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Hot-Dry-Rock Geothermal-Energy Development Program

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Annual Report
Fiscal Year
1981

University of California

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Hot-Dry-Rock Geothermal-Energy Development Program

Annual Report

Fiscal Year 1981

Compiled and Edited by

**M. C. Smith
G. M. Ponder**

Contributors

Hot Dry Rock Program Staff

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HOT DRY ROCK GEOTHERMAL ENERGY DEVELOPMENT PROGRAM
ANNUAL REPORT
FISCAL YEAR 1981

Compiled and Edited by
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Hot Dry Rock Program Staff

ABSTRACT

During Fiscal Year 1981, activities of the Hot Dry Rock Geothermal Energy Development Program were concentrated in four principal areas: (1) Data collection to permit improved estimates of the hot dry rock geothermal energy resource base of various regions of the United States and of the United States as a whole, combined with detailed investigations of several areas that appear particularly promising either for further energy extraction experiments or for future commercial development. (2) Successful completion of a 9-month, continuous, closed-loop, recirculating flow test in the enlarged Phase I System at Fenton Hill, New Mexico -- a pressurized-water heat-extraction loop developed in low-permeability granitic rock by hydraulic fracturing. (3) Successful completion at a depth of 4084 m (13 933 ft) of well EE-3, the production well of a larger, deeper, and hotter, Phase II System at Fenton Hill. Well EE-3 was directionally drilled with control of both azimuth and inclination. Its inclined section is about 380 m (1250 ft) vertically above the injection well, EE-2, which was completed in FY80. (4) Supporting activities included new developments in downhole instrumentation and equipment, geochemical and geophysical studies, rock-mechanics and fluid-mechanics investigations, computer analyses and modeling, and overall system design.

These activities are summarized in this Annual Report, which includes references to more detailed information published elsewhere.

Under an International Energy Agency agreement, the New Energy Development Organization, representing the Government of Japan, has joined Kernforschungsanlage-Jülich GmbH, representing the Federal Republic of Germany, and the U.S. Department of Energy as an active participant in the Fenton Hill Hot Dry Rock Project.

1.0 EXECUTIVE SUMMARY

In the context of geothermal energy, hot dry rock (HDR) is naturally heated crustal rock that is not productive of natural steam or hot water at commercially useful rates because of the absence of circulating natural water in the system. At usefully high temperatures HDR exists everywhere beneath the earth's surface, and that fraction of it that can be reached now, with existing drilling technology, represents the largest supply of usable energy that is accessible to man.

Under unusual geologic conditions, some of this natural heat is transferred to natural steam or hot water trapped beneath the earth's surface in permeable rocks or along large natural fractures. These may constitute economically useful hydrothermal reservoirs. Far more commonly, however, at the depths at which usefully high temperatures are reached, the combination of temperature, pressure, and mineral deposition has reduced the permeability of the rock to the point at which circulation or accumulation of steam or hot water in significant amounts does not occur. This is the typical HDR situation, and the heat in the hot rock represents all but a very small fraction of the geothermal energy in the earth's crust.

To extract this thermal energy and transport it to the surface, the simplest and most economical method is to imitate nature by circulating water through the hot rock. When its permeability is low, this requires that flow passages be created within the rock, with large surface areas for heat transfer. What appears to be the simplest, cheapest, and most environmentally acceptable method of accomplishing this is by hydraulic fracturing.

Hydraulic fracturing is the use of fluid pressure in a wellbore to create cracks that can be extended outward from the well to distances of hundreds of meters. If the cracks intersect or are intersected by a second well, an underground loop is created through which water can be circulated to extract heat from the rock and bring it to the surface. When its useful heat has been removed, the water can be recirculated.

The concept of an HDR energy system of this type originated at Los Alamos in 1970. Since 1972, a program to investigate and develop the method has been sponsored by the U.S. Department of Energy (DOE) and its predecessors. The program is based at Los Alamos National Laboratory, with field experiments principally at the Fenton Hill Geothermal Site about 30 km (20 mi) west of Los

Alamos. Since 1979, supplementary support for the Fenton Hill Project is being provided by agencies of the Governments of West Germany and of Japan.

The overall goal of the HDR Program is to demonstrate the commercial feasibility of HDR energy systems. Accordingly, its principal objectives are: (1) to confirm that the HDR resource base is indeed large and accessible; (2) to develop and demonstrate the feasibility of a commercial technology for recovering thermal energy from HDR; and (3) to verify that the social and environmental consequences of HDR development are acceptable.

During FY81, in addition to the developmental work at Fenton Hill, data collection has continued for a broad regional assessment of the HDR resource base of the conterminous United States. The purpose is to collect and, where possible, supplement all existing temperature information on wells deeper than 50 m (160 ft) in which the temperature regime appears to be conductive; to correlate these data with such other geological, geophysical, and geochemical information as can be obtained; and to summarize and publish the results in forms that will be informative concerning the HDR energy potentials of individual regions and of the U.S. as a whole. Useful data have been provided to the HDR program by the U.S. Geological Survey (USGS) in particular, and from a variety of other sources. In addition, Los Alamos and its subcontractors have collected new information on regions of potential HDR interest in Arizona, Arkansas, Idaho, Illinois, Michigan, Nebraska, New Hampshire, New Mexico, New York, Maryland-Virginia, Vermont, and West Virginia. Where enough reliable information has been assembled to justify it, maps, reports, and technical papers have been published to make the information generally available in a useful form.

Approximately 24 more-limited areas have for some years been under evaluation as possible locations for development of a second HDR experimental site at which to confirm and supplement the results being obtained at Fenton Hill. Seven of these have received particular attention during FY81.

- The Milford Valley in Utah, separated by the Opal Mound fault from the hot-water hydrothermal system of the Roosevelt Hot Springs area. Deep drilling in the valley by several geothermal companies has shown that a very large area is underlain at moderate depths by extremely hot crystalline rock with low permeability and virtually no content of geothermal fluid.

- The Mountain Home area, on the northern margin of the Snake River Plain in Idaho. This has been reported on by Harding Lawson Associates under subcontract to Los Alamos, and additional geologic mapping was done by Los Alamos and Boise State College.
- The Clear Lake area in northern California, separated by the Collayomi fault from the very productive Geysers natural-steam field. Several very hot dry holes have been drilled in the Clear Lake area by various energy companies.
- The Long Valley Caldera in eastern California. In many respects this is quite similar to the Valles Caldera in New Mexico, which is just east of the Fenton Hill experimental site.
- The Cris-Wall area on the eastern coastal plain of the U.S., extending across the Delmarva Peninsula roughly from Crisfield, Maryland, to Wallops Island, Virginia. Under subcontract to Los Alamos, an excellent study of this relatively low-temperature prospect area has been completed by D'Appolonia Consulting Engineers, Inc.
- With support from the HDR Program, a group from Massachusetts Institute of Technology made additional heat-flow measurements and geologic studies of the Conway granites of New Hampshire.

Additional information about HDR possibilities in basaltic formations of the Pacific Northwest was collected in connection with a well-stimulation experiment at Ontario, Oregon, described below, and in planning for a proposed stimulation experiment on the west flank of Mt. Hood -- which was cancelled for lack of funds.

Over a period of several years, the world's first HDR heat-extraction loop has been constructed, modified, and operated successfully at Fenton Hill. It is now identified as the "Phase I" or "Research" system and is a closed, recirculating, pressurized-water loop. Cool water injected through one well (EE-1) is heated as it circulates through hydraulic fractures in hot granitic rock at a depth around 2600 m (8500 ft). The superheated water, pressurized to prevent boiling, is recovered through a second well (GT-2). Its useful heat is removed in heat exchangers at the surface and then the cooled water is reinjected through EE-1 to recirculate repeatedly through the underground fracture system. The system has been operated intermittently in this closed-loop mode since 1978. Major flow tests are identified as "Run

Segments," and many shorter-term experiments have been conducted during and between them.

During FY79 the Phase I system was reworked and its underground flow loop enlarged by additional hydraulic fracturing. It was then flow-tested in Run Segment 4, a 23-day recirculating flow experiment run in October and November of 1979. No measurable temperature drawdown occurred and so Run Segment 5, a much longer flow test, was initiated in March 1980. It continued for 286 days, and its completion and analysis were major activities during FY81.

To enlarge the Phase I system, fluid pressure in EE-1 was used to extend a small hydraulic fracture previously created at a depth of 2930 m (9620 ft), where virgin rock temperature was 197°C. The fracture grew upward through a vertical distance of at least 320 m (1050 ft) and intersected the old fracture system that had been cooled in previous flow tests. Flow during Run Segments 4 and 5 was, then, down well EE-1, up through the newly extended fracture, and across through the old fracture zone to well GT-2.

It was intended to maintain an injection pressure of 9.65 MPa (1400 psi) throughout Run Segment 5, against a back pressure of 1.38 MPa (200 psi) at the production wellhead. However, corrosion/erosion of the cast-steel injection-pump impeller caused injection pressure to decrease slowly with time. (No other corrosion or erosion and no scaling have so far been observed in the system.) Flow rate through the fracture system was generally 5 to 6 m^3/s (80 to 95 gpm) and rate of heat extraction was about 2.2 MW (thermal). Except for a 9-day shut-in to observe temperature recovery and a few shorter shutdowns for special experiments, pump maintenance, or power failures, system operation was smooth and continuous throughout the 9-month run.

Downhole temperature measurements where heated water from the fracture system entered the GT-2 well casing demonstrated a temperature drawdown of 8°C (from 157 to 149°C) over the 9-month period. Preliminary analyses indicate that this represents an effective heat-transfer area -- considering both fracture surfaces -- of about 90 000 m^2 (970 000 ft^2), which is about six times greater than that of the system before it was enlarged. Residence-time studies with a sodium fluorescein dye and with irradiated ammonium bromide showed a volume increase in the fracture system by a factor of about nine as a result of system enlargement, and a further increase -- presumably from thermal contraction of reservoir rock -- during Run Segment 5, which was a linear function of the amount of heat extracted.

A series of radioactive-tracer experiments during Run Segment 5 permitted identification of several separate regions at which fluid entered the fracture system from the injection well and of several exit regions into the production well. Temperature and spinner (flow-velocity) logs showed significant and apparently independent changes in both temperature and flow rate through these various flow paths during the course of the experiment.

