations derived from geophone data. Signals detected by both instruments were processed on line at Fenton Hill, which permitted mapping of source locations of well-resolved signals within 1/2 h after they occurred.

For the first time at Fenton Hill, these hydraulic-fracturing experiments produced energy releases sufficient so that a number of the microseismic signals could be detected at the earth's surface. They were recorded by a surface array of eight portable seismometers and five permanent stations (which are part of the Laboratory's regional net). All were within a few kilometers of Fenton Hill. Data from them confirmed the source locations determined from signals detected in wells EE-1 and EE-3, and also permitted fault-plane solutions for some of the fracturing events.

After fractures had been opened in the uncased section at the bottom of well EE-2, continued pumping produced microseismic signals whose hypocenters mapped as an inclined feature that surrounded the EE-2 wellbore at a well depth of 4390 m (14 400 ft) and sloped upward toward the east at about 45°. With further injection this sloping feature grew upward, but passed below the bottom of well EE-3. Source locations also extended downward to about 400 m (1300 ft) below the injection interval. With continued pumping a second sloping feature appeared, about 430 m (1400 ft) above the first one and approximately parallel to it, to which the focus of microseismic activity gradually moved. During the final injection, the activity spread throughout an oblate volume, apparently representing opening of an extensive set of planes dipping about 40° to the west and striking about 20° west of north. However, almost none of the acoustic signals originated in the vicinity of well EE-3, and it was concluded that the probability was low that continued fluid injection into this fracture system would produce a hydraulic connection between the two wells. The decision was therefore made to try a different method of zone

isolation at a higher level in well EE-2, where the relative positions of the two wells made it more likely that an inclined fracture extending from EE-2 would, in fact, intersect well EE-3.

For this purpose, a sand and clay plug was emplaced in the lower part of well EE-2, leaving an open-hole interval about 144 m (475 ft) long between the top of the plug and the bottom of the casing. After several unsuccessful attempts, a retrievable casing packer was set within the casing about 73 m (240 ft) above the casing shoe. Upon pumping through it, formation breakdown was observed at a wellhead pressure of about 31 MPa (4500 psi), and 908 m³ (240 000 gallons) of water were injected before failure of the drill pipe terminated the experiment. The first microseismic activity occurred adjacent to the borehole at a well depth of 3538 m (11 610 ft), near the center of the openhole interval. The hypocenters then tended to migrate downward and to the south, occupying a roughly ellipsoidal volume. Pipe failures also terminated two subsequent pumping operations, during which another 3220 m³ (851 000 gallons) of water were injected. A second seismic zone developed generally parallel to the first one and a few hundred meters above it. None of the microseismic events from these fluid injections into the upper zone was sufficiently energetic to be detected at the surface. However, statistical analysis of data from the downhole geophone system suggested that fractures were being opened whose orientations correlated with those of sealed, ancient fractures previously observed in drill cores.

The next pumping operation ended quickly with failure of the casing packer, and the rig was furloughed for 1 month to refurbish and improve the downhole equipment. Attempts to extend this high-level fracture system were resumed in September 1982, and were terminated successively by two more packer failures, a tubing failure, and failure of a tubing coupling. The rig was then furloughed again, pending procurement of downhole equipment more resistant to the aggressive chemical environment, and there were no more attempts during FY82 to complete a connection between the two wells.

In the meantime, engineering design, component purchase, and installation of the surface system for the interim circulation loop have been completed except for short sections around the EE-2 and EE-3 wellheads where piping installation must await release of the drilling rig. A new venting system that provides for separation of contained gas from the fluid has been installed and connected to both wellheads. Preliminary design of the surface system for the

final circulation loop has also been completed. The interim system represents about three-fourths of the final system, and most of the components required for its eventual modification have also been procured.

When hydraulic fractures were created in EE-2, an unexpected result was production of large quantities of gas from the reservoir formation. Most of the gas (90 to 99%) is CO_2 but it contains of the order of 60 ppm H_2S and occasional trace amounts of other species. It presents safety problems because of "kicks" (gas eruptions) during rig and logging operations and the toxicity of H_2S . It is believed that the H_2S is also responsible for the series of stress-corrosion-cracking failures of drill pipe, pressure tubing, and couplings that has repeatedly prevented injection of the large volumes of water required to complete a connection between the wells. All such failures so far investigated have been in high-strength steels with tempered-martensite microstructures, and all appear to have originated at indentations where there has been local cold work by handling in elevators, tongs, and slips.

Fault-plane solutions have been made for some of the larger and better resolved microseismic events that occurred during hydraulic fracturing in well EE-2. First motions of acoustic signals from the two zones fractured were quite different. Those from the lower zone, around 4300 m (14 000 ft), had a strike-slip solution, representing either left-lateral slip on a north-south vertical plane or right-lateral slip on an east-west vertical plane. Those from the upper zone, around 3500 m (11 500 ft), indicated normal faulting on a north-south vertical plane. Because the north-south vertical plane is common to both solutions and also to previous experiments and joint surveys, it is believed to be the one on which motion occurs. However, the change in the sense of that motion indicates a major change in the state of earth stresses over a vertical distance of about 800 m (2600 ft). In the lower zone, the greatest principal earth stress is nearly horizontal, plunging slightly toward the northwest, while the least principal stress is also nearly horizontal, plunging toward the southwest. In contrast, the axis of greatest principal earth stress in the upper zone is more steeply inclined, plunging toward the east at 30 or 40°. This change in orientation occurs in spite of the fact that the overburden stress must increase considerably between the upper and lower zones. Because the well was drilled directionally toward the Valles Caldera, this change in tectonic stress field with depth may be related to a

closer approach to either the caldera rim or the regional heat source under the caldera.

Continued environmental surveillance of the Fenton Hill area has included monitoring of the chemical quality of surface and ground waters in the vicinity. No evidence has been found of changes that could be attributed to Fenton Hill operations or to other geothermal exploration or development in the area.

Two ponds at Fenton Hill — originally mud ponds for drilling operations — are now used to store water for hydraulic fracturing. Occasional discharges from them are monitored in accordance with a National Pollutant Discharge Elimination System (NPDES) permit and requirements of the Environmental Improvement and Oil Conservation Divisions of the State of New Mexico. Vegetation and soil samples, taken at various distances down the canyon from the discharge point over a period of 5 years, have been analyzed and show mixed results. Near the discharge point, boron and lithium show a distinct accumulation pattern in the foliage of grass and small aspen trees, while arsenic in roots and fluoride in the soil show a less-distinct pattern. There has so far been no apparent detrimental effect on the vegetation, or any other detectable environmental damage.

Construction of a 5-million-gallon water storage pond at the edge of the Fenton Hill site was completed in July 1982. The pond is fenced, lined, and covered with reinforced rubber, and connected to the circulation loop through pumps and transfer lines.

Although hydraulic fracturing in the deep zone of well EE-2 has produced microseismic signals that could be detected at the surface with sensitive seismometers, the largest events have been orders of magnitude too small to be felt or to produce damage at the surface. The sources of these microearthquakes have been confined to a region within 900 m (3000 ft) of the fluid-injection zone, and the seismic events die away within a day after injection ceases. They pose no threat to Fenton Hill operations or the environment.

Instruments and electronics developed in the HDR Program have operated reliably in the wells of the Phase I system but have often failed from thermal effects in the hotter Phase II wells. Finite-element thermal analysis of the dewar section of an acoustic tool with a typical thermal-protection system has shown that, during initial exposure to high temperature, the temperature

gradient within the dewar was in the wrong direction — from heat sink to electronics section. With continued exposure the gradient reversed, but remained too low to remove heat effectively from the electronics section. Further, the conductance of the heat-transfer paths was too small to transport the heat efficiently even if there had been a relatively high gradient. These deficiencies have now been corrected by using ice, instead of Woods Metal, in the heat sink and installing small heat pipes to transport the heat from source to sink. The result is an increase of a factor of four in tool-survival time at a given temperature, which allows reasonable time for downhole measurements even in the very hot bottom sections of wells EE-2 and EE-3.

An explosive fracture-initiation tool has been developed that can be used either to initiate fractures from a very hot wellbore or to reduce the near-wellbore flow impedance of existing fractures. It is rated for use at up to 300°C (570°F) and incorporates a thermally protected downhole firing module, a detonator containing 1 g of HNS (hexanitrostilbene) explosive, and a shaped charge of AXF-521, a relatively insensitive, thermally stable explosive.

To investigate rock properties and structure between wellbores, a high-temperature acoustic-transceiver system has been developed in which each of two instrument sondes contains two independent magnetostrictive signal sources that transmit at different frequencies, a piezoelectric receiver, and a crystal transducer for zero-time indication. The system can be operated in several different configurations, but it is usually used to scan a series of overlapping, vertical, triangular sections between the wellbores -- by holding one sonde stationary at a series of positions in one well to receive acoustic signals transmitted by the second sonde moving at constant velocity up or down the other well. The series of overlapping scans then represents a survey of a planar section between the two wells, from which information can be extracted concerning acoustic velocities (and therefore elastic moduli), acoustic attenuation, and crack structure.

For real-time mapping of growing fractures, an on-line system has been developed that accepts analog information from downhole triaxial geophones or accelerometers, digitizes, and records it, selects individual signals with amplitudes above a preselected threshold value, and displays them visually. For each such event, the time difference between arrivals of the P (compressional) and S (shear) waves represents distance from source to receiver, and

polarization of the P-wave first arrival indicates direction. A plot of direction and distance for each of a series of microseismic events then permits size, shape, location, and orientation of a fracture to be observed in real time as it grows.

The Los Alamos wellbore heat-transmission code, used to estimate downhole temperatures under a wide variety of conditions, has been modified to include frictional-heating effects and temperature-dependent thermal conductivities, and now gives an improved match to actual wellbore temperature surveys. It is used to predict temperature as a function of depth in advance of such operations as cementing, packer installation, pumping through prestressed casing, and logging runs with temperature-sensitive commercial tools.

Tensile strengths of the Precambrian rocks that constitute the Phase II thermal reservoir have been measured in the laboratory on core samples from well EE-2. They are surprisingly consistent. All tensile strengths measured were about 18 MPa (2600 psi) except for the metavolcanics at 3916 m (12 850 ft), which were about 29 MPa (4200 psi). The measurements were of course made on competent specimens and do not indicate the effect on strength properties of open or weakly sealed ancient fractures.

Fluid pressures required to initiate fractures in competent, essentially impermeable rock around an inclined wellbore, and the geometries of the fractures produced, are strongly affected by stress concentrations around the wellbore. Those in turn depend on borehole inclination, initial pore-fluid pressure, and magnitude and orientation of the least principal earth stress (S_3) and the intermediate principal stress (S_2). Modeling of the situation of a wellbore inclined at 35° to the vertical in the presence of an initial pore-pressure field equal to $0.7 S_3$ indicated that, when S_2 is in the range $1.21 S_3$ to $1.70 S_3$, hydraulic fracturing should occur when fluid pressure reaches $1.6 S_3$, and the fracture plane should be normal to the wellbore axis. At other ratios of S_2 to S_3 , the initial fracture would probably occur by splitting along the length of the wellbore, which might interfere with zone isolation by packers or other means.

An attempt was made to confirm these predictions in the laboratory by pressurizing small, inclined holes in 15-cm (6-in.) Plexiglas cubes loaded in unequal triaxial compression. Quantitative agreement was not achieved, probably because of small sample size and end effects, but qualitative fracturing behavior was generally that predicted by the analysis.

Further tests were made in Plexiglas cubes by pressurizing inclined holes drilled in the plane containing the S_1 and S_3 stress axes. When S_2 was large relative to S_3 , the hydraulic fractures grew in the plane normal to S_3 — the textbook geometry for which the Fenton Hill Phase II wells were designed. When S_2 was only slightly greater than S_3 , fracture growth was predominantly normal to S_2 . For intermediate cases, the fracture began to grow normal to S_2 but then rotated as it grew to become normal to S_3 . The rate of rotation increased with increasing difference between S_2 and S_3 .

Experiments were also conducted with two holes drilled into the Plexiglas. Pressurizing a wellbore produces a significant increment of compressive stress, but this extends only a few hole diameters into the rock around it. It was therefore no surprise that maintaining fluid pressure in one of the drilled holes had no observable effect on the growth of fractures from the other hole. However, if fluid pressures greater than S_2 could be maintained in a large fracture or joint, this would change the directions and magnitudes of S_2 and S_3 within a significantly large volume of rock, which would alter the course of a fracture growing through that volume. Unfortunately, this is not possible except for very small fractures. In general, fluid pressures greater than S_2 cannot be sustained in the fracture. The fracture simply grows at a rate sufficient to keep fluid pressure within it close to the closure stress, which is less than or equal to S_2 .

Hydraulic fracturing in jointed rock has been simulated with a regular two-dimensional rectangular grid made up of 256 square blocks, each of which can deform, rotate, and slide. Calculations were performed using FRIP (Fluid-Rock Interaction Program), acquired from the British HDR Project, which permits interactive coupling of fluid dynamics with rock stresses and deformations. Computational results indicate that, when joints are aligned parallel to the principal earth stresses, "classical" hydraulic fracturing should occur — a single fracture propagating at a pressure slightly greater than the minimum earth stress. However, if the joints are rotated 30° from the principal-stress axes, either of two types of fracture patterns can form. When resistance to shear slippage is low or shear dilatancy is large, a single fracture should grow along existing joints inclined at 30° to the axis of greatest principal stress, at pressures that (depending on the coefficient of friction) may be less than the minimum earth stress. Alternatively, if shear resistance is high or dilatancy small, multiple shear fracturing should occur,

opening an array of joints in a branching elliptical pattern whose major axis is rotated 15° from the joint direction. This type of behavior, extrapolated to three dimensions, probably explains why the microseismic-source-location maps representing the Phase II hydraulic-fracturing experiments are roughly ellipsoidal volumes, and why the acoustic signals from individual fracturing events have relatively strong shear components.

Using a finite-element-based algorithm to solve the equations for conservation of mass and energy in the flow of a compressed liquid, a modeling study has been made of the effect of non-Darcy flow on the long-term thermal behavior of fractured geothermal reservoirs. In one case examined, for a single fracture in granite, it was shown that non-Darcy flow retarded the buoyancy drop of incoming fluid, which decreased the area of the fracture swept by the fluid. Such effects can be important to long-term heat extraction.

The finite-element heat-and-mass-transport code (FEHM) has been supplemented with the facility for solving the convection-diffusion equation. It is being used to develop type curves for the concentration of a tracer measured in fluid produced from an HDR reservoir after the tracer was added in various modes to the fluid injected into the reservoir. These curves will be used both to facilitate inversion of field data and to gain understanding of such reservoir characteristics as anisotropy and heterogeneity of permeability, multiple flow paths, and flow channeling.

Most previous modeling of Fenton Hill tracer tests has been based on superposition of several solutions for one-dimensional flow conduits, giving sharp concentration peaks for tracer arrival at the production wellhead. However, because of variations in transit times along two-dimensional flow lines in a real fracture, tracer concentration at the production well actually appears to be dispersed. Taking this into account, tracer concentration at the production well has been modeled as a function of time for both continuous and limited-time injection of tracers and for both a finite and an infinite single fracture. One conclusion reached is that modal volume is an excellent measure of the fraction of total fracture volume within which flow distribution is determined principally by well spacing, and therefore is closely related to effective heat-transfer area. (Modal volume is the volume of fluid produced from a fracture after a finite-duration tracer injection and before a maximum is reached in tracer concentration in the outflow from the fracture.)

This provides additional justification for the argument that the heat to be

extracted from a fracture is dependent primarily on inlet-to-outlet spacing rather than actual size of the fracture.

Predictions of the useful lifetimes of HDR heat-extraction systems have so far been based on extrapolations of the rate of temperature decrease of the fluid produced. This is not practical for a reservoir being developed for commercial use because of the very long flow-testing period required to achieve a temperature drawdown great enough to be extrapolated with confidence. It therefore is important that other methods be developed that can evaluate thermal drawdown on the basis of a much shorter test. Two tracer techniques are being investigated for this purpose.

One of these techniques is the use of the silica geothermometer. Fresh water would be pumped into the reservoir through the injection well and held there for a sufficient period for water at each location to become saturated with silica at the temperature of the rock with which it was in contact. Then a reverse flush would force this water back up the injection well, where its silica content would be monitored. Because the rock nearest the injection well should be the coolest in the reservoir, the first water to reach the surface should have the lowest silica content. Thereafter, silica content should increase, representing higher temperatures in more remote regions. For circulation systems more complex than single fractures, additional information about flow paths through the reservoir would be required from well logging and nonreactive tracer tests. Iterative and numerical methods of analyzing the information collected from such experiments are now being developed.

The silica-dissolution method requires a system shutdown and introduces the danger of thermal-expansion damage to the casing of the injection well when hot water is returned through it. A second possible approach, which would avoid these difficulties, is the use of chemically reactive tracers added to fluid being circulated normally through the fracture system. It would rely on the strong temperature-dependence of first-order, liquid-phase, irreversible chemical reactions, and would require use of a suite of tracers whose reactions within the fractures have a variety of activation energies. If suitable reactive tracers can be identified, certain approximations can be made that should make possible quick estimates of thermal drawdown and projected reservoir lifetime.

A stress-deformation analysis has been made of the possibility of hydraulically expanding a ductile metal liner or casing into intimate contact with

the borehole wall instead of cementing it in place. It was concluded that the best liner or casing material for this purpose would have very high elastic modulus and the lowest practical yield strength.

Effort in the areas of resource evaluation and site selection during FY82 has gone largely to completion of projects initiated in previous years. This has resulted in a large number of publications dealing with exploration methods, regional studies, detailed investigations of individual HDR prospect areas, and analysis of the HDR resource base of the conterminous United States. A revision of the conductive-geothermal-gradient map of the United States was published, with many new data.

One new resource-evaluation project was initiated in FY82. In cooperation with Phillips Geothermal Co., a geochemical and hydrologic investigation was undertaken of shallow aquifers in the Milford Valley, west of the Roosevelt Hot Springs hydrothermal area in Utah. Its principal objective is to determine whether or not there is a sufficient fresh-water supply to support operation of a commercial-scale HDR power plant in what has been identified as a particularly promising HDR geothermal area.

Previous economic studies of HDR energy systems have concentrated on their possible use as heat sources for generating electricity. However, their potential usefulness for direct-heat applications is probably equally important. Accordingly, a case study has been made of the economic feasibility of substituting an HDR system for an oil-fired boiler to heat the main base of the National Aeronautics and Space Administration (NASA) Flight Center at Wallops Island, Virginia. Significant cost benefits were found to result from any of several HDR system configurations. A sensitivity analysis showed that where geothermal gradients are greater or depths to basement rock are less than at Wallops Island, net benefits should be even larger.

The International Steering Committee for the Fenton Hill Hot Dry Rock Project met in Washington, D.C., on April 22, 1982, to review the technical and the financial situation of the project.

The Executive Committee of the National Hot Dry Rock Program Development Council met in Albuquerque, New Mexico, on April 2, 1982, to review the progress and plans of the HDR Program.

On June 21-24, 1982, an HDR-Exploration Workshop was held in Los Alamos. It brought together subcontractors and researchers from throughout the United

States who have been involved with, or are simply interested in, HDR exploration techniques.

A list of publications and presentations is presented in the Appendix.

1.0. INTRODUCTION

1.1. The HDR Concept and Program

The overall objective of the HDR Program is to develop and demonstrate the technology required for the commercial extraction of energy from xero-lithic geothermal sources -- hot rock formations that contain insufficient natural geofluid for economic production and are popularly called "hot dry rock." The HDR heat-energy extraction technique conceived at the Los Alamos National Laboratory, conceptually illustrated by Fig. 1, involves artificial introduction of water into, and closed-loop circulation through, a man-made geothermal reservoir created by hydraulic fracturing at depth of the hot, low-permeability rock between two boreholes. The system is maintained under sufficient pressure to assure production of superheated liquid water, rather than steam. The usable energy is extracted by one or more heat exchanger(s) in the surface loop and transferred to a working fluid that delivers the heat energy to its end application(s).

1.2. Synopsis of the HDR Program Through FY81

The HDR concept originated at the Los Alamos National Laboratory in 1970. During 1971, the available information on the equipment and techniques required to create such a system was collected, together with existing data on the geology, hydrology, and heat flow in the vicinity of the Valles Caldera -- an area of geologically recent volcanism just west of Los Alamos, New Mexico. Under sponsorship of the U.S. Atomic Energy Commission, the area was further investigated, and in 1972 a slim exploratory hole (GT-1) was drilled in Barley Canyon, on the western volcanic apron of the caldera. Its depth was 785 m (2576 ft) and it penetrated 143 m (469 ft) into the Precambrian granitic basement. Bottom-hole temperature was 100.4°C. Experiments conducted in it during 1973 demonstrated that the basement rock could be fractured hydraulically at moderate pumping pressures and that its permeability was low enough to contain pressurized water with a very low leak-off rate.

Fig. 1.
HDR concept.

During 1974, a second exploratory hole (GT-2) was drilled at Fenton Hill, about 2.5 km (1.5 mi) south of GT-1. Its bottom-hole temperature was 197°C at a depth of 2929 m (9610 ft). Experiments in it also confirmed that the basement rock could be fractured hydraulically at moderate pumping pressures and had very low permeability.

Under sponsorship of the U.S. Energy Research and Development Administration, a second hole (EE-1) was directionally drilled at Fenton Hill in 1975. It bottomed at 3064 m (10 053 ft) where the rock temperature was 205°C, but it did not intersect the GT-2 fracture system as was intended. However, another hydraulic fracture made from EE-1 did permit enough flow through the intervening rock so that useful flow experiments were possible. During 1976, while these experiments were in progress, equipment and techniques were developed to determine more precisely the relative positions of the boreholes and fracture systems. With this information, the bottom section of GT-2 was redrilled twice during 1977. The first redrilling reduced flow impedance between the two wells significantly and the second reduced it still further, to the point where a useful heat-extraction experiment appeared possible. Equipment was therefore installed to connect the two wells at the surface through a heat-exchange system that would extract the heat from the pressurized superheated water and dissipate it to the atmosphere. This Research (Phase I) System was, then, a closed loop consisting of an injection well, EE-1; a system of hydraulic fractures at a depth around 2650 m (8700 ft); a production well, GT-2; and a pair of forced-draft, air-cooled, heat exchangers.

With some temporary components, the Phase I system was successfully flow-tested in a 4-day run at the end of FY78, during which the temperature of the produced fluid reached 130°C and the rate of heat extraction rose to 3.2 MW(t). After completion of the more permanent surface system, a 75-day flow test was conducted in FY79. A series of experiments indicated that the effective heat-transfer area of the fracture system was equivalent to that of a circular hydraulic fracture with an effective area of about 8000 m² (86 000 ft²). Downhole flow impedance decreased throughout the test so that, with an essentially constant pressure difference between the two wells, flow rate through the system increased continuously to the maximum that the surface piping could accommodate (about 17 m³/s, or 270 gpm). Because this rate was high relative to the heat-transfer area exposed in the fracture system, the system cooled rapidly and the water produced approached a nearly constant

temperature of 87°C at the end of the test. However, the increase in flow rate more than compensated for this, so that rate of heat extraction rose steadily to about 5 MW(t) and then, with reduced flow, remained nearly constant between 4 and 5 MW(t). Rate of water loss decreased with time, to about 1.5% of the flow rate through the system, and water quality remained good at <2000-ppm total dissolved solids. No induced seismicity or other significant environmental effects were observed at the surface.

Subsequently, a 38-day flow test was run with relatively high back pressure on the production well to increase fluid pressure throughout the underground loop. It was terminated prematurely by deterioration of cement around the casing of the injection well. However, it demonstrated a further significant decrease in flow impedance from pressurization of the entire fracture system.

Recementing of the EE-1 casing was accomplished during FY79, together with intentional sealing of the main entry from the well into the fracture system, which was behind the casing. Fluid pressure in EE-1 was then used to extend a hydraulic fracture previously initiated in the open-hole section below the casing. This fracture propagated upward into the complex fracture system from which heat had been extracted in earlier experiments. However, it permitted fluid injection from EE-1 into essentially uncooled rock at a point about 200 m (650 ft) lower than the main entry point of the original system. Intensive investigation and extended flow testing of this enlarged Phase I heat-extraction system was a major activity at Fenton Hill during FY80 and FY81. In Run Segment 4, a 23-day recirculating flow experiment conducted in October and November 1979, heat was extracted at an average rate of 3 MW(t) and the general behavior of the system was observed. Because no measurable temperature drawdown occurred during this experiment, a longer test — Run Segment 5 — was initiated in March 1980 and continued into FY81 over a period of 288 days. This experiment, which completed testing of the Phase I system, was of sufficient duration to produce measurable thermal drawdown and demonstrated that the enlarged research reservoir now provided an effective heat-transfer area of about 50 000 m² (representing fracture cross-sectional area — or that of one side of the fracture only).

An electric-power generation experiment was conducted as part of the Phase I Run Segment 5. In May 1980, a skid-mounted binary-cycle electrical generator was installed on a bypass line in the Phase I surface system at

Fenton Hill. Heat from about 3 kg/s of geothermal fluid at 132°C was used to boil Freon R-114, whose vapor drove a turboalternator. Air-cooled heat exchangers were used throughout. The unit was operated only intermittently, but during operating periods it reached its full-rated capacity of 60 kVA and slightly exceeded its overall design-cycle efficiency of 5.7%. The power produced was actually used on site to partially offset facility demand. It is currently on standby pending completion of the Phase II system discussed below, which is expected to produce significantly higher fluid temperatures and correspondingly higher generating efficiencies.

While testing of the Research System was being completed, planning proceeded for the construction and operation of a larger, higher temperature, Engineering (Phase II) System. This phase of work is dedicated to development of commercially usable technology for creation, control, and useful-life assessment of an HDR reservoir more nearly representative of an industrial application. The Phase II system consists of two new wells, EE-2 and EE-3, to access a multiply-fractured reservoir region in 300°C rock that will be created in two stages: an interim configuration and the final configuration. The latter will be designed to produce a nominal 35 MW(t) with not more than 20% drawdown in 10 years.

Drilling the first well, EE-2 — the Phase II injection well — began at Fenton Hill in April 1979 and was completed in May 1980 at a vertical depth of about 4400 m (14 400 ft) and a rock temperature of about 320°C. Drilling of the production well (EE-3) began in May 1980 and was completed to a depth of 4000 m (13 000 ft) in August 1981.

Progress of the Los Alamos National Laboratory HDR Project was sufficiently encouraging so that, at the beginning of FY79, the Division of Geothermal Energy* of the DOE formally established a nationwide HDR Geothermal Energy Development Program based at Los Alamos, New Mexico. Under a Program Director at DOE Headquarters, this broadened program is managed from a Program Office at Los Alamos National Laboratory by a Program Manager based there, together with an Associate Program Manager from DOE/ALO. During FY81, and continuing into FY82, the major Program activities other than the Fenton Hill Project comprised: identification and preliminary characterization of other HDR areas that appeared particularly suitable for future HDR development; evaluation of

*Now the Division of Geothermal and Hydropower Technologies.

the HDR resource underlying the contiguous United States; and investigations of the legal, regulatory, environmental, economic, and other institutional factors that would affect development of HDR systems throughout the U.S.

Under an International Energy Agency (IEA) agreement, direct participation in the Fenton Hill Project by KFA-Jülich, the energy research agency of the Federal Republic of Germany, and by NEDO, the New Energy Development Organization of the Government of Japan, began in FY80. This involves partial financial support of the Project, participation in its planning and management, and assignment of West German and Japanese scientists to work as project staff. Cooperation with ENEL, the Italian National Energy Agency, continued under a bilateral agreement, as did informal cooperation and coordination with individuals and organizations from several other countries.

1.3 Objectives for FY82

The specific programmatic objectives for FY82, by program element, were as follows.

TECHNOLOGY DEVELOPMENT

FENTON HILL PROJECT

- Preliminary surveys and pressurization experiments to be completed in the Phase II wells preparatory to fracturing.
- Interconnection of the EE-2 and EE-3 wellbores with an initial set of fractures, thereby creating the interim Engineering (Phase II) Reservoir.
- Installation of the Fenton Hill Phase II interim surface system.
- Completion of construction, and filling, of the 5-million-gallon Fenton Hill storage pond to meet the requirements of the Phase II system.
- Continued geochemical analyses, seismic monitoring, analytical modeling, laboratory experimentation, and field support of the Phase II system.
- Continued environmental monitoring of the Fenton Hill site and its environs.
- Continued instrumentation support and development.

RESOURCE EVALUATION

DATA GATHERING AND ANALYSIS

- Complete gathering of existing geophysical/geologic data used for regional and national evaluations.
- Continue assembling geothermal gradient data from wells throughout the conterminous U.S. and issue a second-edition geothermal gradient map of the U.S.
- Complete the midcontinent investigation of new and existing HDR-related geothermal-anomaly data between the Rocky Mountains and the Appalachians.
- Wrap up the evaluation of geophysical techniques for HDR resource exploration.

SITE CHARACTERIZATION

- Complete the case study and final report on the Mountain Home (Idaho) prospect.
- Complete heat-flow/thermal-gradient measurements and analysis of geologic/geophysical data for the Conway Granite (White Mountains, New Hampshire) prospect.
- Complete preliminary evaluation of geologic/geophysical data at the Clear Lake (California), Salton Trough (California), and Dixie Valley (Nevada) prospects.
- Perform a hydrologic study of the vicinity of a well-of-opportunity in the Roosevelt Hot Springs area.

COMMERCIAL FEASIBILITY ASSESSMENT

- The technical feasibility of producing thermal energy from HDR and converting it to electrical energy has been demonstrated in the Phase I system. Assessment of commercial feasibility will continue through the establishment of the interim Phase II reservoir and through internal economic studies, including a case study in FY82 of a space-heating application at Wallops Island, Virginia.

2.0. RESOURCE EVALUATION AND SITE SELECTION

This part of the HDR Program was reduced drastically in manpower and funding from previous years. Thus, most effort was expended in finishing pre-existing projects. The only new project initiated in FY82 was a geochemical and hydrologic investigation at the Roosevelt Hot Springs HDR prospect, Utah.

2.1. Data Gathering and Analysis

The object of this task has been evaluation of the HDR resource base of the conterminous U.S. through work by in-house researchers at Los Alamos and through Laboratory subcontractors. No new work was initiated in FY82 and, because of lack of manpower, the existing FY80 estimate of the HDR resource base to a depth of 10 km stands at 5.9×10^6 quads for the conterminous U.S.^{1,2} No refinement of this estimate is currently planned.

2.1.1. Review of HDR Geothermal Resource. An in-depth analysis of the HDR geothermal resource in the conterminous U.S. was published in FY82.² The report breaks the country into six subareas (Fig. 2), discusses the geologic and geophysical aspects of various tectonic provinces that are important for HDR exploration, and evaluates those HDR prospects for which we have sufficient data. Additional sections discuss the magnetotelluric exploration work conducted in Arizona-New Mexico and the first Los Alamos geothermal gradient map of the U.S.

2.1.2. Geothermal Gradient Map. A revised version of the geothermal gradient map of the U.S. exclusive of Alaska and Hawaii was published.³ This second edition presents a compilation of over 1700 wells that have been measured for temperature below 50 m (360 ft) and whose temperature/depth profiles are linear, or composed of linear segments. The data are displayed at an enlarged scale of 1:2 500 000 and in a new color-coded format showing location, depth, and gradient of each well. Over 200 references are also included. The proof-copy of the map, published in cooperation with the National Oceanic and Atmospheric Administration, was presented at the Geothermal Resources Council Annual Meeting in San Diego, California (October 1982) with enthusiastic response.

2.1.3. Subcontractor Projects. The existing subcontract with Purdue University to define the HDR resource in the midcontinent region of the U.S. was still not complete at the end of FY82, and the contract was extended to

Fig. 2.
Regions established for evaluation of the hot dry rock geothermal resource.

March 1, 1983. A concise review of this project was presented in the FY81 annual report.⁴

No new heat-flow measurements were obtained by Los Alamos or its subcontractors in FY82 although final reports on geothermal gradients and heat flow were published on previous work in Ohio-Pennsylvania,⁵ the Gulf Coastal Plain,^{6,7} and West Virginia.⁸ A detailed investigation of heat flow and radioactivity in New Hampshire was recently published using some data funded by Los Alamos.⁹

A final technical report was submitted on the flame-jet drilling techniques used to drill heat-flow holes in the White Mountains of New Hampshire.¹⁰ A 3.15- to 3.95-cm hole (8 to 10 in.) was drilled to a depth of 334 m (1096 ft) in Conway Granite at the Coleman Quarry, New Hampshire. Drilling rates varied from about 6 to 30 m/h. The resulting hole was used to measure thermal gradient by Simmons and co-workers of the Massachusetts Institute of Technology, who also collected cuttings to determine thermal conductivity of the granite. The resulting heat-flow data will be combined into a Laboratory report with other heat-flow values obtained by Simmons in the New Hampshire-Vermont region.

2.2. Geophysical Methods for HDR Exploration

This task was designed to develop techniques that can be used to evaluate the HDR resource and to find HDR prospects. Research efforts during 1982 were concentrated on two-dimensional modeling and interpretation of the magnetotelluric data collected in Arizona and New Mexico from previous contracts. Highlights of this work include three completed east-west, two-dimensional electrical models across the Rio Grande Rift and Jemez lineament.¹¹⁻¹³ These models indicate that the Jemez lineament represents both a structural and a thermal crustal boundary. Two north-south, two-dimensional electrical models across the southern boundary of the Colorado Plateau in Arizona have been completed. These models indicate that the southern boundary of the Colorado Plateau is marked by an intense, deep, crustal fracture zone. The existence of this zone of crustal weakness, when coupled with the recently collected stress data of Aldrich and Laughlin¹⁴ and the previous Rio Grande Rift lithosphere-thinning studies of Ander,¹⁵ has led us to propose an active model of rifting for the Rio Grande Rift. Refinements of the two-dimensional models will continue as the modeling code is brought up on the Cray computer and will result in additional two-dimensional modeling profiles in Arizona.

Other research efforts were concentrated on correlating crustal electrical conductivity with the thermal state of the crust. In a global study^{16,17} we found a strong direct correlation between surface heat flow and electrical conductivity within the crust. We also discovered that the presence of 0.01 to 0.1% free water in fracture porosity must be present in the crust. In a separate study¹⁸ at the University of Texas, we found a strong direct correlation between estimated depth to Curie point obtained from aeromagnetic data and the indicated depth to the pervasive, lateral, deep-crustal electrical conductor. This correlation also infers the presence of from 0.01 to 0.1% free water within the crust. This research is also being continued.

2.3. HDR Geothermal Exploration Workshop.

An HDR exploration workshop was held in Los Alamos from 21 to 23 June 1982 that brought together various subcontractors and researchers from throughout the U.S. who have been involved in or are interested in HDR exploration techniques.

2.4. Site Characterization

This task attempts to evaluate HDR prospects and to determine exploration methods that will eventually pick HDR Site 2. Brief summaries of various HDR prospects throughout the country were presented in the FY81 annual report.⁴ More detailed evaluations of these sites are given in the comprehensive report on the HDR geothermal resource mentioned above or in reports specific to various areas.² No work was initiated on any new prospects in FY82. However, an investigation of the hydrology and geochemistry of shallow aquifers at the Roosevelt Hot Springs HDR prospect was initiated and this project will continue through at least FY83.

2.4.1. Comparison of HDR Prospects. A brief report on geologic and geophysical characteristics, depths to reservoir rocks, and depths to optimal HDR reservoirs (at 200°C) for 24 HDR prospects was published by Goff et al.¹⁹ These authors also discuss some of the additional criteria and considerations that must go into the choice of Site 2, such as type of reservoir rock, availability of water, optimum operating temperature, etc.

A more comprehensive report on this subject discusses candidate sites for HDR development in the U.S.²⁰ The geology and geophysics of the Fenton Hill site is reviewed because this region may be considered an ideal HDR prospect. Three other valuable prospects are then described: The Geysers-Clear Lake region in California, the Roosevelt Hot Springs area in Utah, and the White Mountains region in New Hampshire. These areas are singled out to illustrate the roles of significantly different geology and geophysics, reservoir rocks, and reservoir heat contents in possible HDR developments.

Cross sections of the three areas appear in Figs. 3, 4, 5, and 6 while important geologic and geophysical data appear in Table I. To make rough estimates of reservoir heat contents in rectangular prisms of rock for each area, the heat content, Q , was calculated using a simplified form of the following expression:

$$Q = cA \int_{x_1}^{x_2} T(x) dx \quad . \quad (1)$$

Here, A is the area of each section perpendicular to the length of the prism, c is the volumetric specific heat, and x_1 and x_2 are the depths to the bottom

Fig. 3.
Stylized cross section of The Geysers-Clear Lake region (modified from McLaughlin).²²

Fig. 4.
Cross section of Roosevelt Hot Springs area (modified from Nielson and Sibbitt).²³
The region of hot dry rock interest lies west of the Opal Mound Fault.

Fig. 5.

Generalized geologic map of larger rock masses of the White Mountain Batholith together with generalized geology of bordering units. After Creasy²⁴ and Osbert et al.²⁵ Line A-A' is approximate location of section through three-dimensional gravity model of eastern part of the batholith (see Fig. 6).

Fig. 6.

Section through three-dimensional gravimetric model of the eastern part of the White Mountain Matholith modified from Osberg et al.²⁵ Approximate location of section is shown in Fig. 5.

TABLE I
GEOLOGIC AND GEOPHYSICAL CHARACTERISTICS OF FOUR HDR PROSPECTS COMPARED IN TEXT

Prospect	Geothermal Regime ^a	Province and/or General Geology	Type of Reservoir Rock	Age (if known); Formation	b		c	
					Grad. (°C/km)	Depth (km)	Temperature °C (2 km) (5 km)	
Valles Caldera, New Mexico; Fenton Hill area	YI	Junction Rio Grande rift and Jemez Lineament; silicic caldera, age:	Plutonic and Metamorphic 1.4-0.05 Myr.	Precambrian	60	≥3	≈150	≥300
Clear Lake Region, California	YI	California Coast Ranges east of San Andreas transform zone; Clear Lake Volcanic field, age: 2.0-0.01 Myr	Metasediments and Greenstone	Franciscan Assemblage; Mesozoic	≈80	≥2	≈200	≥350
Roosevelt Hot Spgs, Utah	TT(YI)	Boundary Basin and Range and Colorado Plateau; rhyolitic volcanism, age: 0.8-0.5 Myr	Plutonic and Metamorphic	Mineral Mtns. Pluton, Tertiary; Precambrian gneiss	55-60	>2	≈180	>300
White Mountains, New Hampshire	CR	White Mountains intrusive series bordered by pelitic metasediments	Plutonic and Metamorphic	Conway Granite, Jurassic; Littleton Fm., Devonian	25-27	≥7	≈60	≈130

^a Abbreviations for nature of geothermal regime: YI refers to young igneous heat source associated with Quaternary volcanic field; TT to thermal anomaly in region characterized by young tectonic activity and perhaps lithospheric extension; CR to pre-Quaternary terrane with heat flow from crustal radioactivity and other sources in relatively stable lithosphere. Symbols for other aspects of a regime are in parentheses.

^b Conductive gradient in deeper impermeable zone, if known; otherwise estimated from shallow thermal-gradient boreholes.

^c Minimum depth required to establish high-temperature HDR reservoir (not depth to crystalline and/or impermeable basement rocks).

and top, respectively, of the prism. $T(x)$ is the temperature as a function of x (depth) in the prism. For convenience and because we are mainly interested in first-order comparisons, A was taken to be 10^{11} cm^2 (10 km^2) and $T(x)$ was set equal to the average temperature ($\bar{T}$) of the prism. The depths x_1 and x_2 were taken from Table I as were the temperatures used for calculations of average values. Specific heat c was set equal to $0.6 \text{ cal/cm}^3 - ^\circ\text{C}$, a commonly accepted value for crystalline rocks in the crust.²¹

The basic parameters and calculated results for the four localities are listed in Table II. These data suggest that the localities with Quaternary volcanic rocks generally contain more heat per unit surface area, despite the fact that the lengths of the assumed prisms are not the same for all of the systems. The actual amounts of heat stored beneath some of the prospects may be very large; for example, calculations with $A = 5 \times 10^{11} \text{ cm}^2$ (50 km^2) yield 115 and $83 \times 10^{18} \text{ J}$, respectively, for the Clear Lake and Roosevelt Hot Springs areas ($10^{18} \text{ J} \approx 1 \text{ quad}$). Inasmuch as the total energy consumption of the U.S. is currently about $80 \times 10^{18} \text{ J}$ per year, it is clear that efficient HDR installations at these and other prospects listed in Table I could supply a significant fraction of the energy requirements for the U.S.