Probably because of limited temperature drawdown in the upper reservoir region and constraints on thermal contraction, flow impedance through the fracture system remained nearly constant during Run Segment 5 at 1.6 MPa/l/s (15 psi/gpm). Although this is relatively high, it appears appropriate for individual fractures in the set of parallel fractures contemplated for larger HDR systems.

Water quality remained good throughout Run Segment 5 at <2000 ppm total dissolved solids. As is discussed below, most of the dissolved material evidently was introduced into the circulation loop by flushing out of connate formation water rather than by dissolution of minerals exposed on fracture surfaces. Water loss by permeation of the reservoir rock decreased to about 0.46 l/s (7 gpm) near the end of the run. At the same elapsed time, it was only about 30% greater than in earlier tests run before the system was enlarged -- in spite of an increase in effective heat-transfer area by a factor of six. Presumably this can be explained in terms of reduced permeability at greater depth because of higher compressive loading.

By day 281 of Run Segment 5, about 15 million kWh of thermal energy had been extracted from the enlarged Phase I reservoir. However, the volume increase of the fracture system (measured by tracer residence-time studies) was only about one-tenth of that expected from thermal contraction of an unconfined body of stress-free granite. At least in part, this can be attributed to constraints on relative motion of opposite fracture surfaces imposed by compressive earth stresses. Accordingly, on December 9, 1980, a "stress unlocking experiment" (SUE) was conducted. With well GT-2 shut-in, water was pumped into EE-1 until wellhead pressure reached 15 MPa (2200 psi), which was considered sufficient to inflate the fracture system and thus permit some degree of stress relief by shearing displacements of opposite fracture faces. Then, to equalize pressures throughout the fracture system, EE-1 was shut-in and additional water was pumped into GT-2. Finally, both wells were shut-in.

Downhole geophones were stationed in GT-2 and in a new well, EE-2, to detect the microseismic signals expected to accompany relief of locked-in thermal stresses. Small seismic events, with magnitudes between -4 and -2 on the extrapolated local Richter scale, began to appear when pressure at the EE-1 wellhead reached about 9.5 to 11 MPa (1400 to 1600 psi). Their occurrence rate increased as pumping continued, increasing sharply at about 15 MPa (2200 psi), then died off quickly when pumping into EE-1 stopped. The increase at 15 MPa is believed to represent the onset of additional hydraulic fracturing, while the earlier events apparently represent small shearing displacements along fracture surfaces that had been significantly cooled by fluid circulation. Source locations of the early events fall in a relatively narrow zone, roughly vertical and circular in outline, aligned in an approximately north-northwest direction. With a projected area of about 60 000 m² (650 000 ft²), this is believed to encompass the region from which most of the heat was extracted during Run Segment 5, although -- due to permeation and hydraulic fracturing -- it may also include events that occurred outside that region. The later events tended to scatter more broadly than the earlier ones.

Tracer residence-time measurements indicated an increase in fracture volume of 43% during SUE, about twice the volume increase produced by the 281 days of cooling that preceded it. This was accompanied by a significant reduction in flow impedance through the fracture system, with the largest changes in the exit and -- particularly -- the entrance regions.

Samples of the geothermal fluid circulated during Run Segment 5 were collected regularly at the two wellheads, together with samples of the makeup water. Steady-state concentrations of the dissolved species were established quickly but -- due to dilution with makeup water -- began to decline slowly at about day 100. The ratios among the concentrations of most ions in the solution remained essentially constant throughout the run. This was true even when, in two "fresh-water flushes," part or all of the circulating fluid was replaced with fresh water. From this and the recovery behavior, it was concluded that an indigenous pore fluid of essentially constant composition was being displaced from the reservoir rock throughout Run Segment 5, at a substantially constant rate corresponding to 2 to 5% of the flow rate out of the fracture system. Composition of the recirculating heat-extraction fluid was controlled primarily by this infusion of pore fluid. One result was that the Na-K-Ca geothermometer reflected no change in downhole temperature during the

run, indicating an essentially constant temperature of about 195 to 198°C. The quartz geothermometer was inaccurate due to silica introduced by the pore fluid, but did follow the downhole temperature changes -- with a nearly constant error -- except during the periods of the fresh-water flushes.

Noncondensable gas concentrations remained essentially constant throughout the run. The separated gas was highly enriched in carbon dioxide, depleted in oxygen (relative to nitrogen) and contained traces of hydrogen and hydrogen sulfide. Initial radon concentration was very low but increased with time to a steady-state level of 9 to 10 nCi/l. It did not reflect the appearance of new heat-transfer surface in the fracture system.

Hydrologic, biotic, seismic, and meteorological monitoring of the environment at and around Fenton Hill continued throughout FY81. The only environmental effect that has been detected is accumulation of minor amounts of trace elements in the normally dry stream bed that drains the site. This occurs over a distance of a few hundred meters down slope from the point at which excess water has occasionally been discharged from mud ponds and holding ponds. There has been no detectable effect on surface or ground waters in the area.

In general, heat extracted from the hot basement rock has been dispersed to the atmosphere -- in order to cool the recirculated water before it is reinjected. However, in May 1980, a skid-mounted 60 kVA (net) binary cycle power plant was installed at Fenton Hill, on a hot-water line that bypasses the cooling tower. In it, a Freon (R-114) is vaporized in a pool boiler by heat from the geothermally heated water. The vapor is expanded through a partial-admission, single-stage, axial-flow turbine operating at 3600 rpm. This drives an alternator that generates three-phase electrical current that is phased into the commercial power supply to the site. The exhaust vapor is cooled and condensed in air-cooled heat exchangers. The unit has been operated only intermittently but, aside from minor initial problems with Freon leaks and electrical circuitry, it has operated very well -- at slightly above its design cycle efficiency.

The Fenton Hill Phase I (Research) System provides a convincing demonstration of the technical feasibility and environmental acceptability of creating and operating an HDR system in hot, dry, low-permeability rock. If it were differently located it could supply the energy requirements of a wide variety of users of relatively low-temperature heat. (It could, for example,

heat about 300 average American homes.) It is not, however, an adequate energy supply for a commercial electrical power plant, for which higher temperatures and heat-production rates are required over a lifetime of many years.

It is not yet clear what minimum requirements an HDR system must meet to represent an economical energy supply for a new commercial power plant built during the next few years. A preliminary estimate is that it must be capable of producing about 35 MW(t) at temperatures of at least 200°C for not less than 20 years. To demonstrate this capability, a Phase II (Engineering) System has been designed and is now under construction at Fenton Hill.

The injection well, EE-2, of the Phase II System was completed in FY80 at a vertical depth of 4400 m (14 400 ft) in granitic rock at a temperature of 327°C.

To provide for heat extraction at the required temperature and rate and for the desired system lifetime, it is estimated that a fracture area of about 10^6 m^2 ($11 \times 10^6 \text{ ft}^2$) will be required. This could be produced as a single fracture with a diameter of about 1130 m (3500 ft), but it is not clear that a heat-extraction fluid could be circulated effectively through so large a fracture. Therefore it is planned instead to create a set of parallel vertical fractures each of which has a vertical dimension near that of the largest fracture through which fluid has been circulated in the Phase I System -- about 320 m (1050 ft) between fluid entry and exit points. To permit sufficient horizontal separation between pairs of fractures so that there will be no significant thermal interaction over the projected lifetime of the system, the bottom 1000 m (3300 ft) of well EE-2 was directionally drilled at 35° to the vertical in an east-northeasterly direction (which is normal to the expected azimuthal orientation of the hydraulic fractures). The companion well, EE-3, was to be drilled with a similar inclined section about 320 m directly above the lower section of EE-2.

Drilling of EE-3 began on May 21, 1980, at a location 46 m (150 ft) west of the EE-2 wellhead. Conventional rotary drilling equipment and techniques were used for the first 1964 m (6444 ft) of hole, which penetrated 732 m (2404 ft) of surface volcanics and sediments and 1232 m (4040 ft) of granitic basement rock. Then directional drilling began with positive-displacement downhole motors to turn the hole toward the east-northeast and increase its inclination to 35°. At the end of FY80 (day 131 of drilling) EE-3 had reached

a depth of 3653 m (10 107 ft), an orientation 67° east of north, and an inclination of 24° to the vertical.

Because the temperature limitations of available positive-displacement motors were exceeded at this depth, drilling was resumed at the beginning of FY81 using turbodrills for trajectory correction. When the hole was on course, straight-ahead rotary drilling was used. It was found, however, that -- with similar bottom-hole assemblies and bit loads and at the same depths -- the directional drift of EE-3 was not the same as that of EE-2. Therefore a relatively large number of turbodrill runs were required, and it proved extremely difficult to maintain inclination while correcting azimuth, and vice versa. However, total depth of 4084 m (13 933 ft) was reached on August 7, 1981, after 443 days of drilling. Throughout its inclined section, well EE-3 is approximately 380 m (1250 ft) above well EE-2, which was considered an acceptable vertical separation when the correct inclination and azimuth had been established. The largest horizontal displacement of EE-3 relative to the section of EE-2 beneath it is less than 55 m (180 ft), this occurring at the bottom of the hole because no directional correction was attempted during the last few hundred meters of drilling.

In addition to what appears to have been a normal incidence of washouts, twist-offs, short fishing jobs, and equipment problems, three major events added greatly to the time and cost of drilling EE-3.

- As also occurred during drilling of each of the three geothermal wells previously completed at Fenton Hill, fluid circulation was lost completely in a cavernous limestone zone about 150 m (500 ft) above the granitic basement. Attempts to restore circulation of the drilling fluid with lost-circulation additives and by emplacing a series of cement plugs were unsuccessful. It was finally necessary to case the hole down to the lost-circulation zone and drill on into the basement with no fluid returns. Between two and three weeks of drilling time were lost.
- A twist-off while drilling in granitic rock at about 2350 m (7070 ft) resulted in a difficult and finally unsuccessful fishing job, which was discontinued after 44 days. Attempts to sidetrack the hole by directional drilling off a cement plug were also unsuccessful. (The first five plugs did not harden adequately because of improper formulation of the cement mix used. Subsequent plugs, of apparently good

cement, still were not hard enough to permit drilling out into the very hard rock around the hole.) After an abortive attempt to insert a relatively large-diameter whipstock, the hole was finally sidetracked around the obstruction by drilling off from a smaller-diameter whipstock. Sidetracking efforts required a total of 101 days.

- Finally, at about 4060-m (13 300-ft) depth, another drill-string twist-off required another difficult fishing job. This one was successful, but consumed 45 days plus 9 days to clean out the hole.