The Geysers-Clear Lake geothermal region is associated with silicic volcanic rocks of Quaternary age. We estimate that there are $23\text{--}24 \times 10^{18} \text{ J}$ of heat in a 2-km-deep, $30\text{--}km^3$ prism of rock below the Clear Lake area, if the mass has a surface area of 10 km^2 and an average temperature of 325°C (Table II). This is a very conservative estimate of the actual amount of subsurface heat in the region because dry exploration holes with high temperatures are distributed over an area of at least 300 km^2 , and there is evidence for impermeable units at depth in areas bordering the steam field at The Geysers. For example, at least $700 \times 10^{18} \text{ J}$ of heat could exist in the subsurface, if it is assumed that a $500\text{--}km^2$ area in the region is underlain by rocks at a mean temperature of $\sim 200^\circ\text{C}$ between 2 and 5 km. In spite of these rather impressive estimates, the greatest uncertainty to HDR development in the Clear Lake region is ability to use Mesozoic basement, greywackes, and greenstones primarily, as reservoir rocks. Until successful hydraulic-fracturing experiments have been carried out in these rocks, HDR development in the region is speculative.

By comparison, the Roosevelt Hot Springs geothermal region lies on the eastern margin of the Great Basin, a large region of elevated heat flow. We

TABLE II
ESTIMATES OF HEAT BENEATH 10 km² AREAS AT THE PROTOTYPE HDR SITE AT FENTON HILL
IN NEW MEXICO AND THREE OTHER SELECTED PROSPECTS

	^a Geothermal Regime	Minimum Temperature of Reservoir (Electrical), °C	^b T, °C	^b x ₁ , km	^b x ₂ , km	^b Q, 10 ¹⁸ J
Valles Caldera, New Mexico; Fenton Hill area	YI	200	265	5	3	12.6
Clear Lake region, California	YI	200	325	5	2	23.2
Roosevelt Hot Spgs, Utah; Milford Valley	TT(YI)	200	265	5	2.3	17.0
White Mountains, New Hampshire; Conway Granite	CR	150	185	8	5.7	10.0

^a Symbols same as in Table I.

^b Values directly follow temperature data in Table I for the assumption that electricity may be produced at reasonable depths.

calculate that there is about 17×10^{18} J of heat in a 2.3-km-deep, 27-km^3 volume of rock beneath the Roosevelt Hot Springs-Milford Valley area, if the average temperature of the mass is taken to be 265°C and if the area of the upper surface of the prism is 10 km^2 (Table II). East²⁶ conservatively estimates, however, that the HDR prospect area in Milford Valley could be 160 km^2 ; therefore, some 250×10^{18} J of stored heat could exist below this region. East's data also imply that the area with HDR potential is about 8 times larger than that underlain by known hydrothermal resources.

The Roosevelt Hot Springs area has many characteristics that make near-term HDR development feasible. The subsurface temperatures are adequate for generation of electricity, and technology exists to drill and hydraulically-fracture the crystalline reservoir rocks. HDR-based electricity also could be channeled into existing power lines because a 20 MW(e) plant is planned for the area. Finally, leasing might not be extremely competitive because most of the current interest focuses on the water-dominated systems, with the number of producers being small. The availability of water for HDR development in the area is one issue that is not addressed herein because agricultural interests around the nearby town of Milford may compete for potable water. Environmental and civil issues are not expected to be insurmountable obstacles because the area is remote and essentially a desert.

The regional geology and geophysics (horst-graben structure, young igneous rocks, high heat flow, etc.) of this prospect are very similar to those of other localities in the Basin and Range. A successful HDR system in the Roosevelt area could therefore serve as a prototype for other installations in similar parts of the western Great Basin.

In contrast to the preceeding two areas, which are associated with Quaternary volcanism and tectonics, the White Mountains Batholith is composed of many crystalline intrusions of Mesozoic age. From analysis of thermal gradients, radiogenic heat, and thermal conductivities of the rocks, we estimate that 185°C is a reasonable upper bound for the mean temperature of a 2- to 3-km-thick prism of rock that is centered near 7 km below the White Mountains, much deeper than any geothermal well yet drilled. The amount of heat in a 20- to 25-km^3 volume of rock in this depth interval would be about 10.0×10^{18} J (Table II). This simple calculation suggests that very deep and thus costly drilling would be needed if an HDR heat-extraction system were used to develop electrical power using high-temperature fluids at this depth

here and perhaps in other currently known prospects in the eastern United States.

The successful fracturing of Precambrian granodiorite at Fenton Hill in New Mexico implies that HDR reservoirs could be readily established in the plutonic members of the White Mountain magma series. From gravity and geothermal data, however, some of the plutons are only 2-3 km thick and reservoir rocks at temperatures of 150-200°C could be 6-7 km deep. Thus one possibility in HDR development in the White Mountains is that high-temperature reservoirs might have to be created at great depth in foliated and distorted schists and gneisses in the Littleton Formation or perhaps in underlying metamorphosed units in the Amonoosuc Volcanics.

2.4.2. Mountain Home HDR Prospect, Idaho. A final report on the Mountain Home HDR prospect in the northern Snake River Plain, Idaho, was published in FY82.²⁷ This prospect, which was the focus of a comprehensive case study, was summarized in Ref. 4. A brief report by Arney²⁸ summarizes evidence of previous higher temperatures in rock formations penetrated by the Bostic 1-A geothermal well. According to Arney, alteration-mineral assemblages (which include epidote) in the silicic Idavada volcanics indicate an original temperature of 250 to 300°C whereas the bottom-hole temperature at 2980 m is approximately 200°C. More detailed work on the cuttings from this well is still in progress as is a report comparing surface outcrops and volcanic style of Idavada volcanics in the Mt. Bennett Hills (north edge of prospect) with equivalent rocks in the Bostic well.

2.4.3. Western Nebraska HDR Prospect. A Seasat satellite investigation was conducted on the Western Nebraska HDR prospect to delineate lineaments and other structures that might have influence on evaluation of geothermal resources.²⁹ Although it is stressed that Seasat should be combined with other geologic and geophysical methods, two areas with HDR potential were delineated for additional study and Seasat proved to be a useful tool in interpretation of regional structure in areas having little topographic relief.

2.4.4. Roosevelt Hot Springs HDR Prospect, Utah. A detailed report is in progress on the lithology, down-hole geophysics, and seismic structure surrounding the Acord I-26 hot dry well located 8 km west of the hydrothermal zone at Roosevelt Hot Springs, Utah. The report, done in cooperation with MCR Geothermal Corp., who drilled the well, should provide information on the typical drilling conditions, structure, and temperatures expected at this HDR

prospect. Temperatures reached 230°C at 3855 m in Tertiary granite and Precambrian gneiss. One objective of the report is to suggest a means of using the well in a future HDR system. Other hot dry wells are known in the HDR prospect area as discussed previously by East²⁶ and by Goff and Decker.²⁰

A new project was initiated in May FY82 to investigate the hydrology and geochemistry of shallow aquifers in the Roosevelt Hot Springs area. The object of this study is to see if enough resources exist of cold fresh water in shallow alluvium to circulate in an HDR energy-extraction systems of 50 MW(e) or more. The initial phase of this project, done in cooperation with Phillips Geothermal Co., consisted of sampling 20 springs and wells in the area to obtain data on chemistry and the ²H, ³H, and ¹⁸O isotopes of the waters. From this information, two wells have been picked in the HDR prospect area west of the Opal Mound Fault (Fig. 4) to see how much water they can produce from shallow horizons. In Phase II, a subcontract is being prepared to pump test one or both of these wells and to record geochemical changes during the test. The chemical and isotopic data obtained above are being used to model the shallow hydrology.

It is hoped that a large supply of circulating water will be defined that is useful for future HDR systems but does not compete with agricultural interests in Milford, Utah. This project will continue at least through FY83.

2.5. Wells of Opportunity

This task seeks to extend the HDR program into wells of varied rock types, tectonic settings, and thermal regimes by taking advantage of suitable "wells of opportunity." Due to lack of funds, no wells of this type were entered by Los Alamos in FY82 to perform fracturing experiments or to measure other geophysical properties.

3.0. TECHNOLOGY DEVELOPMENT

3.1. Interim System Wellbore Cleaning

Residue left in the EE-2 wellbore after the drilling rig had moved consisted of a black, amorphous, gummy material, termed "black gunk," that coated the sides of the hole below about 1500 m (5000 ft). This tenacious substance, which coated and clogged logging tools, was apparently composed of degradation products from Torq-Trim (a lubricity agent used extensively during drilling to

prevent high torque of the drilling string), from ground-up rubber drill pipe protectors, rock cuttings, and metal particles. Besides being troublesome for logging and fishing operations, it was feared the gunk would interfere with upcoming fracturing operations and wellbore characterization work.

A cleaning rig was mobilized on site on November 29, 1981, under a contract with CRC-Colorado Well Service, Inc., of Rangely, Colorado. The rig was a mobile unit (CRC No. 68), with a 112-ft, 275 000-lb derrick. A work-string of 10 000 ft of 2-7/8-in., 10.4-ppf, Grade E, and 6000 ft of Grade S-135 American Openhole pipe was used. The pipe was run in to 4617 m (15 146 ft) and a 2% solution of a commercial detergent (Calgon Big Cat) was circulated in the hole for 2 days. The pull required to lift the pipe string decreased from an initial 182 000 lbs to 144 000 lbs as the detergent was circulated. After circulation, the pipe string was pulled out; a thin deposit of gunk coated the pipe between the 915- and 2743-m (3000- and 9000-ft) depths. A second circulation period of 12 h was started after the second trip in the hole, with the pH of the detergent solution adjusted to 12. After the pipe was pulled out, a wireline sampling tool was run in and the hole was determined to be clean. A Hydrojet washing tool was then run in to bottom and the hole volume displaced with fresh water. The pull-out weight on the final trip out was 250 000 lbs. The CRC rig was released after 21 days of operation.

3.2. Interim System Fracturing Plans and Operations

Procurement procedures to obtain a suitable workover rig for use in the EE-2/EE-3 fracturing operations began in January 1982. Evaluation of a number of rigs occurred in February, and on March 17 an award was made to Brinkerhoff-Signal of Denver, Colorado, for their rig No. 78, to begin work in April. The rig consists of a 136-ft derrick, rated for 600 000 lbs hook load, with a 22-ft substructure. It had been designed for geothermal work in Union Oil's nearby Baca field.

During this time, a workover-operations plan was developed to accomplish the following objectives:

- a. Determine equipment/hardware/method required for fracturing.
- b. Create fractures near the bottom of EE-2 that would connect to EE-3.
- c. Measure the initial flow impedance of the fractures.
- d. Map the fractures between the wellbores.

The first step in the plan was the recovery of the ESS-6 gamma logging tool that had become stuck at 14 160 ft in EE-2 on January 28, 1982. A brief summary of rig-related activities is outlined below.

- 4-5 to 4-11 Mobilized Rig No. 78 over EE-2.
- 4-12 to 4-16 Recovered logging-tool wire; tool left at bottom of hole.
- 4-17 to 4-20 Downhole, retrievable, cement test.
- 4-21 to 4-27 Performed lubricity tests; cooled hole; EFI rabbit tests; logging.
- 4-28 to 4-30 Hydrojet notch created at 15 128 ft; cleaned and cooled hole.
- 5-1 to 5-6 Fracturing attempts with Lynes packers.
- 5-7 to 5-10 Cleaned, logged, and cooled hole for cemented-in liner.
- 5-11 to 5-13 Cemented in 4-1/2-in. liner assembly.
- 5-14 to 5-29 Milled out cement, fished out twisted-off pipe.
- 5-30 to 6-2 Fracturing Experiment 2011.
- 6-3 to 6-6 Fracturing Experiment 2012.
- 6-7 to 6-10 Venting; Fracture-Evaluation Experiment 2013.
- 6-10 to 6-15 Logging; Liner-Bypass Experiment 2015.
- 6-16 to 6-19 Venting.
- 6-20 to 6-30 Massive Fracture Experiment 2016; venting.
- 7-1 to 7-5 Set sand plug to 12 000 ft.
- 7-6 to 7-14 Ran Baker packers.
- 7-15 to 7-18 Ran Otis packer.
- 7-19 to 7-28 Fracture Experiments 2018 and 2019.
- 7-29 to 9-18 Rig on standby.
- 9-19 to 10-1 Ran in Baker and Otis packers.

3.3. Environmental Surveillance

3.3.1. Hydrologic Monitoring. The chemical quality of surface and ground waters in the vicinity of Fenton Hill has been determined for use in geohydrologic and environmental studies. Results of past studies and detailed data have been reported elsewhere.³⁰⁻⁴¹

Surface water samples were collected and analyzed from twelve stations on rivers or streams and from two ponds at TA-57. The ponds are used for storage of water that is to be used or has been used in the experimental loop (Table III, Figs. 7 and 8). The spent waters often contain drilling fluids.

TABLE III
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	Ca	Li	Cond (μmho/cm)	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	6-25	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	0.84	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	1.11	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) ^a	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) ^a	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) ^a	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 ^b	6-28	130	25	6	216	1395	0	2200	112	1188	4.7	2.2	5430	88	6.56	40	0.003	9.6	7300	8.2	36
GTP-3	Pond Fenton Hill ^b	6-28	144	47	13	92	495	0	600	89	520	3.9	0.3	2238	172	3.13	13	0.003	4.0	2800	7.7	20

^a Number represents meters below lower Pond (GTP-3) in Lake Fork Canyon.

^b Pond used for drilling fluids and water used in experimental loop.

Fig. 7.
Locations of sampling stations.

Fig. 8.
Locations of sampling stations at La Cueva.

Ground-water samples were collected from four springs, nine wells, a spring-fed tank, and five thermal and mineral springs (Table IV, Figs. 7 and 8).

Since 1974, the annual water quality from the various stations has varied slightly; however, the variations in quality are normal and are caused by seasonal fluctuations. There is no indication of chemical quality of water changes that can be attributed to the HDR or other geothermal development/exploration in the area.

3.3.2. Discharge Monitoring. Discharges from the storage ponds at TA-57 to the environment are authorized by the Environmental Protection Agency (EPA) through a National Pollutant Discharge Elimination System (NPDES) permit. This permit is issued to the Los Alamos Area Office (LAAO) of the DOE. The current NPDES permit was issued effective 15 October 1979 and is scheduled to expire 30 June 1983. A new NPDES permit will be requested in accordance with EPA regulations.

As part of the issuance process, the EPA has requested and received a state certification from the New Mexico Environmental Improvement Division (EID). The permit established daily monitoring, when a discharge occurs, for arsenic, boron, cadmium, fluoride, lithium and pH. The only effluent limitation is that the pH be maintained between 6.0 and 9.0. The EID has also required that discharge activities must cease if the effluent flow reaches the Lake Fork Canyon Road.

In New Mexico the Oil Conservation Division (OCD) is responsible for administering New Mexico ground-water regulations for geothermal operations. Parameters of interest to the OCD include the following: arsenic, barium, cadmium, chromium, cyanide, fluoride, lead, mercury, nitrate, selenium, silver, uranium, and combined radium 226 and radium 228.

A summary of analyses of effluent discharges is presented in Table V.

3.3.3. Biotic and Soil Monitoring. Vegetation and soil samples were taken from the canyon below the holding ponds at Fenton Hill to determine if there was any buildup of arsenic, boron, cadmium, fluoride, or lithium. Samples were taken from the channel at distances of 100, 200, 400, and 1000 m below the effluent discharge point. Controls were taken from the bank of the canyon at the same distances and from the canyon channel far below the point where the effluent discharge sinks into the alluvium.

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	Ca	Li	Cond (μmho/cm)	pH	Temp (°C)
JS-2,3	Jemez Village (Spring)	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 (Spring)	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
JS-1	Jemez Canyon (Hot Spring)	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
JS-5	Jemez Canyon (Hot Spring)	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 Spring)	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 Spring)	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 Spring)	6-29	43	40	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 C.G. (Well)	6-28	56	50	11	3	14	0	148	18	25	0.5	0.6	252	170	0.010	0.1	0.013	0.03	400	7.3	14
Loc. 3	San Antonio C.G. (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	78
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 (Spring)	6-29	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 (Spring)	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	0.04	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	140	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
EFFLUENT DISCHARGES (1982)

	<u>Units</u>	<u>Average</u>	<u>Minimum</u>	<u>Maximum</u>
Flow	gpm	79.0	25.0	100.0
pH	SU		8.0	8.8
TSS	mg/l	161.1	45.0	388.0
SiO ₂	mg/l	88.1	58.1	156.0
Na	mg/l	696.6	490.0	850.0
K	mg/l	45.4	15.0	108.0
TDS	mg/l	3205.2	2275.0	3670.0
TS	mg/l	3366.4	2486.0	3722.0
Mg	mg/l	4.5	2.0	10.0
Fe	mg/l	5.1	1.3	13.4
Cl	mg/l	393.9	90.0	905.0
Ca	mg/l	37.1	31.7	44.0
Al	mg/l	8.4	2.4	25.3
HCO ₃	mg/l	845.7	560.0	1000.0
P	mg/l	1.6	0.3	2.4
Li	mg/l	3.4	0.3	9.3
F	mg/l	2.3	1.2	4.5
SO ₄	mg/l	161.3	71.0	211.0
CO ₃	mg/l	42.9	0	160.0
B	mg/l	10.3	2.3	25.0
Cd	mg/l	1.7	0.0002	23.3
As	mg/l	0.88	0.012	2.5
NO ₃	mg/l	0.31	0.08	0.90
Cr ³	mg/l	0.26	0.005	0.06
Se	mg/l	0.003	0.000002	0.011
CN	mg/l	0.01	0.007	0.016
Ag	mg/l	0.008	0	0.027
Hg	mg/l	0.0005	0.0001	0.0017
Cu	mg/l	0.08	0.02	0.27
Pb	mg/l	0.04	0.002	0.08
Phenols	mg/l	81.5	0.24	343.0
Ba	mg/l	0.91	0.10	2.33
U	mg/l	0	0	0
Mn	mg/l	0.29	0.14	0.52
Zn	mg/l	0.24	0.11	0.45
rRa ₂₂₆	pCi/l	0.20 ± 0.20	0.05 ± 0.01	0.75 ± 1.00

The results obtained to date from 5 years of observation are mixed. Some elements, such as boron and lithium in foliage, show a distinct accumulation pattern. Others, such as arsenic in roots and fluoride in soil, show a less distinct accumulation pattern; and still others, such as cadmium and lithium in soil, show very little pattern at all. These differences in accumulation patterns reflect the different soil physiochemical and plant biophysiological properties of the elements of interest.

Although foliage concentrations of boron and lithium are in the lower end of the potentially toxic range, direct observation of the vegetation (grass and small aspen) growing in the channel shows no apparent detrimental effect from the discharge. Details of this study can be found in Refs. 40 and 42.

3.3.4. Seismic Monitoring. For the first time in the HDR program, microearthquake activity has been detected on the surface seismic network in the immediate vicinity of Fenton Hill. The microearthquakes (local magnitudes between -2 and +1/2) were detected over a relatively large surface area (as far away as 20 km) and were associated with fracture creation attempts in the EE-2/EE-3 well system. This observation is in contrast to previous fracture-creation attempts conducted in the GT-2/EE-1 well system where the microearthquakes produced were very small (less than local magnitude -2) and were only detected downhole on the borehole seismic sensors.

Fracture-creation attempts (experiments numbered 2012 and 2016) near the bottom of the EE-2/EE-3 well system produced microearthquakes that were detectable on the surface seismic network. These increased levels of microearthquake activity may be caused by tectonic-stress release associated with fracture growth during the fracture-creation experiments. The activity is confined to the region near (within 900 m) the fluid injection points and dies away within 12 to 24 h after the cessation of fluid injection.

The magnitudes of these microearthquakes are small and thus pose no threat to the safe operation of the HDR program or the environment. In fact, they have been useful in understanding the state of stress in the deep well-bore region and should assist in reservoir engineering problems. It should be noted, however, that seismic monitoring of the HDR site should continue in the unlikely event that the microearthquakes become large enough in future fracture-creation experiments to pose a potential hazard to the site or surrounding area.

3.4. Interim Surface System

Complete sets of working engineering drawings for both the interim surface system and the final system were completed, and the purchase of all component parts for the interim system, and most of the equipment for the final system, was accomplished. Installation of the interim circulating system was completed, except for small sections around the EE-2 and EE-3 wellheads where drilling equipment interfered with the installation. The electrical distribution for the interim system was completed.

Heat-exchanger plumbing for the interim system was installed, which is about half of the final system. Work on the interim system included installing filters and strainers, five of the seven flow meters, and five of the eight control valves planned for the final system.

A new venting system for the EE-2 and EE-3 wellheads was purchased and installed, as part of the interim loop. The new system allows for two-phase venting, which separates the gas from the fluid, returns the fluid to the circulating system, and dumps the gas into the atmosphere. If necessary, the fluid can be vented to the pond. The new vent system also allows for a more accurate method of gas sampling from the wells.

The circulating system that is to connect EE-2 and EE-3 will be installed after the rig is released from Fenton Hill. The piping for this section, 1000 ft of 6-in.-diam schedule 160 and 180, is to be buried between the two boreholes, connecting the heat exchanger with each. This piping has been purchased and is on site.

3.5. Final Surface System

Design of the final system was completed and a large portion of it (about 75%) was installed as part of the interim system. All of the pipe, flow meters, and central valves for the final system were purchased. Four Meyers 50-gpm supercharger pumps were moved and installed in their new locations upstream from the first-stage pumps for the final system. An electrical system adequate for the final circulating loop was also completed.

3.6. Water Supply and Site Maintenance

New contracts for site maintenance and water hauling were completed with CJC, Inc., a local general contractor, to provide for snow removal, road and building maintenance, and auxiliary water supply. The 100-gpm water-supply

well continued to be a source of dependable water for both the Fenton Hill site and the adjacent Forest Service camp.

Construction for the large storage pond at Fenton Hill began in August of 1981 and continued through to July of 1982. The construction engineers were Smith and Smith of Logan, New Mexico. The design architect was Boyle Engineering Company of Albuquerque, New Mexico. The total construction cost for the pond was \$550 000. This also includes the nearby pumphouse, transfer system between the pond and the HDR circulating system, and the surrounding fence.

The pond holds approximately 5-million gallons when full. It is 200 ft by 250 ft at the surface and slopes to a depth of 23 ft. It is lined with a reinforced (polyester and nylon) rubber. The bottom of the lined pond rests on a sand bedding. The pond has a cover that is made of the same rubber as the lining. The cover floats on the surface of the water with polyurethane pylons. Both the cover and the liner are anchored to the sides of the pond through a buried concrete wall.

The pumphouse next to the pond covers two pumps that transfer the water from the storage pond into the HDR circulating system. The pond and the 40 000-gallon holding tank are connected with a newly installed ductile-iron water pipe (150 psi).

4.0. DOWNHOLE TOOLS AND INSTRUMENTATION

4.1. Thermal-Protection System for Downhole Instruments

The development of an HDR system and of acceptable models for energy extraction from it requires extensive data about water chemistry, acoustic signals, temperature, temperature changes, pressure, and flow rates, at various depths in and between the two wells. The tools and downhole electronics used in making these measurements must withstand the heat and severe mechanical conditions to which they are repeatedly subjected.

Previously, tools and electronics developed in the HDR Program have survived the conditions in the wellbores of the Phase I reservoir, which was about 2930 m deep and had temperatures up to 200°C, but exposure to the higher temperatures and in the more recent deeper wells has caused thermal failure of previously reliable systems.

The two wellbores at the Fenton Hill Site that are being used to develop a commercial-size Phase II reservoir are about 4600 m deep (measured along the wellbores), have a bottom-hole temperature above 320°C and a hydrostatic pressure above 40.3×10^6 Pa. The bottom 1200 m of each wellbore is open hole and is inclined at 35° to the vertical. Because of substances introduced during the drilling process, and subsequent experiments, water chemistry in these wells can vary between neutral, pH = 7, to very basic, pH = 11. Such conditions require downhole electronic tools to be packaged in a pressure vessel that can withstand abrasion from the rough granite and corrosion from the drill-hole water. Each tool must be thermally hardened to survive high temperatures long enough to gather data or make the measurement required. Problems arise when measurements must be made at temperatures above an upper limit of 207°C, which occurs at Fenton Hill well depths greater than about 3000 m. Given an average logging velocity in the open hole, tools must have a minimum thermal life of approximately 4 h in the wells.

The initial thermal-protection design placed the electronics and a heat sink inside a tall, slender dewar that protects the package from conductive and radiative heat transfer. A cutaway illustration of the dewar, electronics, and heat-sink sections is shown in Fig. 9. The sensors, batteries, circuit boards, and other components are mounted on brass rods that are held in place by copper bulkheads. The heat sink is tightly attached to the bulkhead nearest the open end of the dewar. The rods and bulkheads are the only

Fig. 9.

Dewar, electronics, and heat-sink sections of thermal-protection system.

high-conductance heat-transfer paths from the electronics to the heat sink. The heat sink, filled with Woods Metal, is intended to absorb heat from the electronics, melting the Woods Metal at a temperature below the maximum temperature to which electronic components can be reliably exposed. Figure 10 illustrates the temperature history expected during operation. The temperature sensor mounted in the electronics section was expected to show a temperature increase up to the Woods Metal melting point, then a constant temperature while the absorbed heat melts the Woods Metal, then finally another temperature increase after all the heat sink is completely melted.

An instrument tested at 3340-m depth, where the temperature is 220°C, failed thermally after 2-1/3 h. The temperature sensor showed no flattening at 80°C, about 9°C above the Woods Metal melting point.

There were several possible explanations for this: (a) the sensor failed, (b) the heat sink was already melted, (c) the heat-transfer paths available for moving heat from electronics to heat sink were physically too small or their conductance was too small, and (d) the thermal potential between electronics and heat sink was too small or was in the wrong direction. However, examination of the system immediately following the test showed that the heat-sink material was still solid and the sensor was found to be operational and accurate. A choice between the two remaining explanations,

Fig. 10.
Temperature history of heat-sink expected during operation of thermal-protection system.

involved determining the temperature of each subsystem inside the dewar — batteries, heat sink, circuit boards, and stagnant air. This required either a detailed thermal analysis or extensive instrumentation and testing of the system in simulated wellbore conditions.

To deal with these problems, four finite-element thermal analyses have been completed for the dewar section of an acoustical tool with a typical thermal-protection system. The model is a lumped-mass approximation of the real components in each section of the dewar. The analyses include boundary conditions that vary as a function of depth and time and material properties that vary as a function of temperature. Numerical calculations were made using the AYER finite-element heat-conduction code, which solves the generalized two-dimensional heat-conduction equation implicitly. Meshes of the models were constructed using ZONE, a linear finite-element mesher, and input data was prepared using a preprocessor program. The material properties used throughout the analysis are given in Table VI. (A description of the detailed analysis is given in Ref. 43.) Results include heat flux at the tool surface, temperature-time histories of each subsystem, and isotherm-contour plots during the simulation. The analysis showed that the thermal potential between the electronics and the heat sink initially was in the wrong direction and subsequently was too small to remove heat entering the electronics

TABLE VI
MATERIAL PROPERTIES

Material	Density (kg/m^3)	Heat Capacity (J/kg-K)	Conductivity (W/m-K)	Emissivity
Stainless Steel	8171-0.47T	461	16.25	0.1
Brass	8554	571-0.43T	103	
Copper	8940	380	398	
Woods Metal	9400	167.7	18.8	
Bi-Pb Eutectic	10 520	$-128.9+1.22T-1.34 \times 10^{-3}T^2$	$16.85+5.6 \times 10^{-3}T$	
Phenolic	1400	1130	108	
Air	$1.99-2.716 \times 10^{-3}T$	$972.42+0.106T$	$7.43 \times 10^{-2}+6.08 \times 10^{-5}T$	
Equivalent Properties:				
Battery Pack	4611	414	377	
Electronics	13 830	393	214	
Heat-Sink	10 350	$-81.+1.22T-1.34 \times 10^{-3}T^2$	$16.85+5.6 \times 10^{-3}T$	

T = Temperature, K.
Valid for T = 373 to 473 K.

section. Also, the conductance of the available heat-transfer paths from electronics to heat sink was too small to remove that heat efficiently. Significant improvements in survival at high temperatures were achieved by increasing the available thermal capacity of the heat sink, increasing the thermal potential between the heat sink and electronics, and vastly increasing the conductance of the heat-transfer paths.

Without resizing the dewar, the thermal capacity of the heat sink is limited by its volume, and an increase in thermal capacity must be a result of increasing the thermal capacitance and the thermal storage from phase changes of the material. Also, any materials considered must have melting points below 80°C, the maximum temperature that the electronics can tolerate. For each material considered, a calculation was made to determine the enthalpy increase of the solid, energy absorbed in melting, and enthalpy increase of the liquid between the temperature limits of 0°C and 80°C. Material properties and results are listed in Table VII. Ice made from tap water was chosen as the replacement heat-sink material, after considering properties, cost, availability, and handling difficulties.

The choice of a heat-sink material with a melting point farther below 80°C than that of Woods Metal (71°C) provides a much larger thermal potential in the right direction -- from the electronics to the heat sink. For ice, the initial temperature difference is 80° and diminishes with time after the ice melts and the entire package heats up.

Heat pipes replaced the brass-rod mounting rails. For a heat pipe operating at 50°C, the conductance or axial heat flux is $4 \times 10^4 \text{ W/m}^2$, which is vastly larger than the conductance of long, small-diameter brass rods.

TABLE VII
HEAT-SINK MATERIALS

<u>Material</u>	<u>T_{melt}</u> <u>(K)</u>	<u>Density</u> <u>(kg/m³)</u>	<u>Specific</u> <u>Heat</u> <u>(J/kg-K)</u>	<u>Latent</u> <u>Heat</u> <u>(J/kgx10⁵)</u>	<u>Heat</u> <u>Absorbed</u> <u>(Jx10⁵)</u>
Eisocune C ₂₀ H ₄₂	310	880	154.8	2.46	1.59
Woods Metal	344	9400	167.4	0.325	2.88
Gallium	303	6095	372	0.445	3.81
Ice	273	9130	192	3.35	4.58

These changes in the thermal-protection system improved its operation by allowing energy to be absorbed as latent heat in addition to the energy already absorbed as enthalpy increases. The tool-survival period at given temperatures was increased by a factor of 4, which allowed reasonable time for making necessary measurements.

4.2. Explosive Fracture-Initiation Tool

The explosive fracture-initiation tool was designed to deploy and detonate a small explosive charge at a preselected position in the open borehole section of the EE-2 or EE-3 geothermal wellbore. The detonation of a shaped-charge explosive can be used either to reduce the wellbore impedance of existing fractures or to initiate fractures in the selected zone -- after which pressurization of this zone with water will extend the fractures into the formation. The explosive fracture-initiation tool is rated for wellbore temperatures of 300°C and incorporates a downhole firing module, high-temperature detonator, and shaped high-explosive charge (Fig. 11). The capacitive-discharge firing system is charged from a surface control unit through an armored instrument cable. The downhole sonde houses the shaped high-explosive charge and the dewar that provides thermal protection for the firing system. The tool consists of a sinker-bar nosepiece, a tubular section containing the explosive charge, the firing circuit, and a cablehead sub for attachment to the armored logging cablehead. Seals, capable of withstanding a wellbore fluid pressure of 41 MPa ($\sqrt{6000}$ psi) and a hole temperature of 320°C, are located at all make-up connections of the tool.

Compressive springs (wave-type and helical) are used to restrain both the dewar and the explosive-charge detonator from shifting while being lowered into the hole and from swelling caused by thermal expansion as the tool heats up in the wellbore.

The detonator (a Reynolds Industries modified RP-84) is a separate unit that contains only hexanitrostilbene (HNS) explosive. This relatively insensitive secondary explosive provides maximum safety from accidental detonation, as well as the stability required in a high-temperature environment. The detonator is a slapper initiator that contains 1 g of explosive. The high-current, high-power electrical energy pulse sent from the downhole firing module vaporizes a foil that accelerates a flyer, which in turn detonates the

Fig. 11.
Explosive fracture-initiation device; 3.25-in. o.d. x 222.0-in. long, pressure limit of 10 000 psi, temperature limit $>300^{\circ}\text{C}$.

explosive instantaneously by impact energy. The explosive is pressed to near-crystal density and is completely separated from all conductive parts. This enhances the detonator's safety characteristics and improves its long-term stability.

The detonator is placed in a welded stainless steel housing, open at one end, with a Kemlon high-pressure feedthrough (16B-839) used to connect the high-voltage coaxial cable (Fig. 12).

The explosive used in the fracture-initiation system (AFX-521) was evaluated at the Laboratory for use as a thermally stable explosive. The results of this evaluation revealed that the AFX-521 was a very unusual explosive. In addition to its unsurpassed thermal stability, it is relatively insensitive to impact, spark, and pure shock (gap tests). It is as sensitive as PBX-9404 in the minimum priming test and its wedge-failure thickness is

Fig. 12.
Detonator housing.

very small. This combination of properties suggests that AFX-521 is an excellent choice for a thermally stable booster application such as the HDR downhole explosive systems.

The downhole firing module (Reynolds Model FS20) is housed in a 1-3/8-in.-diam x 10-in.-long aluminum tube that is potted to protect it from vibration and shock while the tool is lowered into the borehole.

Electrically, the firing module consists of an inverter and a voltage tripler charging a 0.5- μ F energy storage capacitor to $\sim$ 4500 Vdc. An over-voltage spark gap is provided at the output, which self triggers when the high voltage is approximately 4500 Vdc.

Power requirements downhole are $\sim$ 20 Vdc, 300 mA to power the inverter. Power is supplied from the uphole control unit. Input voltages uphole depend on cable length, temperature, and cable resistance to ground. The logging cable now in use has seven conductors, is 7600-m (25 000-ft) long, has a resistance of $\sim$ 250 Ω , and a minimum resistance of 1 M Ω to ground.

Operation of the downhole firing module requires three conductors. These conductors are used for a $\sim$ 20 Vac input, high-voltage monitor, and ground.

The dewar and pressure vessel are used to protect the firing module from the high-pressure/high-temperature downhole environment.

The surface control unit is packaged in a 9-in. x 5-in. x 6-in. moisture-sealed carrying case. On the front panel is the connector that joins the unit to the downhole cable, an ac power outlet, and monitoring instrumentation. The unit meter monitors the high voltage developed in the downhole firing

module and serves as an indicator that the unit has fired. The control unit arms and fires the system. A safety interlock plug renders the control box inoperative when removed. A detailed description of the high-temperature explosive, detonator, and downhole firing module is given in Ref. 44.

4.3. Acoustic-Velocity Transceiver

The borehole acoustic-velocity transceiver is a downhole sonde designed to operate in the severe geothermal environment encountered at Fenton Hill. The downhole sonde contains the essential transducer components designed to facilitate the acquisition and handling of the enormous amounts of cross-wellbore data that make possible two-dimensional measurements of rock formations situated between wells. The measurements are used to determine seismic velocity (and thereby elastic moduli), attenuation, and crack structure.

Each downhole transceiver tool contains an acoustic-source transmitter and a receiver (Fig. 13). The transmitter housing contains two independent 2-J magnetostrictive signal sources. The transducers operate at frequencies of 8.5 kHz and 17 kHz, respectively. Each transmitter can be manually or automatically triggered at rates of up to five pulses per second. The transducer scrolls are separated by lead blocks for acoustic isolation. Shot-break (zero time) crystal transducers are mounted coaxially with each of the transducer scrolls. These crystals are connected in series and the output amplified and transmitted to the surface.

The receiver consists of a piezoelectric transducer that has an equivalent response at each transmission frequency. Both the transmitter and the receiver transducer are submerged in oil and contact the borehole fluid through a thin metallic shell. The lower end of each oil-filled chamber is connected through a helical pipe to an expansion bellows for pressure equalization.

The transceiver system incorporates a surface control unit. The surface unit controls the transmitter firing rate and selects a transducer for the desired frequency. The receiver gain mode (automatic or manual) and surface gain are selected at the control unit, which also displays dewar temperatures monitored in the downhole units. The receiver signal is combined with timing pulses and transmitter-power and receiver-gain indications used for data processing. Both the transmitter and the receiver are omnidirectional. The electronics are mounted in a dewar containing a low-temperature-melting

Fig. 13.
Los Alamos National Laboratory dual well logger.

eutectic used as the heat sink to maintain operating temperatures for at least 6 h in the hot boreholes.

Because of variability in acoustic properties of the reservoirs, the strength of signals transmitted between boreholes changes greatly during logging. Two features of the downhole electronics avoid the time-consuming inconveniences that could result during logging under this condition. Receiver gain may be manually overridden or automatically set based on received-signal amplitude. In either mode, receiver gain is encoded on the telemetry to surface recording facilities. Manual override is used in instances when the clearest possible compressional-wave arrival is desired; the automatic

gain setting is used when entire unsaturated transmitted waveforms are of interest.

For cross-hole acoustic work two independent transceiver tools and associated surface control and wireline units are used so that a complete transceiver can be placed in each well used in a cross-hole survey. In this configuration simultaneous acquisition of along-the-well and cross-hole data is possible. Alternatively, the system has been designed so that each transmitter and receiver may be operated independently from separate wirelines. Thus a rock body may be studied simultaneously from a third well or the inventory of hardware in any one well may be reduced to a lone transmitter or receiver.

The basic configuration of a cross-hole survey is a sequence of operations called scans that results in information about vertical pie-shaped reservoir cross sections. Figure 14 illustrates the relationship between a scan and a survey. Because of the need for high-gain, low-noise measurements, signals are transmitted between wells only while the receiver is stationary. During a scan the transmitter is moved while continuously transmitting

Fig. 14.
Relationship between scan and a survey in obtaining cross-hole data.

signals, from a position below to a position above the receiver depth or vice versa. As many as 600 signals are transmitted between wells during a single scan. One or more scans make up a survey. The number and overlap of scans determine survey resolution and the extent to which one- or two-dimensional information can be recovered concerning reservoir properties.

To optimize recovery of two-dimensional special information concerning a reservoir property, the value of that property should be measured along as many nonparallel signal propagation paths as possible within the depth interval under inspection. However, as the inclination of the path from the transmitter to the receiver position increases, propagation path lengths increase so that signal strength decreases. Similarly, as inclination changes, the position of the receiver relative to the radiation pattern of P- and S-wave emissions from the transmitter changes. Figure 15 shows the data recorded during a recent cross-hole acoustic-transceiver experiment in a geothermal well. Consequently in designing a survey, in addition to maximizing the number of nonparallel ray paths, account must be taken of changes in the separation distance of tools and radiation-pattern effects. Superimposed on these considerations are the operational limitations of downhole components in

Fig. 15.
Record of a cross-hole acoustic scan.

terms of transmitter power and receiver sensitivity. Survey design parameters are calculated on site with computer software prepared for that purpose, making use of preliminary cross-hole acoustic measurements of signal strength in the study formations and computations of interwell distances from wellbore-deviation surveys available at the site.

4.4. On-Line System for Recording and Locating Microseismic Events

Microseismic events recorded during hydraulic-fracturing experiments provide important information on the size, location, and orientation of a growing hydraulic fracture. The microseismic data are obtained from the high-temperature triaxial geophone sondes deployed in the deep geothermal wellbores. If these data are processed in real time, a "map" of the fracture system may be produced as the pressurization experiment continues. The surface recording and analysis system provides the capability of on line fracture mapping. The surface equipment consists of an HP9845 computer interfaced to three Biomation Model 1015 digitizers. The Biomation cycled-memory digitizers monitor the six analog inputs from two downhole acoustic detectors. Each detector contains a triaxial geophone or accelerometer array. Each digitizer has four analog inputs and can be triggered from any one of the microseismic input signals. The digitizers may be "ganged" so that one pre-selected microseismic signal will trigger all three units. Each Biomation unit has a selectable time base and a variable delay time, which provides a delay sweep allowing display of several milliseconds of background signal before the microseismic data signal. The trigger is determined by setting an amplitude threshold from a preselected geophone output. Typically, the system is set up as shown in the block diagram (Fig. 16).

Digitizer 1 has a long time base with three analog inputs from one acoustic detector in one of the boreholes and the fourth analog signal coming from one of the horizontal components of the second acoustic detector located in an adjacent borehole (Fig. 17). This unit allows the determination of the time delay between the arrivals of the compressional (P) wave and the shear (S) wave ($P - S$ time). This information is a measurement of the distance from the respective acoustic detectors to the origin of the microseismic event when the velocities of the acoustic waves in the formation are known. The remaining two digitizers are programmed with a short time base for enhanced first arrivals of the P-waves. Each digitizer records and displays the three

Fig. 16.
Acoustic detection data acquisition system.