In sum, these three major mishaps account for almost exactly one-half of the total time required to drill EE-3, and considerably more than one-half of its cost.

Because of cementing problems experienced during the drilling of EE-3 and previous geothermal wells at Fenton Hill, a laboratory capable of relatively fundamental studies of cements was established during FY81. It contains or has available to it an autoclave capable of 35 MPa (5000 psi) pressure and programmable to reproduce the temperature profiles experienced by cements at any point in the wellbore; several smaller autoclaves for long-term exposures of cement samples to downhole conditions; light and electron microscopes; x-ray-diffraction and x-ray-fluorescence units; and equipment for measuring physical and mechanical properties. With these facilities cement formulations for and cuttings from the first five plugs placed in EE-3 during sidetracking attempts, and a core retrieved from the fifth plug, were investigated. It was determined that insufficient silica flour in the cement formula had permitted formation of a weak, friable phase in the final cement. With an increased silica-flour addition, the sixth plug set up properly and a core cut from it had good properties -- although it was still not hard enough to permit sidetracking. By the standard compressive-strength criterion, this and the cements used for subsequent plugs were good; many had strengths above 41 MPa (6000 psi). The casing cement used in EE-3 was also found to have excellent mechanical properties.

In addition to testing cements, rock-mechanics studies during FY81 have centered on investigation of the properties of Phase II reservoir rocks. On core samples from near the bottom of well EE-2, measurements have been made of Young's modulus, bulk modulus, Poisson's ratio, and thermal expansion, at temperatures up to 250°C, a confining pressure of about 34.5 MPa (5000 psi), and a pore-fluid pressure of about 33 MPa (4800 psi). Among the various samples

tested, the elastic moduli and expansion coefficients were found to differ by factors up to more than two, which may have important effects on hydraulic-fracturing and subsequent reservoir behavior.

Four new special-purpose wireline tools for downhole use were designed and fabricated during the drilling of EE-3. These were: (1) a shaped-charge high-explosive device intended to open a bell-shaped cavity around the wellbore to facilitate sidetracking off a cement plug. This was a backup for the whipstock, and it was not necessary to use it. (2) Another shaped-charge explosive device, fabricated as backup for a commercial tool which, on the first attempt, was unsuccessful in severing the drill pipe above a stuck bottom-hole assembly. Since the commercial tool was successful on a second attempt, this Los Alamos tool has also not yet been used downhole. (3) A wireline sidewall sampler, used to sample a black residue left on the borehole wall by thermal degradation of an organic lubricant added to the drilling fluid. This is a relatively simple scraper, which worked well. (4) A temperature-activated fluid injector, used to introduce tracers or other liquids into the borehole at predetermined depths. Its design is based on the use of any of a series of fusible-alloy plugs that melt at specific temperatures, and it too worked well.

Instrument cables for downhole measurements in hot geothermal wells are a continuing problem. During FY81, four specially manufactured samples of high-temperature coaxial cables were tested in the Los Alamos Cable Test Facility. Best overall performance was by a cable constructed with a sintered TFE Teflon dielectric and a TFE jacket. It maintained usable electrical properties up to 350°C, which is above the bottom-hole temperature of EE-2, the deepest Fenton Hill hole.

Use of a coaxial instrument cable will require downhole multiplexing for transmission of data to the surface. A prototype FM multiplex system for downhole use has been designed, assembled, and tested satisfactorily at the surface in transmission of triaxial-geophone outputs over 4752 m (15 000 ft) of armored coaxial cable.

To produce 35 MW(t), the final Phase II Fenton Hill System may require as many as 14 parallel fractures connecting the inclined sections of wells EE-2 and EE-3. Design of the surface facilities for this system was completed in FY80, and has not been changed. However, before completion of the final system is attempted, it is intended to construct an "interim" Phase II System

in which to evaluate hydraulic-fracturing techniques and problems in this more demanding environment, determine fracture orientations and flow impedances, and investigate flow distribution among parallel fractures. It will consist of approximately three parallel fractures, expected to produce less than 20 MW(t) -- which can be dissipated to air by the existing heat exchangers of the Phase I System. Modifications of the surface facilities required to complete this interim loop, and to control and instrument it, were designed during FY81. However, acquisition of hardware was postponed into FY82, pending completion of well EE-3 and relief from budgetary constraints.

Other Fenton Hill facilities were improved during FY81. A Site Operations Building was completed, which contains the machine shop and welding facilities, a small conference room, and an office for the Site Manager. A modular structure was erected to house the data-collection equipment for the Phase II System, and at the end of the fiscal year about one-half of the required instrumentation had been installed in it. A foundation was poured for the tower over the EE-2 wellhead, and the tower itself was completed. The water-well pump was replaced with one capable of delivering 6 m^3/s (100 gpm), and a series of aquifer tests indicated that the aquifer from which the water is drawn can comfortably produce water at that rate without excessive drawdown in the well. Construction of a 19 000 m^3 (5×10^6 gal) pond to store water for hydraulic-fracturing and loop operations began at the end of FY81.

At the Laboratory, an apparatus has been constructed and a series of experiments run to investigate the mechanics of fluid flow through rough-walled, self-propped, hydraulic fractures. In the initial experiments, an idealized sawtooth roughness has been used, with the roughness peaks aligned. Here the friction factor is typically 100 to 1000 times that in pipe flows, and a quite different flow behavior is observed. As relative roughness increases, flow at first remains smooth -- in the Darcy regime. Then, in the fully rough regime, the friction factor at first increases with relative roughness and then actually decreases as the flow channel begins to act like a series of disjointed but individually smooth miniducts. Finally flow again becomes quite smooth, closely approaching the behavior expected of perfectly continuous smooth ducts.

A new finite-element computer code, FEHM (Finite Element Heat and Mass), has been developed. It can solve for flow and temperature distributions in a highly fractured rock matrix with complex flow paths and for permeation into

the adjacent rock, then use this information to calculate stress distribution in the geothermal reservoir. The code will handle three-dimensional problems and multiphase flows, and is characterized by strong numerical stability.

Plains Electric Generation and Transmission Cooperative, with support from DOE completed a preliminary study of the feasibility of constructing a 10 MW (electric) generation and transmission system at Fenton Hill, to be supplied with energy from the Phase II System after the HDR Program has concluded its experiments there. Assuming that those experiments are successful and that Plains Electric can acquire the site, a draft version of the study estimates costs (in 1981 dollars) of \$13 537 000 for surface facilities including structures, turbine-generator, all construction and testing, and \$1 720 000 for contingencies. With the benefit of no fuel cost beyond system maintenance, the generating system is considered to be economical and feasible to pursue.

For comparison, an economic study by Los Alamos National Laboratory projects a surface-plant cost (in 1981 dollars) of \$62 500 000 for a 75 MW(e) power station. Including projections for the costs of exploration, site acquisition and development, drilling and completions, and hydraulic fracturing, this leads to a total cost of \$154 000 000 for a 75 MW(e) plant, and an estimated break-even busbar cost of 44 mills/kWh of electricity produced. This analysis based drilling-cost estimates on cost experience for wells EE-2 and EE-3, which led to an estimated total drilling cost that was precisely one-half of the total cost of the 75 MW(e) system. Presumably this can be improved upon in future drilling.

Los Alamos HDR personnel and equipment have been involved in direct support of industrial activities of two principal types during FY81. In addition to component and instrument-sonde testing for the HDR Program, the Los Alamos Instrument Sonde Test Facility has been used to test a variety of commercial equipment and products including pressure housings, float-valve seals, wiper plugs, cement formulations, and a firing system for downhole detonators. Los Alamos crews and equipment also participated in two well-stimulation experiments, at the Baca Location in northern New Mexico and at the ORE-IDA Foods facility in Ontario, Oregon. In the Baca experiment, downhole geophones were used to detect and locate the sources of microseismic signals produced by hydraulic fracturing in a nearby well. In the ORE-IDA experiment, temperature and spinner surveys showed that the stimulation attempt was unsuccessful

because most of the fluid pumped into the well left it through the uppermost of several sets of casing perforations, so that no significant fluid pressure was developed at greater depths.

The Executive Committee of the National HDR Program Development Council met in Albuquerque, New Mexico in March 1981. Its principal recommendations were: (1) to continue background experiments in the Fenton Hill Phase I system; (2) to install heavier casing in well EE-3 than was originally planned; (3) to initiate hydraulic-fracturing experiments in EE-2 near the bottom of its open-hole section; (4) to proceed as soon as possible to select a second site for HDR experiments; and (5) to organize a Technical Committee on Equipment Technology.

Under an International Energy Agency (IEA) agreement, the New Energy Development Organization (NEDO), representing the Government of Japan, has now joined Kernforschungsanlage-Jülich GmbH (KFA, representing the Federal Republic of Germany) and the DOE in the Fenton Hill HDR Project. Scientists from both Germany and Japan are in residence in Los Alamos and participating as Staff Members in project activities. All three countries contribute financially to project support and are represented on the Fenton Hill Steering Committee. That committee met three times during FY81 to consider legal and financial aspects of the agreement and to review progress, problems, and planning of the project.

The Third Annual Hot Dry Rock Information Conference was held in Santa Fe, New Mexico, in October 1980 and was attended by about 250 individuals. Other HDR informational activities have included publication of reports, maps, and technical papers, (see Appendix A) presentations at a number of conferences and meetings, and briefings and tours for a very large number of visitors from throughout the United States and several other countries. Press, radio, and television coverage of the HDR Program has been frequent, detailed, and generally very favorable.

2.0. INTRODUCTION

2.1. The HDR Concept

In the context of geothermal energy, HDR is defined as naturally heated, unmelted crustal rock, which does not produce natural steam or hot water at commercially useful rates. HDR exists everywhere at varying depths and at

temperatures which, when not high enough for economical generation of electricity, are often sufficient for a variety of direct uses such as space heating and food and chemical processing. Just that small fraction of it that can be reached routinely with existing drilling methods represents an essentially inexhaustible supply of heat, potentially capable of contributing substantially to the world's energy needs. The overall goal of the HDR Program is to demonstrate the commercial feasibility of geothermal energy derived from HDR. Its principal objectives, therefore, are to confirm that the potential HDR resource is indeed large and accessible; to develop a realistic commercial technology base for extracting the energy therefrom; and to verify that the environmental and social consequences of HDR development are acceptable.

Under somewhat unusual geologic conditions, meteoric water penetrates deeply enough to be warmed to usefully high temperatures by the earth's internal heat and then, rising buoyantly, is trapped within confined aquifers or limited volumes of permeable rock. The trapped fluid may then constitute an economical hydrothermal resource. Far more commonly, at the depths at which usefully high rock temperatures are encountered, it is found that the combination of temperature, pressure, and mineral deposition has reduced any pre-existing permeability to a value too low to permit natural formation of an exploitable hydrothermal reservoir. This is the typical HDR situation. Occasionally, however, a hot permeable formation is encountered which, because of some geologic barrier, is not reached by the ground-water circulation and is therefore unproductive of geothermal fluids. HDR thermal reservoirs may, then, vary widely in permeability, but very low permeability is the rule.

Although a wide variety of methods can be suggested for extracting energy from hot dry rock, the simplest -- and probably the most economical -- of these is to imitate nature by circulating water through it. Usually this will require that connected porosity somehow be created within the hot rock with enough exposed surface so that water flowing through it can extract heat from it at usefully high temperatures and rates over long periods of time. Again, a variety of methods can be suggested for producing the required flow passages and heat-transfer area. Of these, the one chosen for initial investigation in the HDR Program was hydraulic fracturing.

Hydraulic fracturing is the use of fluid pressure in a borehole to create and extend fractures outward from the hole. The fractures produced are thin

cracks, usually roughly circular in outline. The condition of stress in deeply buried rock is such that these cracks in general are substantially planar, vertical, and in any given locality have a consistent azimuthal orientation. Simply by continuing to pump pressurized water into it, a hydraulic fracture can be extended for hundreds of meters, providing a very large area to transfer heat to water flowing through it.

In the HDR concept currently being investigated, two drilled holes are connected at depth by one or more hydraulic fractures produced in low-permeability hot rock. Cool water pumped down one well is heated by circulation through the crack system and recovered as pressurized hot water through the second well. Its useful heat is extracted at the surface and the cooled water is returned to the first well to be recirculated and reheated.

2.2. Synopsis of the HDR Program Through FY80

The HDR concept described above 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 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 leakoff rate.

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 confirmed that the basement rock could be fractured hydraulically at moderate pumping pressures and had very low permeability.

Under sponsorship of the 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 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 exchanger that would extract the heat from the pressurized 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 forced-draft, air-cooled heat exchanger.

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 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 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 l/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 produced 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. Since no measurable temperature drawdown occurred during this experiment, a longer test -- "Run Segment 5" -- was initiated in March 1980 and continued into FY81. Its results are discussed in detail below.

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%. 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.

Drilling the first well, EE-2, of a second circulation loop began at Fenton Hill in April 1979 and was completed in May 1980 at a vertical depth of about 4500 m (15 000 ft) and a rock temperature of about 320°C. It is intended to be the injection well of a larger, deeper, hotter Engineering (Phase II) System designed to produce heat at a temperature and rate approaching those required for economical generation of electricity. Drilling of its companion well, EE-3, began in May 1980, and at the end of the fiscal

year it had reached a depth of 3044 m (10 000 ft) on a trajectory about 300 m (1000 ft) above that of EE-2.

Progress of the Los Alamos National Laboratory HDR Project was sufficiently encouraging so that, at the beginning of FY79, the Division of Geothermal Energy (DGE) 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's Albuquerque Operations Office (DOE/ALO). The HDR Program Office is responsible for research and development activities at Fenton Hill, Laboratory support of these activities, and extension of the HDR Program to the rest of the United States. During FY81, the major Program activities elsewhere than at the Los Alamos National Laboratory and Fenton Hill comprised: identification and preliminary characterization of other HDR areas that appeared particularly suitable for future HDR development; a continuing search for a second site in a different geological environment that might be used for an experimental development generally similar to that undertaken at Fenton Hill; and investigations of the legal, regulatory, environmental, institutional, and economic factors that would affect either experimental or commercial development of HDR systems throughout the U.S.

Under an IEA agreement, direct participation in the Fenton Hill Project by KFA-Jülich, the energy research agency of the Federal Republic of Germany, began in FY80. This involves partial financial support of the Project, participation in its planning and management, and assignment of a limited number of West German personnel to work as project staff. Negotiation of a similar agreement with NEDO, the New Energy Development Organization of the Government of Japan, was successfully completed during FY81, and 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.

2.3. Objectives and Plans for FY81

Planning of the principal elements comprising the HDR Program included the following major activities and objectives for FY81.

Technology Development: Highest programmatic priorities were given to completion and analysis of Run Segment 5 in the Phase I System and to completion of

wellbore EE-3, the Phase II production well. Preliminary surveys and pressurization tests were to be conducted in EE-2, the injection well of the Phase II System. Analytic and laboratory support, environmental surveillance, and development of necessary instruments, equipment, and test facilities were to continue.

Resource Evaluation: Collection of geologic and geophysical data relevant to evaluation of the HDR resource base was to continue on both a regional and a local scale, leading to improved estimates of the accessible resource base, a more nearly complete geothermal-gradient map of the U.S., and identification of areas that are particularly promising either as locations for HDR Experimental Site 2 or for possible commercial development.

Institutional Issues: The Environmental Analysis Report for the Fenton Hill Site was to be revised to include new and projected site modifications and experimental operations. At a reduced level, legal and institutional studies of constraints on HDR development were to continue.

Commercial Feasibility Assessment: Economic studies of HDR energy systems were to continue at a reduced level at Los Alamos National Laboratory.

3.0. RESOURCE EVALUATION AND SITE SELECTION

This part of the HDR Program falls into four categories: (1) evaluation of the HDR resource for the conterminous U.S., (2) development of techniques that can be used to evaluate the resource and to find HDR prospects, (3) evaluation of HDR prospects and of exploration methods that can be used to help pick HDR Site 2, and (4) experiments in "wells of opportunity," generally hot dry wells, in which Los Alamos can evaluate properties of potential reservoir rocks at HDR sites other than Fenton Hill, New Mexico.

Los Alamos activities were concentrated on Items (2) and (3) during FY81. No attempt was made to update our FY80 estimate of the HDR resource base to a depth of 10 km.¹ This estimate is 5.9×10^6 Quads for the conterminous U.S., but will be refined after publication of our revised geothermal gradient map of the U.S. in FY82.

3.1. Data Gathering and Analysis

Data gathering for the regional HDR assessment of the conterminous U.S. consisted of work done in-house and by subcontractors. Laboratory personnel continued to update and computerize the geothermal gradient data files. These

files were increased by one-third and a program to plot the data was completed. A series of maps showing geological and geophysical information necessary for HDR exploration was initiated for the southwestern U.S. Two maps, (1) locations and ages of volcanic rocks younger than 3 Myr, and (2) contemporary stress orientations, have been completed. Progress by subcontractors included further refinement of geothermal models based on increased geochemical and geophysical data in the Midcontinent. The first gravity map and a bottom-hole temperature-gradient map of West Virginia were prepared. Data gathering for specific sites is continuing for the "Ogallala High" in western Nebraska, the Upper Mississippi Embayment, the Illinois 'Deep Drill Hole, and the Cayuga geothermal and gravity anomaly in New York. A total of 77 new heat-flow measurements was reported by various subcontractors: 6 in Arkansas by R. Roy; 46 in Georgia, Florida, Alabama, and Mississippi by D. L. Smith; 4 in Ohio and 6 in Pennsylvania by Y. Eckstein; and 15 in New York by D. Hodge.

Temperature-Gradient Map and Computer Data Base. As part of the regional HDR assessment of the conterminous U.S., we are collecting information on wells deeper than 50 m (135 ft) that have been logged for temperature gradient. This compilation is an attempt to gather all true measured (not bottom-hole) temperature data across the country for use in geothermal (HDR and conventional) exploration. Thermal gradients are calculated only for measurements that appear to reflect a conductive thermal regime. Temperature logs showing obvious hydrologic disturbances are therefore not included. These data do not measure the influence of thermal conductivity on the gradient and must be interpreted accordingly.

The data set includes well name, latitude and longitude, depth of interval logged, heat flow and thermal conductivity (where available), geothermal gradient, and reference. The data are filed in a computer for automatic plotting by state, groups of states, or the entire U.S. at various scales. Sources of data include scientific journals, USGS and DOE open-file reports, state geological survey publications, university theses, and a minimum of unpublished private company information. An estimated 1500 wells will be on file by the spring of 1982. The geothermal-gradient data will be presented on a map of the U.S. using colored symbols to represent depth of measurement and temperature gradient. Each well will be keyed to a table that will list all other available information.

Kron and Heiken's² first edition of the gradient map coincided with the publication of a USGS preliminary temperature-gradient map by Guffanti and Nathenson.³ Their data set consists of approximately 200 wells deeper than 600 m (1968 ft) that were logged for temperature gradient. Assuming that variation in thermal conductivity is minimal at this depth, a reliable, conductive geothermal gradient can usually be calculated. These temperature gradients are inferred to exist regionally in a conductive thermal regime to a depth of 2 km.

The two gradient maps are complementary. Whereas Guffanti and Nathenson emphasize the deep, regional thermal regime, Kron and Heiken provide abundant information on the shallow thermal regime as well as showing the deeper data. The shallow data tend to reveal local thermal anomalies and are therefore a valuable exploration tool. Extreme caution must be used when extrapolating these temperature gradients to depth since changes in the thermal conductivity of rocks directly affect the gradient. The USGS map, on the other hand, defines broad areas with average geothermal gradients that are expected to be encountered when drilling to depths of a few kilometers. It is less an exploration tool than a geophysical evaluation of the deep, regional thermal regime.

3.1.1. Status of Data Gathering and Analysis

Midcontinent. The Midcontinent Hot Dry Rock Group, a consortium of researchers from Purdue University, University of Pittsburgh, University of Texas at Dallas, University of Texas at El Paso, and New Mexico State University continued their testing of exploration strategies and their compilation of geophysical data for the midcontinent east of the Rocky Mountains and west of Ohio.

The Midcontinent HDR Bibliography has been expanded by the addition of numerous citations generated by the consortium's investigations and by use of computerized bibliographic information retrieval systems.