Fig. 17.
Record of a microseismic event from three orthogonal geophones.

analog geophone outputs from one of the downhole packages (Fig. 18). The polarization of the P-wave arrivals is calculated to determine the directions from the respective detectors to the sources of the microseismic events. Thus, the direction and distance of each event relative to each detector can be determined and the fracture growth can be plotted in real time.

The software package has been designed to allow the HP9845 to control the entire acoustic-detection system. During a typical hydraulic-fracture or high-pressurization experiment, many microseismic events are detected. All events are recorded on analog tape for future analysis. A dedicated software interface allows the HP9845 computer to control the Biomation 1015 digitizer on a priority interrupt basis. This in turn allows the operator to visually inspect those events displayed on the graphics that appear to have well-resolved first arrivals of both the compressional and shear waveforms. These events are then selected to be stored on floppy disc, S-P time is determined, and the location code is initiated. The event position is plotted relative to the detector locations. Numerous events are recorded and analyzed in this

Fig. 18.
Enhanced record of P-wave first arrivals.

manner on line during the pressurization experiments, resulting in a mapped pattern of fracture growth.

5.0. RESERVOIR ENGINEERING

5.1. Phase II Hydraulic Fracturing Experiments

Three pressurization tests and seven hydraulic-fracturing experiments have been conducted at the Fenton Hill test site during FY82 (Fig.19 and Table VIII). Although none of the fracturing attempts conducted to date have resulted in hydraulic communication between the wells, useful data have been obtained regarding the reservoir. The microseismic measurements made during these fracturing experiments are separately discussed in the next section "Microseismic Measurements of Hydraulic Fracturing."

5.1.1. Full Open-Hole Pressurization Tests. Small pumping experiments were conducted in EE-2 (Expt. 2003) and in EE-3 (Expt. 2006, 2007) to provide initial information concerning formation permeability and the possible existence of open fractures.

Fig. 19.
Wellbore configurations for major fracturing experiments.

TABLE VIII
SUMMARY OF PRESSURIZATION AND HYDRAULIC-FRACTURING EXPERIMENTS

Expt. No.	Well	Date	Zone Isolation Method	Vertical Depth (ft)	Injected Vol. (bbls)	Injection Data	
						Max. Pressure (psi)	Max. Rate (bpm)
2003	EE-2	1-6-82	open hole	--	13	2070	0.2
2006	EE-3	1-19-82	open hole	--		1480	0.5
2007	EE-3	2-27-82	open hole	--		1500	1
Lynes I	EE-2	5-2-82	Lynes Packer (open hole)	14 180	3	2200	--
Lynes II	EE-2	5-6-82	Lynes Packer (open hole)	14 160	12	4400	3
2011	EE-2	5-30-82	Cemented Liner/PBR	13 950	3300	7000	6.5
2012	EE-2	6-14-82	Cemented Liner/PBR	13 950	20000	6600	30
2016	EE-2	6-19-82	Cemented Liner/PBR	13 950	31000	6750	35
2018	EE-2	7-19-82	Otis Packer (9-5/8-in. Casing)	11 200	5700	6900	14
2019	EE-2	7-24-82	Otis Packer (9-5/8-in. Casing)	11 200	247	5800	5

5.1.1.1. Expt. 2003. This was the first pressurization of EE-2 and took place on January 6, 1982. Water was pumped into EE-2 at a nominal rate of 9 gallons per minute (gpm) to a final wellhead pressure of 2070 psi. The wellbore was exceptionally tight; there was no evidence of breakdown, and only about 30 gallons of water permeated the rock during the 2.5-h-long pressurization. A total system compressibility of 5.16×10^{-6} /psi was computed from the pressure-time curve. This was within 3% of the predicted fluid compressibility of 5.32×10^{-6} /psi.

5.1.1.2. Expt. 2006. This experiment determined the pressure required to inject water into the formation surrounding the open-hole section of EE-3. The pressure and flow-rate histories during the experiment are shown in Fig. 20. Well EE-3 was pressurized at 16 to 19 gpm to a maximum wellhead pressure of 1480 psi, at which point a pre-existing fracture or fractures opened up and accepted water. Although the pressure-time curve actually did exhibit a broad maximum, no classical breakdown was observed. Upon repumping,

Fig. 20.

EE-3 wellhead pressure and injection rate, Expt. 2006, full open-hole pressurization.

the pressure rose to a maximum value of 1390 psi and then remained essentially constant. Estimates of total minimum earth stress ranged from 5290 to 5940 psi, which was 1245 to 1900 psi above hydrostatic. Using flowing temperature surveys it was estimated that the pre-existing fracture communicates along 240 ft of the well, and the top of this fracture/well intersection is about 20 ft below the casing shoe, corresponding to a wellbore depth of 10 350 ft (10 120 ft true vertical depth). The temperature surveys indicated no flow behind the casing, nor was evidence of flow in the annulus detected at the surface. Thirty-one good-quality seismic signals received at the geophone package in EE-1 were detected with the Biomation Monitoring System — three during the 1/2-h-long initial pump and 28 during the 4-h-long repump. S-P delay times of these signals confirm that water was entering the formation just below the casing shoe in agreement with the temperature log. There was no detectable evidence of flow in EE-2.

5.1.1.3. Expt. 2007. The purpose of this experiment was to determine the minimum earth stress. As shown in Fig. 21, the Kobe pumps were used to pump into EE-3 at 9, 32, and 40 gpm, and shut-ins occurred twice. Estimated

Fig. 21.

EE-3 wellhead pressure and injection rate, Expt. 2007, full open-hole pressurization.

earth stress ranged from 1200 to 1400 psi above hydrostatic. Subsequent shut-in temperature logs indicated a much smaller zone of water acceptance, but this was based on a very small thermal anomaly, of the order of 1°C . This interval, just below the 9-5/8-in. casing shoe, appears to be only 10% as long as the 240-ft anomaly found in Expt. 2006.

5.1.2. EE-2 Fracturing Operations Using a Lynes Open-Hole Packer. The first attempts to create fractures from the bottom portion of EE-2 and extend them upward to EE-3 were conducted by using a Lynes open-hole packer.

5.1.2.1. First Lynes Packer Test. After cleaning and cooling EE-2, the pressurization test with Lynes inflation-type packer was made on May 2, 1982 (Fig. 22). The Lynes packer assembly was set in the open-hole section at 6:30 pm on May 2 with the packer centerline at 14 981 ft. An initial weight of 170 000 lb was stacked out. Pumping at 9 gpm began at 7:06 pm and was shut-in at 500 psi at 7:14 pm. Pumping resumed at 7:22 pm and the level was increased to 800 psi and held. Pumping began again at 7:32 pm and the pressure was held at 1700 psi. An additional 55 000 lb was then stacked out on the packer for a total of 125 000 lb. Pumping with the 19-gpm Kobe pump began at 7:40 pm. As the pressure increased, the shear-pinned bull plug blew out

Fig. 22.

EE-2 wellhead pressure and injection rate, first fracturing attempt with open-hole packer.

between 2700 and 2800 psi. The system was shut-in at about 2250 psi. Lack of pressure and flow in the annulus indicated that the packer was set satisfactorily.

A total of 115 gallons had been pumped into EE-2 when, during the course of changing out the injection-pressure transducer, the shut-in pressure dropped by 33 psi. Pumping at 19 gpm was initiated at 8:30 pm but pressure and flow conditions in the annulus indicated packer by-pass, so pumping was terminated at 8:36 pm. The packer was out of the hole at 5:15 am on May 3 and major blow-out damage was evident on one side at the downhole end of the element and a smaller blow-out region was found on the downhole end approximately opposite.

5.1.2.2. Second Lynes Packer Test. The second fracturing operation in EE-2 was conducted on May 6, 1982, after cooling the wellbore. The borehole assembly tagged bottom at 15 145-ft depth and the Lynes packer was set at 14 989 ft. The open-hole section below the packer was pressurized starting at 7:05 pm. Water was pumped into EE-2 at the rate of ~ 17 gpm to a final pressure of 4200 psi (Fig. 23). To minimize the pressure difference between the upper and bottom sides of the packer element, water was pumped into the annulus above the packer. Water flow into the annulus through the packer started at 7:12 pm and continued to the end of experiment, which was brought about by damage of the packer. There was no evidence of the initiation of a major fracture.

5.1.3. Fracturing Attempts Using a Cemented-in Scab Liner/PBR Assembly. As a single open-hole Lynes packer was not successful in establishing fractures at around 15 000-ft depth, a series of three pumping experiments using a cemented-liner/PBR assembly was conducted at the end of a 150-m (492 ft) portion of EE-2.

Fig. 23.

EE-2 wellhead pressure and injection rate, second fracture attempt with open-hole packer.

5.1.3.1. Expt. 2011. The first fracturing operation through the liner was conducted on May 30, 1982. The Dowell rig-up for pumping and pressure checks was completed by 7:30 am on May 30. Initially, 1000 psi was applied to the backside (i.e., in the annulus above the liner). Kobe-pump injection began about 9:00 am and the pressure was raised smoothly. Backside pressure was increased to 2000 psi and maintained. The breakdown soon occurred at about 4800 psi under a flow of 14.2 gpm. The pressure and flow rate in the wellbore during the experiment are shown in Fig. 24. The experiment was terminated by pumping equipment breakdowns with about 3300 bbls injected.

5.1.3.2. Expt. 2012. The second fracturing attempt below the PBR-liner in EE-2 was conducted on June 4 and 5, 1982. The pressure and flow rate histories in the wellbore are shown in Fig. 25. After a few false starts, the pumping began at 10:37 am and continued with several flow rates to 2:00 am on June 5. After about 19 700 bbl were injected, the experiment was terminated by the scheduled shut down, but no connection to EE-3 was achieved.

5.1.3.3. Expt. 2016. After a leak test to evaluate the PBR, the third major fracturing attempt from the region below the PBR-liner assembly was conducted on June 20-21. The primary objective of this experiment was to connect hydraulically the holes in EE-2 and EE-3, utilizing a greater amount of injected fluid and somewhat higher injection rates, up to 35 barrels per minute (bpm). After the 5-bpm prechill pumping, from 1:15 am to 5:00 am on June 20 to preshrink the pipe and set the weight stack out, the injection rate was increased smoothly through 10 bpm, 15 bpm (5:45 am), 20 bpm (7:08 am), and 30 bpm around 8:00 am with 0.05% J313 friction reducer added to reduce the pipe friction to 85-100 psi/kft. This 30-bpm rate was maintained through most of the day. There was a 1-h shut down at noon to change out a malfunctioning blender and another from 5:00 pm to 7:00 pm to remove and repair the rig's ram seals. The backside leak remained essentially constant at 1.0 to 1.3 bpm with no indication of either a significant leak in the PBR seals or a fracture around the liner assembly.

The pumping progression accumulated 100 000 gallons by 6:45 am, 400 000 gallons by 11:00 am, 600 000 gallons by 2:00 pm, 1 000 000 gallons by 10:00 pm, 1 200 000 gallons by 12:45 am June 21, and a final total of 1 290 000 gallons when pumping was terminated at 1:00 am. The experiment was terminated because no apparent connection had been achieved with EE-3, the microseismic data from the EE-1 geophones showed that the seismically active region was

Fig. 24.
EE-2 wellhead pressure and injection rate, Expt. 2011, first fracture attempt with PBR/liner assembly.

Fig. 25.
EE-2 wellhead pressure and injection rate, Expt. 2012, second fracture attempt with PBR/liner assembly.

by-passing the EE-3 wellbore, and there was a significant leak in the master valve below the frac head. The pressure and flow rates in the wellbore during the experiment are given in Fig. 26.

5.1.4. Fracturing Experiments Using a Casing Packer. Although we succeeded in making large fractures during the experiments of 2011, 2012, and 2016, we failed to achieve hydraulic communication with wellbore EE-3. The location of the microseismic events associated with the experiments pointed out that the fracture zones were inclined about 45° from the vertical and deviated from the lower portion of EE-3. Based upon these microseismic results, fracture attempts were planned in the upper portion of Phase II reservoir region, isolated between a retrievable casing packer and a sand plug.

5.1.4.1. Expt. 2018. The fracturing attempt of the upper portion of EE-2 was conducted by using an Otis casing packer on July 19 and 20, 1982. Figure 27 summarizes the pressure and flow rate in the wellbore. After pressure test of lines, pumping at 2 bpm started at 4:23 pm, July 19, and terminated at 2:04 am on July 20 by a frac-string failure.

Fig. 26.
EE-2 wellhead pressure and injection rate, Expt. 2016, third fracture attempt with PBR/liner assembly.

Fig. 27.

EE-2 wellhead pressure and injection rate, Expt. 2018, first fracture attempt with casing packer and sand plug.

5.1.4.2. Expt. 2019. A second attempt to pump into the open-hole section through the casing packer was again terminated by failure of the frac string after about 10 000 gallons of fluid had been injected.

5.2. Microseismic Measurements of Hydraulic Fracturing

We monitored microseismicity during hydraulic-fracturing experiments using two downhole, three-component seismic packages: a triaxial geophone package, and a new accelerometer package. The geophone package was always stationed near the bottom of EE-1, at 2927 m (9600 ft), whereas the accelerometer package was placed in deeper, hotter regions in either EE-2 or EE-3, depending on which hole was available as an observation hole. Due to temperature limitations, the accelerometer lifetime was quite short, less than 6 h on station, and the instrument experienced problems that reduced its effectiveness compared to the geophone package. The accelerometer still provided crucial data on the relative delay of signals arriving at the stations, which greatly improved our confidence in the seismic locations.

As in the past, seismic locations were determined from the polarization of the P (pressure) wave and the S-P delay time.* Improvements in the polarization measurements have been effected based on work by Matsumura.⁴⁵ To facilitate rapid processing of microseismic data, this code, together with a new set of mapping and S-P-time auxiliary programs was implemented on desk-top computers. Because of these improvements we can now analyze the microseismic events on a real-time basis, providing maps of the data within 1/2 h after the seismic events occur. Whenever possible, location maps have been calibrated using signals from detonators fired at known locations in EE-2 or EE-3.

We monitored seismic activity during nine attempted hydraulic stimulations during FY82. Of these, eight produced seismicity and three produced large numbers of events with more than 1000 processable events recorded during each experiment. In fact two of these experiments (2012 and 2016) produced events that were energetic enough to be observed on surface seismic stations that were located more than 10 km from the source region. These experiments occurred during stimulations of the lower region of the Phase II reservoir, i.e., the bottom 137 m (450 ft) of EE-2 (depth range 4248 - 4385 m). One additional experiment (2018), the first major stimulation of the upper reservoir, did not produce events large enough to be detected on the surface, but did produce large numbers of microearthquakes. The much smaller injection of Expt. 2019 also produced no events detectable at the surface. (However a very large pump into the upper reservoir at the beginning of FY83 did produce many such events.)

Results from the four pumping experiments during FY82 are described in detail below.

5.2.1. Microseismic Results of Expt. 2012, Fracturing in Lower Reservoir, Below PBR-Liner Assembly in EE-2. This experiment, as well as the other experiments discussed in this section, are described in more general terms in the previous section "Phase II Hydraulic-Fracturing Experiments." About 840 000 gallons of water were injected during Expt. 2012. Seismic activity was observed 4-1/2 h after the start of pumping. These events occurred on an inclined feature that intersected the EE-2 wellbore at a depth of 4390 m (14 402 ft) and extended 400 m (1312 ft) below the injection

* The time difference between arrival of the P- (pressure) wave and the slow S- (shear) wave.

interval. Subsequently, this feature grew upwards toward the bottom of EE-3 and a second parallel feature, located 430 m (1410 ft) higher, also became active. Gradually, the focus of seismic activity moved to this upper zone. Activity on the lower feature stopped 7-1/2 h after the start of pumping. The location and growth of seismic activity during this experiment are shown in Fig. 28.

5.2.2. Microseismic Results of Expt. 2016, Fracturing in Lower Reservoir, Below PBR-Liner Assembly in EE-2. During Expt. 2016, 586 000 gallons of water were injected. Significant seismic activity -- but at an initially low event rate -- began 5 h after the start of pumping at a total injected volume of 320 000 gal. These early microearthquakes occurred roughly 450 m (1476 ft) east of the termini of holes EE-2 and EE-3, and at a vertical depth of about 3700 m (12 140 ft). Surprisingly these early events occurred significantly above the injection point. Subsequently, seismic activity increased and spread in an oblate region dipping between 30° and 60° from the vertical (towards the west), and striking roughly perpendicular to the wellbore direction. Figure 29 is representative of the seismic activity observed. Significantly, there were almost no seismic signals originating from the vicinity of the bottom of EE-3. In comparison, recall that seismicity in Expt. 2012 started below the injection interval of EE-2 and later concentrated on a second inclined (40° from the vertical) feature surrounding the bottom 200 m of EE-3.

5.2.3. Microseismic Results of Expt. 2018, Fracturing in Upper Reservoir Between EE-2 Casing Packer and Sand Plug in EE-2. Microseismic activity was recorded during the first stimulation of the upper reservoir (Expt. 2018) in which 240 000 gallons of water were injected. In this experiment no calibration using detonator signals was attempted. As shown in Fig. 30, the first seismic activity observed during this experiment occurred adjacent to the injection wellbore at a depth of 3538 m (11 600 ft), near the center of the injection interval. With increasing time, the seismic activity tended to migrate downward and to the south, filling out a dipping "sausage-shaped" volume. A few hours after the start of pumping, we observed a second seismic trend, generally parallel to the first seismic zone but a few hundred meters higher. This zone eventually attained the same lateral dimensions as the main or lower seismic zone and activity persisted here until the end of the experiment, although at a lower rate than occurred in the lower zone.

Fig. 28.
Locations of seismic activity from
Expt. 2012.

Fig. 29.
Locations of seismic activity from
Expt. 2016.

5.2.4. Comparison of Microearthquake Locations in the Upper and Lower Reservoirs. The locations of seismic events from two experiments (2012 and 2016) in the lower reservoir and one in the upper reservoir (2018) are summarized in Fig. 31. Several observations are suggested by this figure. First, the locations of events that occurred during stimulation of the lower reservoir were dispersed throughout a much larger region than those that occurred during experiments in the upper reservoir; a fact that may be related

Fig. 30.
Locations of seismic activity from
Expt. 2018.

Fig. 31.
Summary figure showing seismic event
locations from Expts. 2012, 2016, and
2018.

to the larger volumes pumped during injections into the lower zone. Secondly, events occurring in the lower reservoir seem to define extensive 45° dipping planes, which strike approximately 20° W of N. However, no such pattern is visible in the upper reservoir, where the events seem to define a simple geometry of planes.

5.2.5. Internal Structure of Maps of Microseismic Activity. When microseismic event locations are plotted as a function of time in plan and elevation views, it is often possible to interpret sequences of events as defining linear or planar features. However, when widely scattered events occur in three dimensions it is often possible to identify individual planes that may intersect others. To search for statistically significant planes (and hence, the likely orientations of real structures), a computer program was written that computed the dip and strike of the planes defined by every combination of three seismic event locations. The rationale is that combinations that do not represent physical features will be randomly distributed and will have a low probability of occurrence, whereas those combinations of three events that do represent real features will have a relatively higher probability of occurrence. Results of this type of analysis for 93 event locations from Expt. 2018 are shown in Fig. 32. Statistically significant planes determined by this technique are (a) N0-20°W dipping 55-65°W; (b) N15-25°E, vertical; and (c) N20-40°E, dipping 70-85°W. Orientations b and c correspond fairly well to the directions N42°E, 81°S and N49°E, 87°S, which are reported by Laney et al.⁴⁶ from cores taken in EE-2. They also observe a plane striking N30°W and dipping 10°E, which may correspond to orientation a.

5.2.6. Microseismic Magnitude - Frequency Relations. There is a well-known statistical relation between earthquake magnitude and frequency called the Ishimoto-Iida relation,⁴⁷

$$n(A) dA = k A^{-m} dA, \quad (2)$$

where A is the maximum trace amplitude for a particular event, which in turn can be related to the earthquake magnitude, $n(A)dA$, the frequency of the earthquakes for which the maximum trace amplitude lies between A and $A + dA$, and k and m are constants. Under a simple assumption that the hypocentral distances are approximately the same, Suzuki⁴⁸ showed that the above relation is equivalent to the well-known Gutenberg-Richter empirical formula when $m = b + 1$.⁴⁹

The coefficient m is an important parameter in describing the nature of earthquakes. The m value for earthquakes has been studied by many investigators and found to characterize seismicity within various regions, and it is found that regional and temporal variations of m may reflect variations of the

Fig. 32.