Work on evaluating exploration strategies consisted primarily of continued refinement of geothermal models of the strategy test sites in Nebraska, Michigan, and Arkansas based on further analysis of geochemical and geophysical data. Specific data assembled from these sites included encouraging data from western Nebraska confirming the existence of the "Ogallala High" with heat flows as high as 182 mW/m^2 . Gravity profiles through the Michigan test site are being analyzed for refinement of that model and additional heat flow,

geologic, and geophysical data are being integrated into the Upper Mississippi Embayment-Arkansas model.

A Bouguer gravity anomaly map has been prepared for the Illinois Deep Drill Hole area. Analyses of core specimens from the hole include chemical, magnetic susceptibility, modal composition, specific gravity, gamma ray spectrometry, age dating, and other geophysical properties.

Initial steps were taken to investigate gravity and magnetic anomaly signatures associated with granitic plutons in the midcontinent. As part of this project, an HDR Midcontinent Aeromagnetic Index was assembled from information obtained from the USGS.

The final report on the midcontinent work will be available next year.

Heat-Flow Measurements in the State of Arkansas. Six new heat-flow values were reported for Arkansas ranging from 44.35 mW/m^2 [(1.06 heat flow unit (HFU))] to 130.96 mW/m^2 (3.13 HFU). Greatest confidence was placed on two values; 45.61 mW/m^2 from Glenwood and 44.35 mW/m^2 from Little Rock. The most promising geothermal area is in the southern counties where geothermal gradient estimates show a higher-than-normal trend.

Gulf Coastal Plain. Heat-flow studies of the Gulf Coastal Plain were conducted during FY80 and FY81 by Douglas L. Smith and his associates at the University of Florida. A total of 46 new heat-flow values was determined in southwestern Georgia, Florida, Alabama, and Mississippi during the 20-month project. The Gulf Coastal Plain is characterized by low-to-normal heat-flow values. Near Pensacola, Florida, thermal gradients are approximately 32°C/km and temperatures can be extrapolated to 50°C at a depth of 1 km. In northern Louisiana and a portion of adjacent southwestern Mississippi, thermal gradients of $35\text{--}46^\circ\text{C/km}$ and heat-flow values as great as 87.78 mW/m^2 (2.1 HFU) were observed. A broad area of relatively high heat flow was identified, and a three-parish area of particular interest was recognized. Higher heat-flow values in northern Louisiana may be associated with salt diapirs and/or subsurface alkalic igneous rocks.

New York and West Virginia. Heat-flow studies were conducted in New York and West Virginia during FY81 by Dennis Hodge and his associates at the State University of New York at Buffalo.

In his continuing evaluation of the thermal stratigraphy of New York, Hodge measured heat flow from 15 wells, made thermal conductivity determinations on rock chips from 5 wells, and obtained bottom-hole temperatures for

1200 wells from the literature. He also prepared silica heat-flow and thermal-gradient maps of central and western New York and correlated the information thereon. A geological interpretation based on detailed gravity and magnetic investigations was made for the area encompassed by the Cayuga geothermal and gravity anomalies. Geophysical data were obtained from 1000 new gravity stations and 600 new magnetic stations. In addition, Hodge studied the theory and methodology of making temperature measurements in air-filled boreholes.

Hodge also completed the first gravity map ever made in West Virginia, prepared a bottom-hole temperature-gradient contour map of the state, and sampled and analyzed the waters from all 50 hot springs in the state.

New England. Heat-flow studies were conducted in southern Maine, New Hampshire, and Vermont during FY81 by Gene Simmons and his associates at the Massachusetts Institute of Technology (MIT). A total of 25 new heat-flow values was determined including a reprobings of the Redstone quarry, New Hampshire borehole, and the new flame-jet drill hole at the Coleman quarry, New Hampshire. Contour maps were prepared of thermal-gradient and heat-flow values in New Hampshire and Vermont. Also, a contour map of the earth's gravity field was made for Bellows Falls, Vermont, and environs. A strong correlation between the gravity anomaly and the heat-flow anomaly and thermal gradient was noted by Simmons.

The flame-jet drilling project at the Coleman quarry in Madison, New Hampshire, was monitored and formation fragments were sampled by MIT personnel.

Ohio and Pennsylvania. Heat-flow studies of the Allegheny Plateau were conducted under two successive contracts by Yoram Eckstein and his colleagues at Kent State University during FY79 and FY80, but the results were not reported until June 1981. Four heat-flow values were determined, two in Ohio (56.9 and 57.3 mW/m²), and two in Pennsylvania (77.0 and 83.7 mW/m²). Thermal-conductivity measurements were made on sedimentary core samples from 12 holes in Ohio and six in Pennsylvania.

3.1.2. Southwestern U.S. HDR Resource Evaluation Maps.

To evaluate the HDR potential of a region, information on the geothermal gradient or heat flow and the depth to possible reservoir rocks is of primary importance. Although gradient data are the most direct means of detecting thermal anomalies, generally the data points are sparsely distributed. In addition, disturbances from local aquifers may create

problems in interpretation. For these reasons, indirect evidence, such as the location of young volcanic centers, depth to the Curie point, and depth of the deep electrical conductor, is important for defining broad regions with elevated heat flow. A series of maps for the southwestern U.S. is now being generated, which will include, at a scale of 1:1 000 000, location and age of young volcanic rocks, heat flow, stress-field orientation, depth to reservoir rock, seismicity, depth to electrical conductor, Curie-point depth, locations of population centers, and the location of power grids. The first of these maps has recently been published. It illustrates the location and age of volcanic rocks younger than 3 Myr and is an update and modification of the map by Luedke and Smith.⁴ Reference 5 tabulates similar data for rocks younger than 5 Myr in Arizona and New Mexico. The second map in the series, which shows the contemporary stress-field orientation, is completed and should be published by early 1982. Data compilation for the depth-to-reservoir map is continuing.

3.2. Geophysical Methods for HDR Exploration

Both regional and site-specific geophysical investigations have been and are being performed for HDR exploration. The basic approach of the regional work has been to map various geophysical parameters that may indicate regions of elevated heat flow and, thereby, identify possible regions favorable for HDR site exploration. The regions under investigation contain several formerly targeted HDR prospects.

The primary methods currently being used and evaluated for HDR exploration are both detailed and regional gravity measurements and magnetotellurics (MT). The regional MT investigations consist of several long profiles in Arizona and New Mexico. The data collection has taken several years and was completed in May 1981. The modeling and interpretation is underway now and should be completed by the end of FY82. Further explanation of this approach to HDR exploration is given in Refs. 6-8. One of the regional MT profiles passes through the Castle Dome HDR prospect. Preliminary results from these data are reported in Refs. 9-10. A detailed MT study^{6,7,11,12} of the HDR prospect in the Zuni Mountains of New Mexico is integrated into the regional MT study. The final paper on this work is being written. Both the regional and detailed MT studies in the Zuni Mountains have been integrated into an ongoing study of the Jemez lineament.^{6,13} The first HDR site at Fenton Hill lies within the Jemez Mountains near the intersection of the Jemez lineament

with the Rio Grande rift. An attempt to correlate the depth to the deep electrical conductor, determined from MT modeling, and the temperature at depth is underway.¹⁴

The regional gravity work was aimed at mapping the thickness of the crust and lithosphere beneath the Rio Grande rift and adjacent Colorado Plateau and Great Plains, and correlating this thickness with heat flow. Standard two-dimensional gravity modeling of two 700-km-long profiles has been performed. The results of a profile at 34°40'N latitude are given by Ander.^{6,15} The results of another profile at 37°N latitude have not been published, but a final paper is in preparation.

For the detailed gravity work, a two-dimensional ideal-body computer code has been developed to model two gravity anomalies. The computer code, named IDB2, finds the greatest lower bound on the maximum density for all sources confined to a preassigned region, by constructing an approximation to the gravity ideal body in that region. The ideal body is the solution fitting the data that has the smallest possible maximum density. Any density solution confined to the region of interest must then somewhere reach or exceed the ideal body density bound, output by the program. A description of the technique along with examples of its use is given by Ander.⁶ The technique has been applied to a gravity anomaly associated with the Zuni-Bandera volcanic field, New Mexico, a targeted HDR prospect.¹⁶ The technique was also applied to a gravity anomaly associated with the Lucero uplift, located on the western flank of the Rio Grande rift in New Mexico. The Lucero anomaly was investigated as a possible HDR prospect, but after the investigation it was removed from the list of possible sites. A complete Bouguer gravity map of the Socorro 1°x2° quadrangle, New Mexico, was produced, and two papers on these studies have been submitted for publication.¹⁷⁻¹⁹ In the future this powerful technique may be applied to other gravity anomalies associated with possible HDR sites such as the Clear Lake region, California, or Castle Dome, Arizona. It is hoped that in FY82 a three-dimensional version of this computer code may be developed.

3.3. Site Characterization

Approximately 24 areas within the U.S. have been under evaluation for possible development as a second HDR site. These potential sites fall broadly into three categories according to the nature of their thermal anomalies:

(1) Quaternary magma - hydrothermal ("volcanic" or "igneous") systems such as The Geysers-Clear Lake region or Long Valley, California,

(2) regional thermal anomalies of tectonic origin such as the Basin and Range Province, often enhanced by recent magmatic activity, as at Roosevelt Hot Springs, Utah, and

(3) pre-Quaternary plutonic and metamorphic complexes such as the Conway Granite, New Hampshire, and the Delmarva peninsula of Maryland-Virginia.

Most, but not all, of the sites contain crystalline basement similar to the rock in which the first HDR system, at Fenton Hill, has been developed. All are characterized by anomalously high heat flow. This section briefly describes the sites worked on by Los Alamos this year. Table 3-I presents all the sites currently under consideration. Following sections describe sites where considerable Los Alamos effort was utilized in evaluation.

Roosevelt Hot Springs, Utah. Roosevelt Hot Springs area in southwest Utah (Fig. 3-1) is considered to be one of the best prospects for HDR Site 2 for several reasons. First, deep drilling by several geothermal companies has shown that a major portion of Milford Valley is underlain by high-temperature Tertiary granite and Precambrian gneiss having low permeability and virtually no geothermal fluids (Table 3-II). Second, the relatively small hydrothermal system being explored by Phillips Geothermal Company and others will be utilized by a 20 MW(e) demonstration power plant in 1983 or 1984. Thus, a power network will be close at hand. Third, the area does not appear to be environmentally sensitive to continued geothermal development. Fourth, shallow ground-water supplies suitable for large-scale circulation through a HDR system appear to be available in the Quaternary sediments of Milford Valley.

Los Alamos has prepared a preliminary evaluation of the HDR potential of the Roosevelt area using geologic, geophysical, and geochemical criteria.²⁰ The area of good HDR potential appears to be at least 160 km² or roughly eight times the area of known hydrothermal resources. HDR interest is focused west of the Opal Mound (Dome) fault, which is the western boundary of the 260°C hydrothermal system to be commercially developed.

Los Alamos activities in this region during FY81 consisted mostly of evaluating existing data and contacting university and industrial interests in the area to determine possible avenues of HDR development. An informal seminar led by experts of University of Utah Research Institute and University

TABLE 3-I
HOT DRY ROCK PROSPECTS IN THE U.S. WITH CRITICAL DATA REGARDING RESERVOIR ROCKS, CONDUCTIVE TEMPERATURE GRADIENT, AND EXPECTED TEMPERATURES AT DEPTH

	Thermal Anomaly Type ^a	HDR Reservoir Rock	Formation and Age (if known)	Cond. Temp. Grad., °C/km ^b	Depth to ^c HDR Reservoir, km	Temp. @ 2 km, °C	Temp. @ 5 km, °C	Status of Prelim. HDR Evaluation
Name								
1 Aquarius Mtns, AZ	R	Plut/Meta	Precambrian	35-41	5	>95	>200	complete
2 Castle Dome, AZ	R	Metasediments	Livingston Hills, Mesozoic	55	>3.5	>130	>200	complete
3 Springerville, AZ	V(R)	Plut/Meta	Precambrian	50	>4	>100	>200	underway
4 Clear Lake Region, CA	V	Metaseds/Greenstone	Franciscan Mesozoic	>80	>2	>200	>350	underway
5 Coso Hot Spgs, CA	V	Plut/Med	Sier-Nev. Bath., Mesozoic	35-45	>2	>140	>250	started
6 Long Valley Caldera, CA	V	Plut/Meta	Sier-Nev. Bath., Mesozoic	38	>3	>150	>250	complete
7 Salton Trough, CA	V(R)	Plut/Meta	Sou. Calif. Bath., Mesozoic	--	>3	--	>250	started
8 Mountain Home, ID	R(V)	Plutonic	Idaho Bath., Mesozoic	60-70	>3	>130	>250	case study underway
9 Crisfield, MD	P	Plut/Meta	"Piedmont" basement, Paleozoic	30	>8	>60	>135	case study complete
10 New Madrid, MO	P	Plut/Meta	Precambrian	13-26	>8	>45	>110	underway
11 Western Nebraska	P	Plut/Meta	Precambrian	32-36	>6	>60	>135	underway
12 White Mountains, NH	P	Plut/Meta	Conway Gran., Jurassic; Littleton Fm., Devonian	25-27	>7	>60	>130	underway
13 Rio Grande rift, NM	R(V)	Plut/Meta	Precambrian	25-55	>3.5	>90	>200	locally underway
14 Valles Caldera, NM	V	Plut/Meta	Precambrian	55-65	>3	>150	>300	complete
15 Zuni Uplift, NM	V(R)	Plut/Meta	Precambrian	25-65	>4	>100	>200	complete
16 Desert Peak, NV	R	Metaseds/Gran. Intrus.	Jurassic-Tertiary	15	>2.2	>210	>260	underway
17 Dixie Valley, NV	R	Metaseds/Gran. Intrus.	Triassic	70	>3	>150	>250	started
18 Cayuga Lake, NY	P	Plut/Meta	Precambrian	36 ^e	>7	>90	--	underway
19 East Aurora, NY	P	Plut/Meta	Precambrian	32 ^e	>8	>70	--	underway
20 Elmira, NY	P	Plut/Meta	Precambrian	36 ^e	>7	>80	--	underway
21 Brothers Fault Zone, OR	V(R)	Rhy. Intrus./Basalt	Und. volcanics, Tertiary	50-75	>3	>100	>250	underway
22 Mt. Hood, OR	V	Stratified Basalt	Eocene?	65	>3	>115	>250	underway
23 Vale, OR	R	Stratified Basalt	Flood basalt, Tertiary	60-90	>3	>120	>300	underway
24 Roosevelt Hot Spgs, UT	V(R)	Plut/Meta	Min. Mtns. Plut., Tertiary	55-60	>2	>180	>300	complete

^a P = Pre-Quaternary plutonic and metamorphic rocks, R = regional thermal anomalies of tectonic origin, V = Quaternary volcanic field, () = secondary heat source
^b Conductive thermal gradient in deep impermeable zone (if known) or estimate from gradient wells.
^c Depth required to establish HDR reservoir using rock at minimum of 200°C (not depth to crystalline and/or impermeable basement rocks).
^d Conductive gradient below 2700 m; isothermal at >210°C from 975-2700 m.
^e Gradient may be less in deep Precambrian basement.

TABLE 3-II
DATA FROM SELECTED DEEP GEOTHERMAL WELLS IN ROOSEVELT HOT SPRINGS REGION, UTAH

No.	Name	Operator	Depth, m	BHT, °C	Formation at Depth	Comment
1	Well 82-33	Phillips Pet.	--	--	Gneiss-Granite	Dry; data proprietary
2	Well 9-1 ^a	Phillips Pet.	2049	227	Gneiss-Granite	Dry
3	Utah State 52-21 ^b	Getty Oil	2281	202	Gneiss-Granite	Dry
4	Acord 1-26 ^b	MCR Geothermal	3855	230	Gneiss-Granite	Dry; heat flow = 3.5 HFU

^a Ref. 21
^b Ref. 20

of Utah was hosted by Los Alamos in June 1981 to discuss the relevant geology and geophysics of Roosevelt Hot Springs KGRA (known geothermal resource area) with an eye toward HDR projects.

Los Alamos is now engaged in discussions with a consortium of companies (MCR Geothermal; Geothermal Kinetics Inc., Group-7; and Roosevelt Hot Springs Corporation) the latter having drilled the Acord I-26 hot dry well in the Milford Valley. A report is being drafted that evaluates the Acord I-26 well in detail and suggests a scenario for utilizing the Acord well in a future HDR

Fig. 3-1.

Roosevelt Hot Springs area in southwest Utah, showing location of hydrothermal system with respect to Opal Mound fault. The area of HDR interest lies west of the fault. Numbers refer to wells in Table 3-II.

system. Other issues such as power networks, environmental concerns, and water supply also will be addressed.

Los Alamos would like to initiate a study in FY82 to investigate the local hydrology of the area west of the Opal Mound fault. The object of this study would be to determine if water supplies exist to operate HDR systems and to see if the water quality is suitable for continued high-temperature circulation through them.

Los Alamos has prepared an advertisement that was placed in Commerce Business Daily to solicit information and/or cooperative arrangements with any party having hot dry wells in the Roosevelt area or other geothermal areas (Fig. 3-1).

Mountain Home, Idaho. The Mountain Home, Idaho, HDR prospect lies just east of Mountain Home on the northern margin of the Snake River Plain. Heat

flow is generally 84 mW/m^2 (2.0 HFU) all along the northern margin of the western plain. This part of the margin was selected for study because it did not appear to be as badly faulted as other sections of the margin, and because there were two deep wells with gradients of 61 and 64°C/km .¹

Harding Lawson Associates have completed their study of the area and a final report of the results will be available soon. Gravity modeling done by them suggests that the Idaho Batholith may not extend beneath the volcanic rocks of the Snake River Plain as far as the southern boundary of the prospect, but is likely to be reached within 3 km of the surface 3-5 km north-northeast of that boundary line. Gravity and telluric data suggest the best regions for HDR development are the southeast and central portions of the prospect where high resistivity and absence of observed faulting suggest less fracturing of the basement rock (Fig. 3-2).

Geologic mapping in the Mt. Bennett Hills by Los Alamos and Boise State University has been completed, and the map will be published soon. The purpose of the mapping was to define structural trends and the nature and extent of surface faulting, and to describe the Idavada volcanics so we could make a stratigraphic correlation with cuttings from the Bostic 1A well. It is not expected that the results of this work will affect the evaluation shown in Fig. 3-3.

The Geysers-Clear Lake Region, California. The Geysers-Clear Lake region, located about 150 km north of San Francisco, California, is the largest commercial geothermal development in the world today [$\sim 900 \text{ MW(e)}$]. Electrical production comes from a vapor-dominated geothermal system surrounding The Geysers proper. This system is separated from a region of smaller hydrothermal systems and (apparently) hot dry rock, to the north, by the Collayomi fault zone (Fig. 3-4). Although this region to the north is very attractive for HDR exploration by virtue of high temperatures in several hot dry wells, little work was accomplished by Los Alamos on this prospect in FY81 due to lack of funding.

Los Alamos has attempted to gain access to existing hot dry wells in cooperation with industry to study rock properties and heat flow of Franciscan assemblage rocks considered to be the reservoir rock for HDR development. Some attempt has also been made to determine the lease status of geothermal companies with respect to areas of HDR interest.

Fig. 3-2.
Generalized cross-section through the target prospect, Western Snake River Plain, Idaho.

Fig. 3-3.
Location of Snake River Plain target prospect.

Fig. 3-4.

The Geysers-Clear Lake region, California, showing major right-lateral strike-slip fault zones of the San Andreas system in relation to the Clear Lake volcanic field and the Cache Formation: Dashed line outlines the Geysers steam field; numbers refer to deep wells listed in Table 3-III. Area of HDR interest underlies the Clear Lake Volcanics and adjacent areas.

Los Alamos would like to prepare a report in FY82 summarizing the HDR potential of the region. This report will use existing data published by the USGS in their evaluation of the region for conventional geothermal resources but would also utilize additional analysis of subsurface structure beneath the Clear Lake volcanic field. Future efforts at Clear Lake are still subject to availability of funds.