Distribution of dips and strikes determined from the 93 microseismic events located during Expt. 2018. The origin represents perfectly vertical fractures striking north. The abscissa gives the strikes, east of north to the right of the origin, and west of north to the left. The ordinate gives the inclination, relative to the vertical. Each tic-mark represents 10° . (A) Shows all dip-strike combinations having a frequency greater than or equal to 6.25. (B) Frequency >12.5 . (C) Frequency >25.0 . (D) Frequency >37.5 . Labels a, b, and c in Fig. D refer to orientations a) $N0-20^\circ W$, dipping $55-65^\circ W$; b) $N15-25^\circ E$, dipping vertically; and c) $N20-40^\circ E$, dipping $70-85^\circ W$.

state of stress and the heterogeneity of geological media.^{50,51} Consequently a study of m value for the microearthquakes (acoustic emissions) observed during hydraulic fracturing is of interest.

We report m values for microearthquakes occurring during Expt. 2012, having a maximum trace amplitude larger than 4 mm (peak-to-peak). The relation between the maximum amplitudes and the number of occurrences for hourly

intervals during the experiment was examined, and a typical example is given in Fig. 33, which shows frequency versus maximum amplitude in logarithmic coordinates. The inclination of the trend line in this figure gives the m value.

As shown in Fig. 34, the number of microearthquakes observed per hour during Expt. 2012 correlates well with the injection flow rate. Note that the time delay of the event rate compared to the flow rate is about 4 h. The values of m for hourly time intervals are shown in Fig. 34(c). The values of m vary from 2.17 to 2.43 during the experiment. Temporal variations of m may reflect variations of the heterogeneity of material in the Phase I reservoir; however, the differences may not be significant at the 95% confidence level. A possible reason is that the relatively narrow dynamic range (about 20 dB) and

Fig. 33.

Frequency distribution of events with respect to trace amplitude obtained from the interval 21:00 to 22:00 h in Expt. 2012. The m -value in Ishimoto-Iida's formula is also shown in the figure.

Fig. 34.
Expt. 2012 time-histories of: (top) wellhead pressure and injection rate; (middle) hourly number of events; and (bottom) m-values.

high-frequency cut-off (about 100 Hz) of the observation system used restricts conclusive evaluation.

5.2.7. Microearthquake Fault-Plane Solutions. This subsection presents fault-plane solutions of some of the larger events that were induced during the hydraulic-fracturing experiments. As discussed earlier, two separate zones were stimulated, one near the bottom of the reservoir (the lower zone) and one near the top (the upper zone). Using the unique seismic instrumentation available at the HDR site we can record microearthquakes within 1 km of the source and can locate them very precisely. Hypocenters from each stimulation formed clusters that were separated from each other in space.* Events from these two groups, when recorded on a surface array, had characteristic patterns of first motions that were quite different, implying different fault-plane solutions for the two groups. The lower group has a strike-slip solution, either left-lateral slip on a north-south vertical plane or right-lateral slip on an east-west vertical plane. The upper group also has a north-south vertical fault plane but the sense of motion indicated normal faulting. Because the north-south vertical plane is common to both solutions, we believe it represents the true fault plane, but the change in the sense of motion indicates a major change in the state of stress near Fenton Hill over a distance of less than 2 km.

The largest of the induced microearthquakes at Fenton Hill were recorded on a surface net consisting of eight portable stations, each with a Geotech S-500 seismometer and sufficient telemetry equipment to relay the data back to a central recording facility at the geothermal site. Along with the temporary net we also used data obtained by five permanent stations, part of the Laboratory's regional net. Locations of all these stations used in this study are shown in Fig. 35. All these stations are within a few kilometers of Fenton Hill.

All events in either the upper or lower reservoir had nearly identical patterns of first arrivals so a composite of all the data was used in each of the fault-plane solutions. Using this process we made two fault-plane solutions, one for the upper reservoir (Fig. 36) and the second for the lower reservoir (Fig. 37). Note that in both cases we have plotted the first

* Events detectable at the surface from fluid injection into the upper zone were first observed early in FY83, but are included in this discussion.

Fig. 35.

Map of the area near Fenton Hill showing the locations of our temporary surface seismic array.

arrivals on the upper hemisphere. We made this rather unconventional choice because the stations are so near to the source region; the first arrival will be an upgoing rather than a downgoing ray. The fault-plane solution for the lower reservoir is a very well constrained strike-slip on either a north-south or an east-west trending fault plane, either right-lateral strike-slip on a vertical east-west plane or left-lateral strike-slip on a vertical north-south plane. The fault-plane solution for the upper reservoir contains one well-defined nodal line, once again a vertical north-south trending plane. The second plane is not well constrained by our data, however, and several possible nodal planes are indicated in Fig. 36. No matter what we assume for the second nodal plane, slip on the north-south nodal plane must contain a substantial vertical component. In fact, the slip vector on this plane must dip at least 50° from the horizontal. Thus the fault-plane solution for the

Fig. 36.

Fault-plane solution for the upper reservoir. The greatest and least principal components are indicated by P and T, respectively.

upper reservoir suggests either a high-angle reverse fault or a normal fault, but a strike-slip solution such as inferred for the lower reservoir is not consistent with the upper-reservoir data.

These fault-plane solutions, one for the upper reservoir and one for the lower reservoir, are clearly inconsistent, but a nearly vertical north-south trending fault plane is present in both solutions. Because the solutions are similar in this respect and because similar fracture orientations have been observed before, both during joint surveys and during hydraulic fracturing experiments,⁵² we think that the north-south plane represents the true fault plane.

Directions of the principal components of stress are also indicated in Figs. 36 and 37. For the lower reservoir the greatest principal earth stress (P) is nearly horizontal, plunging toward the northwest, while the least

Fig. 37.
Fault-plane solution for the lower reservoir.

stress (T) is also nearly horizontal, plunging toward the southwest. In contrast, the P axis in the upper zone is much closer to vertical, plunging to the east at an angle of 30 or 40°.

Aki and Richards⁵³ and the discussion in the following section on rock mechanics — Modeling Hydraulic Fracturing in Jointed Rock — show that when earthquakes result from reactivation of pre-existing fractures the state of stress inferred from fault planes is not well constrained because the direction of rupture will be controlled by the orientation of pre-existing rupture planes. However, the shear stress acting on the fault plane must be parallel to the slip vector because the shear stress is the force causing the blocks to move. Because the fracture planes are apparently the same in the upper and lower reservoir whereas the direction of slip is significantly different, the state of stress must also have changed. The slip vector has a larger vertical component in the upper reservoir compared to the lower reservoir, about 1.5 km away. It is concluded that the maximum principal earth stress changes from

nearly horizontal in the lower reservoir to predominantly vertical in the upper reservoir in spite of the fact that the overburden stress increases by 24 MPa in this interval. Such a change in stress may be accounted for by the fact that the Fenton Hill HDR site lies near the boundary of the Valles Caldera. Because the geothermal wells were directionally drilled toward the east, the lower reservoir is 1 km closer to the Caldera rim and presumably closer to the underlying magma chamber. Thus the change in the tectonic stresses implied by the change in the fault-plane solutions may be related to subsidence of the Caldera or cooling of the nearby magma chamber.

5.3. Reservoir Modeling

5.3.1. Wellbore Heat-Transmission Modeling. During recent workover operations at the Fenton Hill HDR site, a wellbore heat-transmission computer code (WBHT) was used to simulate downhole temperatures. Downhole temperature predictions were desired for planning of operations involving temperature-limited equipment. Such operations included commercial logging for wellbore characterization, use of packers with temperature-sensitive elements in fracturing attempts, the cementing of liners, and minimizing temperature-induced stresses in the casing.

The WBHT code was designed for modeling the flow of compressed liquid in either uniaxial or countercurrent flow conditions. The equations that are solved describe the convective heat transport in the wellbore and annulus and the heat conduction in the rock matrix. These equations may be written for the wellbore:

$$\frac{\partial(\rho_w u_w)}{\partial t} + \dot{q} \frac{\partial(\rho_w h_w)}{\partial z} + Q_{r-w} = 0 \quad (3)$$

and for the rock:

$$\rho_r c_r \frac{\partial T}{\partial t} + \frac{\partial}{\partial z} (k \frac{\partial T}{\partial z}) + \frac{1}{r} \frac{\partial}{\partial R} (kR \frac{\partial T}{\partial R}) + Q_{w-r} = 0 \quad (4)$$

Here T is the temperature, h is the enthalpy, k is the thermal conductivity, $\dot{q}$ is the volume flow rate, ρ is the density, u is internal energy, c is specific heat, t is time, z is depth, R is radial distance from the center of the wellbore, Q is a heat-transfer expression for interchange between rock and water, and subscripts w and r refer to the water and rock, respectively. These equations are augmented by appropriate initial and boundary conditions. The

equations are discretized using finite differences, then a block iterative method is used to solve the resulting algebraic equations.

The code has been verified against published radial-heat-flow solutions⁵⁴ and very good numerical accuracy was achieved with a 400-node grid. Table IX shows typical input data used in the computer program.

Examples of modeling of operations in EE-2 from April 21 to May 15, 1982 are illustrated here.

Figures 38 and 39 show the flow-rate schedule (half-hour averages) and the computed bottom-hole (~ 15150 ft) and casing-shoe (~ 11580 ft) temperatures.

Figures 40 and 41 show matches between temperature surveys and wellbore-code predictions during this time.

The WBHT model has been modified to include frictional-heating effects and temperature-dependent thermal conductivities, to improve predictions.

5.3.2. Non-Darcy Flow in Fractured Geothermal Reservoirs. Non-Darcy effects are common in high-velocity flow in fractures. The question of short-term pressure-transient testing in a fractured geothermal reservoir was previously addressed in Ref. 55. Studies this year deal with the effect of

TABLE IX
PARAMETERS FOR WELLBORE MODEL

<u>Parameter</u>	<u>Value</u>
Rock density (ρ_r)	2500 kg/m ³
Rock specific heat (c_r)	1000 J/kg°C
Radial extent	40 m
Depth along wellbore	4660 m
True vertical depth	4396 m
Nodes in R direction	10
Nodes in z direction	40
Flow rate	variable
Initial temperature distribution [T(°C), z = depth along wellbore (m)]	T = 15.3 + .093 z for z $\leq$ 747 m T = 60.7 + .0289 z + 5.67 (10 ⁻⁶) z for z > 747 m

Fig. 38.
Flow-rate history for April 21 through May 15, 1982.

Fig. 39.
Computed bottom-hole and casing-shoe temperatures for April 21 through May 15, 1982.

Fig. 40.

Temperature survey in EE-2 wellbore, April 27, 1982, with WBHT code match.

Fig. 41.

Temperature survey of May 10, 1982 in EE-2 with WBHT match including temperature-dependent thermal conductivity and pressure-heating effects.

non-Darcy flow on the long-term thermal behavior of fractured geothermal reservoirs. Detailed derivation of the governing equations has been presented by several investigators⁵⁶ and thus only a summary of the equations will be presented here.

The equations representing conservation of mass and energy for compressed-liquid flow may be written

$$-\nabla \cdot \left(\frac{k\rho\delta}{\mu} \nabla p \right) + \frac{\partial}{\partial z} \frac{k\rho^2 g\delta}{\mu} + q_m + \frac{\partial A_m}{\partial t} = 0 \quad (5)$$

and

$$-\nabla \cdot \frac{k\rho h}{\mu} \delta \nabla p + \frac{\partial}{\partial z} \frac{k\rho^2 g h \delta}{\mu} + q_e K \nabla^2 T + \frac{\partial A_e}{\partial t} = 0, \quad (6)$$

where p is the pressure, ρ is the density of water, μ is the water viscosity, h is the water enthalpy, g is the acceleration of gravity, T is the temperature, K is the thermal conductivity, k is the rock permeability, z is depth, and t is time. The quantities q_m and q_e represent sources or sinks. The accumulation terms A_m and A_e are given by

$$A_m = \phi \rho \quad (7)$$

$$A_e = (1-\phi) \rho_r u_r + \phi (\rho u). \quad (8)$$

Here ϕ refers to the porosity, ρ_r to the rock density, and u and u_r to the water and rock internal energies.

The term δ accounts for the effects of non-Darcy flow. The functional relationship of δ with other physical properties may be expressed as

$$\delta = 1 / \left(1 + \frac{\beta \rho k |V|}{\mu} \right), \quad (9)$$

where V is the velocity of the liquid and β is the non-Darcy coefficient of the liquid phase. Geertsma⁵⁷ has correlated δ , k , and ϕ for a wide variety of materials and has presented the following relation:

$$\beta = 0.005 \frac{1}{\phi^{5.5} k^{0.5}}. \quad (10)$$

Pressure (P) and enthalpy (h) are used as dependent variables.

The functional dependence of the thermodynamic and transport quantities in Eqs. 5 and 6 on P and h are not given here. The formulae given by Faust and Mercer were used.⁵⁸

Equations 5 and 6 are highly nonlinear and are solved with a finite-element-based algorithm. Zyvoloski⁵⁹ describes the numerical procedures. As a particular example, consider a model hot dry rock fracture system, consisting of a single two-dimensional high-permeability fracture embedded in a three-dimensional block of granite. The reservoir data are presented in Table X and a model of the reservoir is given in Fig. 42. Figure 43 shows a

TABLE X
PARAMETERS FOR FRACTURE-FLOW EXAMPLE

Parameter	Symbol	Value
Permeability: Rock	k_R	10^{-18} m^2
Fracture	k_F	10^{-8} m^2
Thermal Conductivity	K	2.9 W/(m°C)
Porosity: Rock	ϕ_R	0.001
Fracture	ϕ_F	1.0
Rock Density	ρ_r	2700 kg/m ³
Rock Specific Heat	C_r	1000 J/kg°C
Reservoir Width	--	60 m
Fracture Horizontal Length	--	100 m
Fracture Vertical Length	--	400 m
Fracture Width	--	0.001 m
Initial Pressure	p_{ij}^0	hydrostatic
Initial Temperature	T_{ij}^0	140.0°C + .055(°C/m)xz(m)
Injection Temperature		118°C
Production Discharge (Production Controlled by Pressure)	q_m	0.05 kg/s
Injection Rate		0.05 kg/s at 118°C

Fig. 42.
Model for HDR reservoir.

Fig. 43.
Temperature-contour map for HDR mode.

temperature-contour map of the fracture face after 1000 days and shows graphically the non-Darcy effect of retarding the buoyancy drop of the incoming fluid, thereby decreasing the sweep area of the fracture. The additional

resistance provided by the non-Darcy flow near the wellbore negates some of the buoyancy-induced spreading of the flow.

The results are dependent on Geertsma's correlation of porosity and permeability. Calculation of flow coefficients is experimentally possible if flow tests are run at several different flow rates. This procedure also helps to differentiate between effects of skin damage near the well and non-Darcy flow: skin-damage effects vary linearly with flow rates whereas non-Darcy effects do not. At high flow rates and hence higher pressures, highly fractured systems may also experience fracture pressurization, which tends to oppose the higher flow-resistance effects of non-Darcy flow. Work needs to be done in the area of detecting and characterizing non-Darcy flow in fracture-dominated reservoirs.

It can be concluded that non-Darcy flow can be significant in the long-term behavior of a fractured reservoir, and it can be modeled.

5.4. Rock Mechanics

5.4.1. Modeling Hydraulic Fracturing in Jointed Rock. Hydraulic fracturing in HDR reservoirs was simulated with a two-dimensional model that incorporates 256 blocks of rock, each of which can deform, rotate, and slide. Calculations were performed with the two-dimensional rock-mechanics code, Fluid Rock Interaction Program (FRIP), which was acquired from the HDR project in the United Kingdom. FRIP is based upon the calculational method previously described in Ref. 60. The rock joints are on a regular rectangular grid and the code permits interactive coupling of fluid dynamics with rock stresses and deformations. For example, an excess of pressure on a block during one computational cycle will result in compression of the block and opening (dilation) of the joints next to it, resulting in additional permeability and changed pressure distribution.

When joints were aligned parallel to the principal earth stresses, the "classical" hydraulic fracturing process, depicted in Fig. 44, was predicted in which a single fracture was propagated at a pressure slightly in excess of the minimum earth stress, and the aperture and shape of the fracture agreed well with simple theory.

When the joints were rotated 30° from the principal stresses, two types of fracture patterns could occur. In the first type, shown in Fig. 45, occurring when resistance to shear slippage was low or shear dilatancy was large,

Fig. 44.
Fracture geometry s, classical
fracturing.

Fig. 45.
Fracture geometry s, single-shear
fracture.

only a single fracture would propagate along the existing joints connected to the injection well and inclined 30° from the maximum principal earth stress. The displacement mechanism was shear slippage and the pressure required for steady propagation was less than the minimum principal earth stress by an amount that depended upon the friction angle. In the second type, corresponding to high shear resistance or small dilatancy, multiple shear fracturing occurred as shown in Fig. 46. Shear slippage along the joints was accompanied by shear-stress drops and the interaction of the stress drop with the applied earth stresses resulted in opening of joints normal to the maximum stress, so that a branching fracture pattern occurred. This fracture pattern, and the computed shear-stress drops, explain why microseismic-event patterns in jointed-rock masses are usually not planar but are ellipsoidal in shape, and why measured microearthquakes result in strong shear waves.

To understand this fracture behavior better, refer to Fig. 47. The main shear fracture has lifted off and slipped in shear. When the faces are no longer in contact there is no friction to support the initial shear stress, so

Fig. 46.
Fracture geometry, branching shear fracturing.

it is reduced to zero, resulting in the stress drop and the fault-plane solution familiar to seismologists (alternating quadrants of increased compression, shown as plus signs, and reduced compression, shown as minus signs). The shear-stress drop requires a change of the y-direction normal stresses to maintain equilibrium, so that a horizontal section in the x-direction taken

about midway between the fracture center and the tip of the main shear fracture has the y-stress profile shown on the top and bottom of Fig. 47. The original normal stress, 1.75σ , is reduced to as low as 1.25σ in the upper right and lower left quadrants, precisely low enough for lift-off and creation of the lateral fractures indicated. These x-direction fractures then allow easy migration of the water into the y-direction joints immediately adjacent and parallel to the main one, so that these joints begin to open. The zone of fracturing is elliptical rather than a single planar feature, as is the case for classical fracturing, and the major axis of the ellipse rotates 15° clockwise from the joint direction, about half the amount that would be required to line up with the maximum principal earth stress.

5.4.2. Effects of Drilling Inclination and Earth Stresses Upon the Orientation of Fractures Initiated in EE-2. When injected fluids do not permeate the formation, as appears to be the case in the nearly impermeable rock around well EE-2, then the breakdown pressure required to fracture the well is not determined simply by the earth stresses, but is instead complicated by the state of stress (stress concentrations) around the borehole.

Fig. 47.
Formation of lateral-shear fractures.

Analysis of the stresses around the inclined EE-2 borehole indicates that fractures will tend to initiate in the $S_1 - S_3$ plane, that is, in the plane of the maximum and minimum compressive earth stresses.⁶¹⁻⁶³ Consequently, classical tensile fractures will not initiate in planes orthogonal to S_3 , which would have resulted in the ideal geometry, but will tend to follow the well-bore and possibly hinder zone isolation and fracturing operations, by, for example, promoting leakage around packers.

It can be shown that the fracturing pressure and orientation for tensile fractures are functions of S_3 , P_0 , and ΔS , where P_0 is the initial pore fluid pressure, $\Delta S = S_2 - S_3$, and S_2 is the intermediate earth stress.⁶⁴ Using available values of P_0 , equations for fracture-initiation pressures, P , are

$$\text{Radial Fractures (non-straddle packers)} \quad P = 1.6 S_3 \quad (11)$$

$$\text{Splitting Fractures, } \theta = 0^\circ \text{ (Unfavorable)} \quad P = 0.97 S_3 + 3\Delta S \quad (12)$$

$$\text{Splitting Fractures, } \theta = 90^\circ \text{ (Favorable)} \quad P = 2.3 S_3 - \Delta S, \quad (13)$$

where θ is the angle between the fracture plane and a vertical plane parallel to the direction of S_3 .