Long Valley Caldera, California. Long Valley Caldera, California, has many similarities to the Valles Caldera, New Mexico. Because of these similarities a preliminary examination of the HDR potential of the Long Valley

TABLE 3-III

DATA FROM SELECTED DEEP GEOTHERMAL WELLS IN THE CLEAR LAKE REGION, CALIFORNIA
(See Fig. 3-4 for Locations)

No.	Name	Operator	Depth, m	BHT, °C	Formation at Depth ^a	Comment
<u>Wells that are hot and 'dry'</u>						
1	S&B #1	Aminoil USA	~3400	very hot ^b	Fran	Dry
2	B&R Unit #1	Aminoil USA	~3400	very hot ^b	Fran	Dry
3	Bouscal #1	Republic	2770	very hot ^b	GV-Sp-Fran	Dry
4	Sullivan #1	E.B. Towne	1970	193	Sp	Dry-abandoned
6	Kettenhofen #1	Getty-Magma- Thermogenics	1910	210	GV-Sp-Fran	Dry-abandoned
7	Magma-Watson #1	Magma-Dow Chem	1755	>200	GV-Sp-Fran	Dry-abandoned
8	Jorgensen #1	Union Oil	~3100	very hot ^b	Fran	Marginal water entry
9	Borax Lake #1	Phillips Pet	~3100	hot ^b	Fran	Dry
10	B-J #1	Aminoil USA	3150	hot ^b	Fran	Dry
11	Torchio-Ferro #1	Cordero-Sun Oil	2445	126	Fran	Dry-abandoned
12	Audry #1	Phillips Pet	~3100	very hot ^b	Fran	Dry
<u>Wells that are hot and 'wet'</u>						
5	Neasham #1	Occidental- Republic	3015	>260	Sp-Fran	Water entry @ 2615 m
13	Sulphur Bank #1	SB Geothermal Power	168	>100	Fran	Abandoned
14	Bradley #1	Earth Energy	643	208	Fran	Abandoned
15	Bradley #2	Earth Energy	1226	163	Fran	Abandoned
16	Clear Lake #1	Magma	460	135	Fran	Abandoned

^a Fran = Franciscan Assemblage; Sp = Serpentine; GV = Great Valley Sequence
^b Confidential Information

Caldera was prepared by Los Alamos during FY81.²² This examination relied almost entirely on recent investigations by the USGS, published in the Journal of Geophysical Research of February 1976.

These investigations demonstrated that volcanism occurred within the area for about the last 3 Myr with peak activity occurring at about 0.7 Myr. Teleseismic and gravity data suggest that magma may still be present at depths of 7 to 25 km beneath the western part of the caldera. Additional evidence

for the presence of magma is provided by the extreme youthfulness of volcanic activity along the Inyo Domes, which may be as young as 450 years.

Geothermal gradients and heat-flow values have a wide range because of both regional differences and the local effects of hydrology. The highest heat flow 157 mW/m^2 (3.75 HFU) was measured at the Devils' Postpile just west of the western caldera margin. This value, approximately 115 mW/m^2 (2.75 HFU) higher than would be expected for the Sierra Nevada province, probably reflects the young magmatic activity on the west side of the caldera. Near hot springs within the caldera, convective heat flow is dominant and very high temperatures and gradients have been observed. At Casa Diablo Hot Springs a temperature of 177°C was reached at a depth of 120 m.

Granodiorites and granites of the Sierra Nevada batholith present on the north, west, and south sides of the caldera would have low primary permeability and unless highly fractured should serve as low-permeability reservoirs for HDR development. The coincidence of high heat flow and low-permeability basement rock on the west side of the caldera makes this area a prime candidate for more detailed geologic investigation leading to resource development. These investigations should include both intermediate and deep gradient measurements and structural studies to evaluate the permeability.

Delmarva. In 1979 the Los Alamos National Laboratory contracted with D'Appolonia Consulting Engineers, Inc. to perform an investigation of a hot dry rock target prospect on the Delmarva Peninsula (the Cris-Wall area, Fig. 3-5). The prospect area which extended roughly from Crisfield, Maryland, to Wallops Island, Virginia, was selected primarily on the basis of evidence for higher-than-normal geothermal gradients collected by investigators from the Virginia Polytechnic Institute and State University. The D'Appolonia investigation has been completed and a summary is available.²³ Copies of the complete report are available at libraries listed in the summary report.

D'Appolonia developed an exploration program suitable for identification of HDR sites in regions of thick sedimentary cover within the eastern U.S. This program consists of:

- (1) use of aeromagnetic and gravity maps to infer basement rock types and depth to basement;

- (2) planning and obtaining seismic reflection profiles to provide additional information, if required by the stratigraphy, of locations of faults, structure, and depth to basement;

Fig. 3-5.
Location of Delmarva Peninsula target prospect.

(3) use of existing wells and/or new shallow [$\sim$ 300-m (1000 ft)-deep] wells located within the area of interest to obtain data for making lithologic correlations and to measure heat flow;

(4) obtaining additional seismic coverage and drilling deeper exploration wells at sites that look especially favorable;

(5) use of an electrical technique at each of these sites that is suitable for evaluating the nature of the fractures and water saturation in the basement rocks.

By applying this program to the Cris-Wall area, D'Appolonia located six sites that are expected to have temperatures greater than 75°C at the basement surface and are at least 1 km from the nearest major fault.

Conway Granite, New Hampshire. In Carroll County, New Hampshire, the Conway biotite granite of Jurassic to Cretaceous age is the youngest of the four complex plutons intruded at a depth of 3 to 7 km into the eastern part of the White Mountains batholith. Radiogenic heat derived from uranium and thorium minerals in the Conway granite -- 17.6 HGU (heat-generation units,

1 HGU = 10^{-13} cal/cm^{3/5}) -- probably accounts for the high surface-heat-flow values of about 88 mW/m² (2.1 HFU) in the overlying area.²⁴ Simmons and Mann made several additional geothermal measurements in the White Mountains in 1980, also obtaining corrected values of about 88 mW/m² (2.1 HFU). E. Decker (Los Alamos National Laboratory, personal communication, 1981) considers the flux in the batholith to be anomalously high by 21 mW/m² (0.5 HFU). Simmons and Mann continued to make heat-flow determinations during 1981 and are preparing a report on the results of their work.

Although low by western U.S. standards, the heat-flow values in the Conway granite are the highest reported in the eastern half of the nation. In New England, which is relatively poor in other types of mineral fuels, the HDR geothermal heat derived from the Conway granite may become an economic resource to supplement local and imported sources of energy.

Browning Engineering Corporation of Hanover, New Hampshire, drilled one hole 330 m (1086 ft) deep in Conway granite in the Coleman quarry in the town of Madison, New Hampshire, in 1981. Much of the year and funds were expended in developing appropriate equipment and methodology for flame-jet drilling in granite using a burner fed by a mixture of kerosine and compressed air.²⁵ Mann monitored the progress of the experimental drilling and collected chip samples from the hole at 10-ft intervals. Potentially, the use of this equipment may provide an inexpensive method for drilling holes rapidly in hard crystalline rocks.

Castle Dome Prospect, Southwestern Arizona. The Castle Dome HDR geothermal prospect is a 1500 km² region situated in west-central Yuma County about 80 km north of Yuma, Arizona (Fig. 3-6). This prospect, investigated by Gutmann,²⁶ includes much of the Castle Dome Mountains, together with parts of the adjacent Chocolate, Middle, and Kofa Mountains and the intervening basins. The area of interest is broadly defined by a negative residual Bouguer gravity anomaly 45 km across, steep-sided in many places and 30 to 50 mgals in magnitude. Three-dimensional gravity inversion indicates a low-density mass in the lower crust between 10- and 20-km depth. Inversion of several magnetic anomalies shows a change in depth to the Curie point from 10 to 15 km outside the area to ~6 km at the center. C. R. Shearer²⁷ reported a maximum geothermal gradient of 70°C/km from a well near the center of the prospect. Preliminary interpretation of a regional MT profile suggests a depth of ~10 km to an electrical-conductive zone (<25 ohm-m) beneath the region.

Fig. 3-6.
Location of Castle Dome HDR prospect.

Geologic field studies by Los Alamos indicate that the Castle Dome Mountains and adjacent ranges are chiefly a thick pile of welded ash-flow tuff probably mid-Tertiary in age. The tuffs rest unconformably on Mesozoic metasedimentary rocks exposed only outside steep margins of the gravity low. Within the margins, which probably demark a huge Tertiary-age caldera, pre-Tertiary rocks are absent. Geologic and geophysical data suggest cauldron subsidence following copious ignimbrite eruptions that were fed from a batholithic complex of Oligocene-Miocene age. After caldera formation, the

volcanic sequence has undergone two episodes of faulting: listric, and Basin and Range block faulting, which complicates the task of assessing the nature of the potential HDR reservoir rock. Additional stratigraphic, structural, and petrologic studies are needed to answer some of the geologic questions but these studies are subject to availability of funds.

Most of the area within the gravity anomaly lies either on the Yuma Proving Ground (U.S. Army) or the Kofa National Wildlife Refuge (U.S. Fish and Wildlife Service) and is closed to energy development. However, a belt of potentially open land extends north-south across nearly all of the gravity low. Yuma Proving Ground itself might be a potential user of any geothermal energy developed.

3.4. Wells of Opportunity

In order to extend the HDR Program into varied rock types, we are taking advantage of suitable "Wells of Opportunity." This endeavor is intended to use drilled wells, which are offered to us by industry, to develop techniques and models for using volcanic or sedimentary rocks as HDR reservoirs and to assess rock properties at potential HDR sites. It is expected that the geometries of these reservoirs may be different from those designed for Fenton Hill, and may make use of permeable but unproductive zones in the well, alone or in combination with induced fractures, to form a circulation loop. Our FY81 field activities in this part of the program centered on two nonproducing wells in Oregon: ORE-IDA No. 1 at Ontario; and Old Maid Flat 7A on Mt. Hood.

ORE-IDA No. 1. The ORE-IDA No. 1 exploratory geothermal well was drilled in 1979 to a depth of 3065 m (10 054 ft) to provide hot water for processing and heating at the ORE-IDA plant in Ontario, Oregon. Although the bottom-hole temperature was about 190°C, the well produced no significant amount of natural geothermal fluid. Accordingly, as is described in Sec. 4.5.4.3, a stimulation attempt was made in May 1981, sponsored jointly by ORE-IDA Foods, Inc., and the DOE, with coordination by EG&G-Idaho and technical support by HDR personnel and equipment from Los Alamos. As is discussed below the attempt was unsuccessful and we were not able to obtain the desired information on the behavior of basalts as reservoir rocks. However, calculations based on the volume of lignosulfonate mud currently in the hole suggest the existence of an open natural-fracture area of about 9400 m² (assuming 1-mm open-fracture width), which is comparable to that of the Fenton Hill Phase I reservoir surface area during Run Segment 2.