These initiation pressures and geometrical descriptions of radial and splitting fractures are presented in Fig. 48. Fracturing occurs at the lowest pressure required for a given earth stress difference, ΔS . For $\Delta S/S_3$ between 0 and 0.21, the fracture orientation is least favorable, i.e., the initiated fracture is parallel to the bore and $\theta = 0^\circ$, so that the fracture tends to be parallel with the bore for a longer distance before, hopefully, changing direction and propagating vertically. The pressure required for this fracture mode varies linearly with ΔS , from 0.97 to 1.6 S_3 . Because of the state of stresses at the well, there is the possibility that this mode of fracture can initiate at pressures slightly lower than S_3 , which might appear to be paradoxical because if the fracture turns away from the well and propagates vertically $P = S_3$ is required. This apparent paradox is a consequence of stress concentrations, which can result not only in amplification, but, at some locations, also reduction of compressive stresses.

When $\Delta S/S_3$ lies between 0.21 and 0.70 the fracture initiation for non-straddle packers is "radial," by far the best case, because the length of

Fig. 48.
 Fracture-initiation pressure and orientation.

intersection with the well is minimized and there is little likelihood of the fracturing fluid leaking around the packer or other zone-isolation element. The pressure required for initiation is constant, $1.6 S_3$.

For greater $\Delta S/S_3$ the fracture-initiation pattern returns to a splitting mode, but is more favorable now, $\theta = 90^\circ$. The initiation pressure actually decreases with increasing $\Delta S/S_3$, varying from $1.6 S_3$ at $\Delta S/S_3 = 0.70$ to $1.3 S_3$ at $\Delta S/S_3 = 1.0$.

For straddle packers in which the axial forces are supported by a rigid connection between the two packers, only very small axial stresses can be induced in the rock so that radial fractures are not possible. In this

situation, the range of $\Delta S/S_3$ for unfavorable splitting fractures is extended to 0.33, and favorable splitting fractures occur from $0.33 \leq \Delta S/S_3 \leq 1.0$.

5.4.3. Comparison of Theoretical and Experimental Fracture Initiations.

We have simulated the above fracturing behavior in 0.14-m cubes of Plexiglas. Approximately 4-mm-diam boreholes are drilled into the cubes at an angle of 30° from the vertical direction and oil is pumped into the hole until the pressure is sufficient to fracture the cubes. The cubes are loaded in the rock-mechanics press so that the vertical stress S_1 is 6.9 MPa, S_2 is varied from 0 to about 1.5 MPa, and S_3 is zero. Because the Plexiglas is impermeable we need not consider effective stresses, but do need to be concerned with the strength of the Plexiglas when evaluating the absolute magnitude of the fracturing pressure. It can be shown that for 30° , rather than the 35° considered above:

$$\begin{aligned}\sigma_1 &= 0.75 S_1 + 0.25 S_3 = 5.2 \text{ MPa} \\ \sigma_2 &= S_2 \\ \sigma_3 &= 0.25 S_1 + 0.75 S_3 = 1.7 \text{ MPa} .\end{aligned}\tag{14}$$

Also, the concentrated hoop stress at the borehole wall is

$$\begin{aligned}\sigma_\theta &= 3 S_2 - 1.7 \text{ MPa} ; \theta = 0^\circ \\ \sigma_\theta &= 5.7 \text{ MPa} - S_2 ; \theta = 90^\circ .\end{aligned}\tag{15}$$

By equating the two hoop stresses it can be shown that if $S_2 = 1.7$ MPa, a fracture is just as likely at 90° as at 0° . In the actual experiments it was found that the dividing stress between fractures at 0° and 90° occurred at $S_2 = 0.76$ MPa. It is interesting to note that when S_2 was less than 0.6 MPa, not only did the fractures initiate at $\theta = 0^\circ$; they actually continued to propagate in this direction, opening against the higher stress S_2 until they penetrated the nearest free surface of the cube.⁶⁵ At this point the oil leaked out and the tests were terminated. The discrepancy between the theoretical and experimental dividing stresses is probably caused by the small size of the cubes and the end effects associated with both the bottom of the hole

and the tubing, i.e., the simulated casing that was glued into the upper portion of the borehole. Nevertheless, the discrepancy is small in absolute terms, only 1 MPa, and suggests that the above theoretical analysis is reasonably accurate.

5.4.4. Laboratory Hydraulic-Fracturing Experiments. Model experiments were carried out to study the phenomenology of hydraulic fracturing from an inclined borehole such as exists at Fenton Hill. Plexiglas cubes of about 6-in. (15-cm) dimensions were used. The simulated boreholes were drilled in the plane containing the S_1 and S_3 (maximum and minimum) principal stresses and inclined 30° to S_1 . Stresses of $S_1 = 1000$ psi (6.9 MPa), $S_3 = 0$ psi (0 MPa), and $0 \text{ psi} \leq S_2 < 150$ psi (1.03 MPa) were used for illustration purposes. For values of the intermediate stress, S_2 , greater than about 100 psi, (i.e., $|S_2 - S_3| > 10\% |S_1 - S_3|$) fracture growth was in the plane perpendicular to S_3 .^{*} This is the normal textbook direction and the one for which the geometry of EE-2 and EE-3 was designed. For values of $|S_2 - S_3| < 5\% |S_1 - S_3|$, corresponding to small values of S_2 , the situation was very different. In these cases fracture growth was predominantly perpendicular to S_2 . Tensile stress concentrations due to S_1 and located along the top and bottom sides of the hole cause this phenomenon. With intermediate values of S_2 (i.e., $0.05|S_1 - S_3| < |S_2 - S_3| < 0.1|S_1 - S_3|$) a transitional case is observed. The fracture begins growing perpendicular to S_2 and turns, within the block, to become perpendicular to S_3 . At values of $|S_2 - S_3|$ above $0.08|S_1 - S_3|$ only 5 or so borehole diameters are needed for turning to be complete. At lower values considerably more space is needed. The results suggest that at low values of $|S_2 - S_3|$ the fractures would eventually have turned perpendicular to S_3 if the blocks had been sufficiently large.

Experiments with two boreholes tested the value of pressurizing the second borehole. When the second borehole is not pressurized, it was seen, as expected, that a significant compressive stress concentration extends only a few borehole diameters away from the borehole. Pressurizing the second borehole was observed not to affect appreciably fracture growth from the first borehole. However, inflating a pre-existing fracture or joint could cause an appreciable effect on fracture growth under special conditions. Inflation of

^{*} We describe results in terms of stress differences because a purely hydrostatic stress, $S_1 = S_2 = S_3$, will have no preferred fracture orientation.

a pre-existing crack to sufficient pressure can locally change the directions and magnitudes of S_2 and S_3 . Inflation pressures in excess of S_2 are required. Pressures 30-50% of $|S_2 - S_3|$ greater than S_2 are needed to affect a significant volume. Only two mechanisms allow pressure in a fracture to become greater than the closing stress: material strength and flow impedance. In rocks, the strength is sufficient for this only in very small fractures, say 5 or 10 cm in diameter. Consequently, at Fenton Hill, only flow impedance can raise the pre-existing fracture pressure significantly above the normal stress.

5.4.5. Tensile Strength of Reservoir Rocks. Brazil indirect tensile tests were performed on EE-2 core samples. Throughout the wide variety of rock types present in the reservoir the tensile strength was remarkably consistent. Tensile strengths were all about 2600 psi (18 MPa) except for the meta-volcanics at 12 850 ft which were about 4200 psi (29 MPa).

5.5. Tracer Studies

5.5.1. Improvements to FEHM Model. The finite-element heat-and-mass-transfer code (FEHM) has been supplemented with the facility for solving the convection-diffusion equation.⁵⁹

The tracer-injection mode considered so far is continuous injection beginning at $t = 0$. After a stationary flow regime is established, the calculation of velocities, energy transport, etc. is no longer performed, as one is interested primarily in the stationary flow (under loop conditions) -- particularly in questions of flow channeling, multiple flow paths, etc.

The underlying physical model is that of a two-phase flow in porous medium. However, only one-phase flow is considered here. The flow is assumed to take place in a thin plane confined on either side by an impermeable medium in which energy is transported only by heat conduction. The finite-element method used in the code accounts for anisotropy and heterogeneity of permeability, thus enabling the study of flow channeling, etc., by assigning some regions a higher or unidirectional permeability. This work has just started.

The main problem in numerical convective-transport studies is that of numerical dispersion, measuring the introduction of an additional term to the physical diffusivity, which results from truncation errors introduced by representing true differentials with finite differences.^{66,67} This may lead to an oscillation in solutions, or the smearing out of sharp points or dis-

continuities. In finite calculations, this difficulty has been overcome by a weighted-residual approach.^{68,69}

One example of a tracer-breakthrough curve is attached (Fig. 49). Fluid velocities have been calculated for a vertical slab of constant thickness (1 m) with dimensions of 200 x 200 m, and no flux boundary conditions. The inlet well, delivering at a constant rate of $10^{-4} \text{ m}^3 \text{ s}^{-1}$, is located at the center line 55 m above bottom, the outlet 90 m above the inlet. The permeability is assumed to be 10^{12} m^2 (1 Darcy), the tracer dispersion coefficient $10^{-6} \text{ m}^2 \text{ s}^{-1}$. Isothermal conditions are established over all time of flow. Maximum time step was 7.2 h. It is planned to compare curves of this type with those obtained by incorporating anisotropy, multiple flowpaths, etc., to allow for a better inversion of field data.

Fig. 49.

Example of a tracer-breakthrough curve. On the abscissa, the number of days elapsed since the start of continuous tracer injection is shown; on the ordinate, the ratio of tracer concentration at the outlet to concentration at the inlet, which is held constant all the time at the value of 1.

5.5.2. Transport of a Nonreactive Tracer Through Fractures with Two-Dimensional Flow. Modeling of Fenton Hill tracer tests has been based primarily upon the superposition of several solutions for one-dimensional flow conduits.⁷⁰ However, because of the variation of transit times along the two-dimensional flow streamlines in a fracture, the tracer concentration at the production well appears to be dispersed. This is hydrodynamic dispersion, and to illustrate its effects two simple fracture geometries are considered. In the first, shown in Fig. 50, the spacing between the inlet and outlet is L , but the fracture itself is infinitely large. The flow streamlines thus have the classic patterns given by a dipole. The first and shortest streamline, ψ_1 , is the straight line connecting the inlet and outlet. If the transit time for this first streamline is t_1 , then if $t < t_1$, the concentration at the outlet well must be zero, but for $t \geq t_1$, c begins to increase. Let the value of the second streamline, ψ_2 , be 0.1, so that 0.1 of the total flow rate lies in the crescent between ψ_1 and ψ_2 . Then the concentration, c , is equal to $\psi_2 = 0.1$ when $t = t_2$. Continuing, for $\psi_3 = 0.2$, arriving at t_3 , then $c = 0.2$ when $t = t_3$ and so forth. Thus

$$c = \psi_i(t_i) \quad (16)$$

and in this way the concentration-time curve at the outlet well can be constructed. Using Ref. 71 it can be shown that the arrival time, t , for any streamline ψ , is

$$\frac{t}{t^*} = 4 \frac{1 - \psi \cot \theta}{\sin^2 \theta}, \quad (17)$$

where $\psi = \psi/\pi$ and t^* is the mean or characteristic time required for flow-rate Q to transport the fluid volume equal to the fracture opening, or aperture, times the area of a circle with a diameter equal to the well spacing. A plot of c vs t/t^* is presented for the dipole fracture in Fig. 51. Note that $c = 0$ until $t/t^* = 1.333$, at which time the flow along the shortest streamline reaches the outlet well and c begins to increase. Because of the slow meandering of the flow along the outer streamlines of the infinitely large dipole fracture, it takes an infinite amount of time for the concentration to attain 1, its maximum dimensionless value. But for most of the flow paths the times are much shorter - for example, 50% of the flow ($c = 0.5$) arrives at $t/t^* = 4$, and 70% arrives at $t/t^* = 16$.

Fig. 50.

Streamlines for dipole fracture. Streamline ψ_1 represents 0% of the flow rate, ψ_2 represents 10%, and so forth.

Fig. 51.

Concentration-time curves for continuous tracer injection. Time t^* is the characteristic mean transit time for the well-spacing-controlled fracture volume.

A more realistic fracture geometry is depicted in Fig. 52, and its concentration-time curve is compared to that of the dipole fracture in Fig. 51. The fracture is relatively confined compared to the well spacing L ; the fracture radius, R , is $2/L3$, whereas for the dipole $R/L \rightarrow \infty$. The fracture aperture, w , was taken as constant for simplicity. The streamlines in Fig. 52 were computed with the TEACH Program.⁷² The first tracer arrival in the realistic fracture occurs at $t/t^* = 0.6$, whereas for the dipole fracture, in which the streamlines fan out more and allow a slower velocity along the shortest streamline, the first arrival was at 1.33. The velocity along the $\psi = 1.0$ streamline is infinitesimally small at some points in the more realistic fracture. (These points are stagnation points and occur at the extreme top and bottom of the fracture at the symmetry line.) So it again takes an infinite time to attain $c = 1$. However, compared to the dipole fracture, the bulk of the flow arrives faster—50% arrives at $t^* = 1$, and 70% at $t/t^* = 1.3$.

Fig. 52.
Streamlines for realistic fracture, $R = 0.667L$.

The production-well concentration curves in Fig. 51 are for the case where tracer is injected continuously. In reality, tracers are usually injected only for a finite time Δt . To find the production-well concentration for finite-duration injection, one differentiates the solutions for continuous injections, and Fig. 53 results. Notice that the concentration-time curves for both fractures are similar: both exhibit sharp arrivals, peaked maximums, and then rapid declines with time. The concentration peak for the realistic fracture occurs very close to $t = t^*$, so that the modal volume, V_p (the volume at the time when c is maximum), which we have often used in the past, is an excellent measure of that volume, $\pi L^2 W/4$, which corresponds to that part of the fracture dominated by well spacing, rather than the actual total fracture volume. Considering the extremes of fracture geometry, with the two cases considered, it is clear that measured modal volumes in the limited-duration tracer-injection test will always provide values close to the well-spacing-dominated volume. Because the modal volume reflects to some degree whatever spreading of the streamlines occurs when R/L is large, it mimics the behavior

Fig. 53.
Concentration-time curves for limited-duration tracer injection. Injection duration is Δt .

of the effective heat-transfer area. This provides additional justification for the argument that, to a first approximation, the heat to be extracted from a fracture is almost independent of its physical size, but is primarily dependent upon the well spacing.

5.5.3. Measuring Temperature Patterns in HDR Reservoirs with Chemically Reactive Tracers. When estimating thermal drawdown in commercial HDR reservoirs, one prefers not to wait until the outlet temperature of the water actually begins to decrease. Prediction of reservoir life is desired long before this occurs, and so it is essential that methods be developed for evaluating thermal drawdown by other means early in a reservoir's life. Thus we are devising methods for measuring temperature patterns in HDR reservoirs remote from the production well. Two techniques are being developed.

The properties of silica dissolution into water offer a basis for a practical method for measuring remote temperatures. Quartz, once dissolved, usually does not precipitate in the same form. Because of the solubility properties of the altered form, significant cooling can take place without precipitation of the dissolved silica. The saturation concentration of quartz increases steeply with temperature, and a residence time of a few hours is sufficient to reach equilibrium at temperatures typical of the higher ones encountered in HDR reservoirs. Because cooling does not precipitate it, the silica content of a water sample indicates the highest temperature reached by a sample during its travel within the reservoir. Consequently, the silica in the water leaving a reservoir can be used as an indication of the maximum temperature encountered in the reservoir.

Silica dissolution also can be the basis for determining the temperature profile within a reservoir. First, fresh water is fed into the reservoir from the injection well, long enough so that the region of interest in the reservoir is completely filled with fresh water. The water is then allowed to remain there for about 2 h, which should be sufficient for the solid quartz and dissolved silica to reach equilibrium. After this, a reverse flush is carried out, which forces the water in the reservoir back into the injection well. It is analyzed for silica concentration when it reaches the surface. Because of temperature drawdown, the lowest temperature in the reservoir will be adjacent to the injection well. The water emerging from the reservoir first will have the lowest silica content. With time, the silica content will rise, indicating the rise in temperature farther into the reservoir. Analysis

of the data will take different paths, depending on what flow pattern exists within the HDR reservoir. Three situations are considered: single-fracture flow, multiple-discrete-fractures flow, and multiple-connected fractures flow. Separate tracer studies will be used to identify the flow pattern within the reservoir.

Analysis of the data is simplest if a single fracture dominates the flow so that the presence of secondary flow paths or even the migration of original pore fluid can be ignored. The length of time that has passed since the start of the reverse flush and the flow rate of the water emerging from the fracture will indicate the location within the reservoir with a particular silica content. The temperature at that point can be directly related to the silica concentration, and the change in silica concentration with time will give the temperature profile within the reservoir.

For the multiple-discrete-fractures model, the average silica concentration in the emerging fluid results from flows originating from several different points within the reservoirs,

$$q_{gr} \bar{C}_{Si}(0,t) = \sum_{i=1}^N q_i C_{Si}(u_i t, 0) \quad (18)$$

In this expression, the values of i represent serially the flows with increasing velocity, i.e., $i = 1$ stands for the flow with the lowest velocity, u_1 , and so on until $i = N$ signifies the flow with the highest value of velocity u_N . The average concentration $\bar{C}_{Si}(0,t)$ is the measured variable in this experiment. The q_i 's (volumetric flow rates in the individual fractures), the u_i 's (linear velocities in the individual fractures), and q_{gr} (the gross volumetric flow rate) are known from nonreactive tracer tests and well logging. With this information, the desired concentration profile $C_{Si}(0,t)$ can be obtained by repeated application of the formula:

$$q_{gr} \bar{C}_{Si}(0,t) = q_N C_{Si}(u_N t, 0) + \sum_{i=1}^{N-1} q_i C_{Si}(u_i t, 0) \quad (19)$$

Because the quantity $u_N t$ is greater than all the other $u_i t$'s at any value of t , the values of $C_{Si}(u_i t, 0)$ in this equation have been determined for all i 's less than N . Only the term $C_{Si}(u_N t, 0)$ is unknown in Eq. (19) at every iteration. Equation (19) thus can be solved repeatedly for values of $C_{Si}(u_N t, 0)$ at increasing values of t until the concentration profile over the entire region at $t = 0$ is obtained. The temperature profile can be determined directly from the concentration profile, as discussed earlier.

When multiple fractures are connected often enough so that frequent mixing occurs, then one-dimensional Taylor dispersion theory suggests that the flow within the system can be modeled by the convective diffusion equation

$$\frac{\partial \bar{C}_{Si}}{\partial t} = D_e \frac{\partial^2 \bar{C}_{Si}}{\partial x^2} - \bar{u} \frac{\partial \bar{C}_{Si}}{\partial x} \quad (20)$$

in which the effective dispersion coefficient D_e depends on the individual flows within the various fractures and the frequency of mixing. For this equation we know the concentration at the two boundaries and the final concentration, and we wish to find the initial concentration profile. This is one of a class of well-known inversion problems that are usually solvable using numerical methods. Such methods are currently being investigated.

Determining temperature patterns in HDR reservoirs by the silica-dissolution method appears to be simple and practical, but it requires interrupting normal system operation during implementation. A second approach, using chemically reactive tracers injected into the circulating water, would not have this drawback. The rates of most chemical reactions are very sensitive to temperature, and this property is used as the basis for remote temperature measurement. The rates of most first-order, liquid-phase, irreversible chemical reactions can be expressed by

$$\frac{dC}{dt} = - A e^{-E/RT} \quad (21)$$

in which A is the pre-exponential factor, E the activation energy, R the gas constant, and T the absolute temperature. If the tracers undergo first-order reactions, this expression can be used in the three model situations described

above. For the single-fracture flow without dispersion, the effluent concentration of the reactant C_f would be described by the expression

$$\ln \frac{C_f}{C_0} = - A\tau \int_{T_{\min}}^{T_{\max}} e^{-E/RT} n(T) dT \quad (22)$$

in which τ is the total residence time of the fluid in the fracture and $n(T)dT$ is the fraction of this time spent at temperatures between T and $T + dT$. Equation (22) is a Fredholm equation of the first kind. If a suite of reactions with various activation energies were used, this equation could be solved for the distribution $n(T)$. This is an inverse problem of a different type than that posed in the silica-dissolution technique, and somewhat easier to solve.

When there are multiple discrete fractures the tracer will appear at a number of different points in time, corresponding to the different resident times in the various fractures, τ_i . Equation (22) then would apply to each of the multiple fractures, and N temperature distribution functions $n_1, n_2, \dots, n_N$ would be obtained.

The multiple-connected-fractures model presents a complicated situation which is still being analyzed.

Some approximations can be made that yield simple techniques giving quick estimates of thermal drawdown and reservoir life. For example, consider the very simple temperature distribution for a single fracture,

$$T = T_i; \quad x/L < \beta \quad (23)$$

$$T = T_r; \quad x/L \geq \beta$$

in which T_i is the water injection temperature and T_r is the virgin rock temperature, which is the sort of sharp thermal break-through front that often occurs for volumetric heat sources; it approximates the usual smooth error-function distribution for one-dimensional flow in rectangular fractures. Using Laplace transforms the ratio of the outlet and inlet tracer concentrations is,

$$C_f/C_0 = 0; \quad t < L/u \quad (24)$$

$$\ln(C_f/C_0) = -\beta k_{\min} L/u - (1-\beta) k_{\max} L/u ; t \geq L/u , \quad (25)$$

where $k_{\min} = A \exp(-E/RT_{\min})$ is the minimum reaction coefficient and $k_{\max} = A \exp(-E/RT_{\max})$ is the maximum coefficient, L is fracture length, u is fluid velocity, and β is the fraction of the fracture that is thermally drawn down from the initial temperature T_r to T_i . Because $k_{\max} \gg k_{\min}$, Eq. (25) simplifies to

$$\ln(C_f/C_0) = -(1-\beta) k_{\max} L/u, \quad t > L/u . \quad (26)$$

Equation (24) states that for a duration equal to one reservoir transit time, L/u (or equivalently, the quotient of reservoir volume V and flow rate Q), the outlet concentration is zero while the initial water, free of tracer, is flushed from the reservoir. At $t = L/u$ (or V/Q), the outlet concentration will suddenly increase to the value given by Eq. (26), thus providing an estimate of the volume of the reservoir analogous to similar estimates provided by chemically inert tracers used in the past. Note that so long as $t \geq L/u$, the outlet concentration is predicted to be steady. This is a consequence of the assumptions that the tracer is injected continuously (at least for the day or so required to perform the tracer test) at the constant value C_i , and that temporal temperature changes are negligible during the tracer test.

A particularly attractive test sequence is to inject a chemical tracer very soon ($\theta \approx 0$) after circulation begins so that β is still zero because the thermal drawdown is negligible. Denoting the asymptotic value of the outlet concentration from this early test as C_0 ($\theta = 0$), Eq. (26) yields:

$$k_{\max} = \frac{-u}{L} \ln \left[C_0(\theta=0)/C_i \right] . \quad (27)$$

Thus the reaction-rate coefficient need not even be estimated from laboratory tests but can be estimated directly from the early tracer test. The reservoir drawdown fraction β can then be estimated for subsequent tracer tests at time θ as

$$\beta(\theta) = 1 - \frac{\ln C_0(\theta)/C_i}{\ln C_0(\theta=0)/C_i} . \quad (28)$$

5.6. Cement Studies

Cement formulations for use in the Fenton Hill HDR geothermal systems were developed and tested. Both Dowell and Halliburton devised formulations appropriate for cementing a liner and PBR assembly into EE-2 at 4420 m (14 500 ft) depth. The static temperature at this depth is about 315°C (600°F). These formulations were tested in our autoclave, which can be programmed to simulate downhole conditions during the setting of the cement. As a result of this testing program three formulations were selected and these were ranked in the order of preference. The preferred formulation was

- Amarillo Class H cement
- 40% silica flour (SiO_2)
- 5.5% Dowell D-121 dispersant-retarder
- 5.43 gal/sk water
- 0.2% Dowell D-46 anti-foaming agent.

The autoclave tests of this and other cement formulations showed that the kinetics of the setting and curing are sensitive to the profile of the temperature recovery of the well. This temperature profile can, to some extent, be controlled by the pumping operations just before cement placement.

Before the PBR assembly was cemented in place the cement and the equipment used to place the cement were tested experimentally by mixing a batch of the cement and pumping it into the well at the selected depth, 4420 m. All the mixing and pumping equipment were the same as those to be used in the final placement of the PBR except that the cement was retained in a pipe instead of being placed in the open hole. After allowing time for the cement to set and start to cure, the pipe was withdrawn from the well and the cement and placement apparatus were inspected. This unique test was very successful.⁷³

Subsequent to the downhole cement test, the PBR assembly was successfully cemented into EE-2. Later in 1982, another PBR assembly was successfully cemented into EE-3 at a depth of 3415 m (11 200 ft). The cement formulation was modified to accommodate the lower static temperature of 215°C (420°F) by reducing the concentration of D-121 to 2.6% and the water to 5.28 gal/sk.

5.7. Wellbore Completion Problems and Investigations

5.7.1. Completion Problems.

5.7.1.1. Gases Emerging from EE-2/EE-3. When hydraulic-fracturing operations were performed in the wells, one result was that large quantities of gases began emerging from the wells. Although a number of gases (H_2 , O_2 , He, CO, H_2S , Ar, and hydrocarbons) were at times present in small quantities, the major constituent is CO_2 . The CO_2 is present to the extent of 90 to 99%. H_2S is present in rather small quantities of the order of 60 ppm.

The gas flows from the wells erratically and EE-3 geysers fairly regularly. One of the few measurements made gave a value of about $8490 \text{ m}^3/\text{day}$ (300 000 SCF/day). During this period about $48 \text{ m}^3/\text{day}$ (1700 cu SCF/day) of water was being vented. At another time it was determined that about equal volumes of gas and water were being vented from EE-2 but no absolute measurement of flow rate was possible.

The emission of these gases presents several problems. (a) A safety problem both because of kicks during workover operations and because of the toxicity of the H_2S ; (b) CO_2 , O_2 , and H_2S are known to cause severe corrosion to the steels used in well completion; and (c) it may be necessary to remove these gases from the circulating fluids after a circulating loop has been established.

5.7.1.2. Corrosion and Failure of Downhole Pipe and Casing. During four attempts to fracture EE-2 and EE-3 hydraulically the frac strings have failed at least six times. Some data on these failures are listed below.

<u>Date found</u>	<u>String and location</u>	<u>Material</u>	<u>Depth of failure</u>
7-9-82	3.5-in. drill pipe, near box end	S-135	~1000 ft
7-24-82	3.5-in. drill pipe, near box end	S-135	~2542 ft
7-27-82	3.5-in. drill pipe, in slips area	S-135	~5549 ft
10-4-82	4.5-in casing coupling	P-110	~9247 ft
10-10-82	4.5-in. casing coupling	P-110	~9300 ft
12-17-82	4.5-in. drill pipe, 7 ft below box end	S-135	~1774 ft

These cracks were examined visually and using a scanning electron microscope. The cracks in the drill pipe were 2 to 3 ft long and generally

parallel to the long direction of the pipe. The cracks in the casing couplings also paralleled the long direction of the casing. All cracks observed seemed to originate at indentations in the steel resulting from handling the pipe with the elevators, tongs, and slips. All of the failures observed occurred in steels that were of a tempered martensite structure. The microscopic examination of the cracks revealed a branching pattern of the cracks indicating failure along prior austenite grain boundaries. These observations plus the analyses of the gases and fluids in the wellbore indicate that the failures were almost certainly stress-corrosion failures, initiated at indentations caused by the tools used in handling the pipe.

Because it is known that as little as 1 ppm of H_2S can cause sulfide stress-corrosion cracking (SSCC) it is assumed that this is the mechanism of failure. However, CO_2 and O_2 in the gases as well as various compounds dissolved in the fluids could also have contributed to stress-corrosion failure.

Steps are being taken to prevent similar failures in future hydraulic-fracturing attempts.

5.7.2. Investigation of Hydraulically Set Casing or Liner. The cementing of liner or casing in geothermal wells can often be difficult because of the high-temperature exposure of the cement during its emplacement and setting. A possible alternative to cementing is to use ductile steel liners and hydraulically expand and deform the liners as shown in Fig. 54 until they are in intimate contact with the rock wall of the well. To investigate this alternative a stress-deformation analysis was performed, similar to the analyses of auto-fretting, the principle of using plastic deformation to strengthen thick-walled pressure vessels, for example, gun barrels. Four pressurization stages were considered,

- (1) elastic expansion of the liner,
- (2) plastic expansion of the liner until the rock wall is contacted,
- (3) continued plastic expansion of the liner and elastic expansion of the rock to the maximum pressure, and
- (4) elastic depressurization of the liner and the rock.

For best sealing of the rock/liner interface, the rock should be pressurized in stage (3) to as high a value of radial stress as possible without fracturing the rock, because rock fractures will provide flow paths around the liner and might hinder later operations in which zone isolation is desired. It is assumed that the rock tensile strength is effectively zero, and that the

Fig. 54.
Expandable-liner concept.

two components of effective earth stress acting on the well are equal and equal to S_{eff} ; then the maximum radial stress that can be exerted on the rock is $2S_{eff}$. The pressurization of the rock during stage (3) results in rock displacement, which then decreases during "springing" in unloading stage (4). The whole operation must be designed so that, at the conclusion of stage (4), the residual rock springing is maximized, resulting in maximum sealing of the contact between liner and rock. The ratio of final to maximum springing [end of stage (4) compared to end of stage (3)] is

$$\frac{\Delta}{\Delta_{max}} = \frac{K - P_y/2S_{eff}}{1 + K}, \quad (29)$$

where Δ is the springing, P_y is the liner yield stress, and $K = (1+\mu)\frac{E_c t}{E_R a}$. In

the last expression E_C and E_R are Young's elastic modulus of the casing, or liner, and the rock, respectively; μ is Poisson's ratio for the rock; t is the liner thickness, and a is the well radius. To avoid loss of contact we require $P_y/2S_{eff} \leq K$. If one also requires that $P_y > 2S_{eff}$ to avoid repeated yielding in unsupported regions of the liner, then one requires $K \geq 1$. A similar conclusion can be derived from Fig. 55 in which the rock-springing ratio is graphed for values of $P_y/2S_{eff}$. The residual springing is a small fraction of its maximum value except for large K . Even if $P_y/2S_{eff} = 0$, and $K = 1$, the springing ratio is only 0.5; if $P_y/2S_{eff} = 1$, a more reasonable value, then the ratio is 0 if $K = 1$, and 0.3 if $K = 2$. One can easily compute other examples, but it soon becomes apparent that reasonable designs require that $K > 1$.

Typically $\mu = 0.25$, the average value of E_R is about 2×10^6 psi, and a is about 4.4 in. Consequently, if a steel liner is used, $E_C = 30 \times 10^6$ psi, then $t \geq 0.2$ in. to satisfy $K > 1$. If, to be somewhat arbitrary, $K = 2$ is selected for conservativeness, then $t = 0.4$ in. For an aluminum liner, $E_C =$

Fig. 55.

Residual rock "spring." E_C is Young's elastic modulus of the expandable casing or liner.

10^7 psi, then we require $t \geq 0.6$ merely to satisfy the minimum requirements of interfacial contact, and $t = 1.5$ in. to be as stiff as a steel liner, so that surprisingly thick liners are required. On a more physical basis this can be explained on the basis that a very stiff liner is required so that, upon depressurization, the elastic rebound of the liner is less than that of the rock. The problem is aggravated by the fact that the liner is pressurized to a final value of $P_y + 2S_{eff}$ at the end of stage (3) but the rock was only pressurized to $2S_{eff}$. Thus the two effects reinforce each other: a stiff liner usually results in large P_y , which in turn requires even greater stiffness to counteract the increased rebound for increased P_y . The ideal liner material would have very high elastic modulus and, if we could set aside fears about repetitive yielding of the liner, zero yield stress.

6.0. COMMERCIAL FEASIBILITY ASSESSMENT

Previous economic studies of HDR energy systems have concentrated on their potential usefulness as relatively high-temperature energy sources for generating electricity, for which they appear promising. Of approximately equal importance, however, is their possible use to supply lower temperature heat for direct use in such applications as space heating, greenhousing, and processing foods, crops, chemicals, and wood products. The technical feasibility of doing this has been demonstrated by the Phase I HDR system at Fenton Hill. Its economic feasibility for one specific case has now been examined at Wallops Flight Center, Wallops Island, Virginia. The case study is reported in detail in Ref. 74 and is summarized below.

The main base of NASA's flight center currently uses oil-fired boilers to deliver an average of 72.8×10^9 Btu [21 300 MWh (t)] annually for space heating, in the form of steam at 125 psig. The bulk of the old distribution piping is being replaced by pipe suitable for distribution of hot water, with which a minimum temperature of 165°F (74°C) would be adequate for space heating.

At Wallops Island, the geothermal gradient is 30°C/km (16.5°F/1000 ft) and the depth to basement rock is about 2750 m (9000 ft). In assessing the economic feasibility of supplying heat for the main base from an HDR system, it was assumed that the geometry of the underground heat-extraction loop would be generally similar to that of the Fenton Hill Phase II system, with the

lower sections of the two wells inclined and extending into basement rock far enough to ensure containment of pressurized water. In the base case considered in this study, it was assumed that a minimum well depth of 3436 m (11 273 ft) would be required and the wells would be connected by a single hydraulic fracture 360 m (1181 ft) in diameter, through which water would be pumped at 830 gallons per minute (52.36 kg/s). A real discount rate of 7.25% was assumed, together with assumptions concerning escalations in drilling cost and the cost of the fuel oil now being used. A useful lifetime of 30 years was specified, and the costs of distribution piping and heat exchangers were included.

Parametric studies were made in which well depth, number of fractures, rates of cost escalation, and discount rate were varied, and the analysis was extended to other hypothetical locations at which geothermal gradient, depth to basement, and heat requirement were different from those at Wallops Island.

For the Wallops Island situation several of the HDR systems considered were found to yield net financial benefits relative to continued use of an oil-fired system. For example: (1) With an initial drilling depth of 3566 m (11 699 ft) and four parallel fractures, all energy requirements would be met for 29 years, but during year 30, reservoir temperature would drop to slightly below the specified 165°F (74°C). To avoid the high cost of redrilling, an increment of temperature would be added during the final year by operating the existing oil-fired boiler. Including that option, total cost of the system was estimated at \$10.9 million and net benefit was calculated to be \$4.1 million, in 1980 dollars, over the full 30-year lifetime of the system. (2) Increasing well depth to 4089 m (13 415 ft) and producing only three fractures would make it unnecessary to provide additional heat, and would produce a net benefit of \$2.9 million.

More generally, an HDR system of this type is clearly feasible in other locations where geothermal gradients are higher and depth to basement is less.

7.0. PROGRAM MANAGEMENT

7.1. Program Organization

During FY82, some significant organizational changes were made in the management structure of the HDR Program within the Los Alamos National Laboratory. With the abolition of the Office of Energy Programs, the HDR Program

was placed under the Chemistry, Earth and Life Sciences (CEL) Directorate, headed by its Associate Director, John H. Birely. Within the CEL Directorate, the program is managed from the Earth and Space Sciences (ESS) Division, as shown in Fig. 56. John T. Whetten is the HDR Program Manager (as well as Deputy Division Leader for Earth Sciences of the ESS Division).

The present programmatic organizational structure is depicted in Fig. 57. As indicated, the HDR Program continues to be field-managed jointly by Los Alamos, as described above, and the Energy Technologies Division of the DOE/ALO(ET), 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 its International Steering Committee, which has jurisdiction over resolution of major programmatic problems and approval of proposed changes with significant schedule and/or fiscal impact.

7.2. International Steering Committee

The Fenton Hill Project's International Steering Committee (ISC) met just once in FY82, at DOE Headquarters in Washington, DC, on April 22, 1982. Present at this fifth meeting of the ISC were the official representatives of the Contracting Parties

Fig. 56.
Los Alamos Directorate for Chemistry, Earth and Life Sciences.

J. C. Bresee (DOE, Chairman)
W. P. Grace (DOE)
W. Schloemer (KFA)
Y. Yamashita (NEDO)

and their advisors. Bresee was introduced, replacing C. Carwile as committee chairman.

Minutes of the previous ISC meeting were approved. Los Alamos presented fiscal summaries for FY80 and FY81, which were also duly approved. A draft of the HDR annual report to the IEA was accepted without change.

R. B. Olwin of Los Alamos gave an overview of the Project's status, focusing upon accomplishments since the previous ISC meeting. M. Kuriyagawa, NEDO assignee to Los Alamos, made a detailed presentation on the results of EE-2 and EE-3 pressurization experiments and their implications. The FY82 Annual Operating Plan was then discussed in some detail.

The remainder of the meeting was devoted to the FY83 budget prospects. Bresee discussed the FY83 "President's Budget" from the perspective of budget-related actions that had recently taken place in Congress. The implications were discussed by the Committee at large. The next meeting was scheduled for early FY83, probably in October at a time and place to be determined.

7.3. HDR Program Development Council

The seventh meeting of the Executive Committee of the National Hot Dry Rock Program Development Council ("the PDC") was held in Albuquerque on April 2, 1982. Present were committee members

S. K. Bazant (Plains Electric Cooperative)
R. Greider (Geothermal Resources International)
G. V. Keller (Colo. School of Mines), Chairman
L. J. P. Muffler (U.S. Geological Survey),

ex-officio members

W. P. Grace (DOE/ALO-ET)
A. J. Jelacic (DOE/DGHT)
R. B. Olwin (Los Alamos)
M. C. Smith (Los Alamos), Secretary,

Fig. 57.
HDR programmatic organizational structure.

Technical Committee chairmen

G. Bodvarsson (Reservoir Engineering Committee)

R. L. Christiansen (Site Evaluation Committee)

and others.

Keller was elected the new chairman of the Executive Committee, replacing outgoing chairman C. M. Swinney. A major portion of the meeting was devoted to the fiscal posture of the Program and the long-delayed FY82 budget release.

Los Alamos reported on the resource evaluation effort, distributed draft copies of a resource-base assessment, and indicated that a revised geothermal gradient map of the U.S. was ready for printing by the National Oceanic and

Atmospheric Administration. The possibility of industrial involvement in the development of a second HDR site was again discussed. Los Alamos also presented a status review on the Fenton Hill Project, preliminary results of recent economic studies, the program schedule for fiscal years 1982-83, and detailed plans for the impending fracturing operations in well EE-2.

The Committee's discussion and recommendations touched a broad range of topics:

- (1) the Committee strongly and unanimously endorsed the two-stage approach ("interim" and "final" configurations) to constructing and testing the Phase II reservoir;
- (2) Plains Electric Generation and Transmission Cooperative, Inc., would require DOE-funded Los Alamos support for several years, if it were to decide to exploit the Fenton Hill Phase II reservoir commercially;
- (3) even in face of highly uncertain budgetary projections, the Committee recommended proceeding with an "adequately comprehensive" technical plan sufficient to meet the Program's overall goal in a sense satisfactory to industry;
- (4) the Committee unanimously endorsed concentrating all field experiment effort in the Fenton Hill Project until that project attains its objectives;
- (5) Keller reported on the Soviet HDR program, as he understood it;
- (6) candidates were suggested for the vacant fifth position on the Committee, who will be contacted during the period before the next meeting.

It was tentatively agreed that the PDC would meet again in 6 months.

7.4. Liaison with Navopache

Liaison was maintained during FY82 with Pan American Energy Corporation representing NAVOPACHE Power Co. Several meetings were held with E. L. Kaufman, President of Pan American, to discuss site selection in eastern Arizona and west-central New Mexico. Two general areas were recommended for a second or alternative site. One of these is in the area south of Sanders, Arizona, where several heat-flow and gradient measurements indicate the presence of a thermal anomaly. The source of the anomaly is unknown but it could be related either to the Jemez lineament or to radioactive granites of

the Defiance Uplift. A second recommended area lies west of Springerville, where recent work indicates that the youngest volcanism of the region is located. Potassium-argon ages obtained by Los Alamos indicate an age of about 750 000 years for this activity.

7.5. Roosevelt Hot Springs, Utah

This project was initiated in May FY82 to investigate the hydrology and geochemistry of shallow aquifers in the Roosevelt Hot Springs area. It is hoped that a large supply of circulating water will be defined that is useful for future HDR systems but does not compete with agricultural interests in Milford, Utah. This project will continue at least through FY83.

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