Old Maid Flat 7-A. The Old Maid Flat 7-A exploratory hole was drilled in 1980 by DOE on a Northwest Geothermal Company lease on the west flank of Mt. Hood. The well was drilled to 1837 m (6027 ft) through a mixed volcanic sequence and bottomed in altered basalt believed to be Eocene in age. The well produced less than 0.06 μ /s (1 gpm) from the lower formation. Maximum temperature at depth was 113°C (234°F).

Extensive planning was done for hydrologic and fracturing tests of the basalt formations in the lower 122 m (400 ft) of the well. As the hole is uncased below 363 m (1190 ft), the problems with hardware encountered in the ORE-IDA well were not present. The formations to be tested are of great interest as they are similar to what would be encountered at depth over much of the Northwest. The test was planned for August, but the work was cancelled for lack of funds.

Blanket Orders. A Well-of-Opportunity Blanket Purchase Order is being prepared to permit fast response when a well is offered. The contractor for this service, to be selected by competitive bidding, will provide search and liaison services (including legal support), engineering services for the design of experimental well-testing programs, fracturing and completion services, and hardware (including workover rigs) for this work. The contract will be awarded on a one-year basis.

4.0 FENTON HILL TECHNOLOGY DEVELOPMENT PROJECT

4.1 Continued Assessment of Research Reservoir

4.1.1. Energy Extraction Run Segment 5. Run Segment 5 was a long-term (286-day) flow test of the second hot dry rock reservoir at the Fenton Hill field site. This second reservoir was created by fracturing an interval of granitic rock located at a depth of 2.93 km (9620 ft) in the same wellbore pair used in the creation of the first, smaller reservoir. The new fracture system has a vertical extent of at least 320 m (1050 ft), suggesting that the combined heat-transfer area of the old and new fracture systems is much greater than that of the old system. The virgin rock temperature at the bottom of the deeper interval was 197°C (386°F).

Downhole measurements of the water temperature at the reservoir outlet, as well as temperatures inferred from geothermometry, showed that the thermal drawdown of the reservoir was about 8°C and preliminary estimates indicate

that the minimum effective heat-transfer area of the new reservoir (both fracture surfaces) is $90\,000\text{ m}^2$ ($970\,000\text{ ft}^2$), which is about six times larger than the first reservoir.* Thermal energy was extracted at a rate of 2.2 MW. Reservoir residence-time studies with sodium fluorescein and irradiated ammonium bromide indicate that the volume of the second reservoir is nine times larger than that of the first reservoir. Near the end of the experiment the rate of water loss permeated to the rock surrounding the fracture system was $4.6 \times 10^{-4}\text{ m}^3/\text{s}$ (7 gpm).

Despite the much larger fracture size, this loss rate was only 30% more than that of the first reservoir after an equivalent period of time. The flow impedance, a measure of the resistance to circulating flow through the reservoir, was $1.6\text{ GPa}/\text{m}^3/\text{s}$ (15 psi/gpm) under low back-pressure conditions. No seismic activity was observed at the surface as a result of system operation although a small number of microearthquakes were detected that were attributed to a nearby drilling operation.

The results of this experiment show that the enlarged system created by fracturing from the same pair of wellbores as the older system possesses a much larger heat-transfer system with only a small price being paid in additional water loss. These results hold great promise for commercial-size HDR reservoirs.

4.1.1.1. Operations. The general plan for Run Segment 5 was the same as that used for earlier experiments. Water was injected into borehole EE-1 and the geothermally heated fluid extracted from borehole GT-2B. The heated water was cooled with an air-cooled heat exchanger and then recirculated, with the downhole water loss replenished through a makeup pump. A description of the surface equipment may be found in Ref. 28. As the experiment was to be a long-term heat-extraction test, constant surface pressures with essentially constant flow rates were maintained. The only major perturbation of these conditions was a 9-day shut-in midway through the

*Because a factor of 0.5 appears in conductive heat-flow equations, it is convenient in many heat-extraction calculations to consider the heat-transfer surface presented by one side of the fracture only -- which is only one-half of the total heat-transfer area. That convention is followed in much of the body of this report. Therefore, where confusion might result, a statement is usually included that the heat-transfer area being discussed is one side of the fracture only (one-half of the total area) or both sides (the total heat-transfer area in contact with fluid flowing through the fracture).

pressures of 9.65 MPa (1400 psi) at EE-1 and 1.38 MPa (200 psi) at GT-2B were planned.

Run Segment 5 was characterized by smooth operation. The pumps were quickly brought up to the desired pressures and remained there except for the scheduled 9-day shut-in at day 68, periodic logging runs, and shut-ins caused by temporary power failures. During the last two-thirds of the experiment, a gradual decrease in the wellhead pressure was observed. This decrease in pressure was attributed to a reduction in input flow due to corrosion or erosion of pump-impeller surfaces. During the last 120 days of the experiment, a significant increase in the water loss was observed. This was due to a connection that developed into the EE-1 annulus. This leak also caused an increase in the bottom-hole temperature of EE-1 due to heating by the injected fluid. The makeup system adequately handled the increased flow requirement. For a description of the data-acquisition system, see Ref. 28.

4.1.1.2. Water Losses. The water loss from an HDR system is very important because this water must be provided from some outside source. This information can be vital for environmental as well as economic reasons. The water-loss rate, i.e., the rate at which water permeates the rock formation surrounding the fracture system, is the difference between the injection rate and the produced, or recovered, rate at the production well. The water-loss rate is a strong function of system pressures and flow rate. Wellhead pressures and flow rates for Run Segment 5 are presented in Figs. 4-1 and 4-2. The actual measurement of the volumetric rate of water loss was performed with the makeup-water flow meter except for short periods when these data were not available. Then the actual difference between the EE-1 and GT-2 wellhead flow rates was used. Because the makeup pump provides the difference between the injection rate and the produced flow rate (after the latter is cooled by the heat exchanger), this measurement eliminates nearly all of the small error that would be caused by temperature-induced density differences.

Figures 4-3 and 4-4 are the data for the duration of Run Segment 5. Figure 4-3 is the water-loss rate as measured by the makeup-pump flow meter and Fig. 4-4 is the integral of the water-loss rate. Starting about day 150, a fracture connection from the pressurized reservoir formed in the annulus region of EE-1, resulting in flow to the surface through the annulus. This caused the makeup water to increase dramatically and made it difficult to analyze the water loss during the last 130 days of the experiment. There was

Fig. 4-1.
Wellhead pressures for Run Segment 5.

Fig. 4-2.
Wellbore flow rates for Run Segment 5.

Fig. 4-3.
Water-loss rate for Run Segment 5.

Fig. 4-4.
Cumulative water loss for Run Segment 5.

also another perturbation in the water-loss data caused by a 9-day shut-in experiment starting on day 68. For these reasons the first 70 days [labeled (1) in Fig. 4-3] are used for comparison with other experiments.

These integrated losses are shown again in Fig. 4-5. Here curve 2 is the Run Segment 2 result scaled linearly to the Run Segment 5 pressure. The remaining difference is only 30% of the Run Segment 2 losses.

It is interesting to compare the results of this experiment with that of previous experiments. In this way the relationship between system size and water loss may be examined. Direct comparisons of the raw data indicate that the water-loss rates for the enlarged reservoir evaluated in Run Segments 4 and 5 are approximately 40% higher than the smaller, first reservoir evaluated in Run Segment 2 (the 75-day test). Because the operating pressure (EE-1 surface pressure) was ~10% higher during Run Segment 5, the reservoir parameters governing water loss were not more than 30% greater for Run Segment 5 as compared to Run Segment 2.

Use of the pressure-dependent diffusion model^{28,29} confirms this comparison. Curve fitting to the water-loss-rate data from Run Segment 5 with this model also indicates that the reservoir parameters that determine the response to short-term pressure transients are different than the parameters of the first reservoir tested in Run Segment 2. These short-term transients reflect local properties of the reservoir and indicate that flow in the lower part of the reservoir is governed by a higher stress than in the earlier reservoir.

4.1.1.3. Flow Impedance. The flow impedance, defined as the difference of the inlet and outlet pressures divided by the outlet flow rate, is an important parameter used in determining pumping requirements.

Measurements of impedance for the main flow period (March 10 to December 8) are shown in Fig. 4-6, both uncorrected and with buoyancy corrections. The uncorrected impedance is simply the difference between the injection and production wellhead pressures divided by the circulated through-flow rate measured at the GT-2B production wellhead. The corrected impedance accounts for the fact that the water in the injection well was colder than in the production well so an additional pressure difference existed because of density variations. Generally, uncorrected impedances are 20% lower than corrected values. In reviewing the overall impedance behavior shown in Fig. 4-6, it may

be helpful to refer back to Figs. 4-1 and 4-2, which show wellhead pressure and flow rates for the same period of time.

Note that the fracture system described in the section on system geometry had an impedance of 14.2 MPa/ℓ/s (130 psi/gpm) before the hydraulic fracture treatments of March 1979. During Run Segment 4 the impedance was nearly constant at about 1.8 MPa/ℓ/s (17 psi/gpm), corrected for buoyancy. One of the goals of Run Segment 5 was to observe the impedance behavior during a long-term heat-extraction test.

The knowledge of the impedance distribution will help in the understanding of fracture geometry. This information may be valuable in defining methods to reduce localized impedances. See Ref. 30 for a discussion of Run Segment 5 distributed impedances.

4.1.1.4. Heat Transfer. The heat-transfer system in Run Segment 5 is complicated and is governed by flow in several large fractures. In the past, analyses of the heat-transfer system were made that assumed a system of independent fractures. In the earlier system of Run Segment 2, this proved useful and good fits were obtained. In the present experiment, draw-down and recovery as well as flow measurements suggest that the reservoir can be modeled best as a system of parallel, thermally interacting fractures. The multiple-fracture model was fitted to the wellbore-fracture intersection thermal behavior, while the independent-fractures model was fitted to the thermal behavior of the wellbore total flow. Fits for the independent and multiple fracture models are given in Figs. 4-7 and 4-8, respectively. It is interesting to note that despite the differences in the two models and the data they were fitted to, the heat-transfer areas they yielded were close: 50 000 m² for the independent-fractures model and 45 000 m² for the multiple-fractures model (considering one side of the fracture only). See Ref. 31 for a complete analysis of fracture growth with heat extraction.

4.1.1.5. Seismicity. Reservoir seismicity was monitored with a surface seismometer array and a geophone package that was positioned downhole in EE-2 in the reservoir vicinity. EE-2 is a well recently drilled for the Phase II reservoir. For this experiment it served merely as an observation well. The surface array consisted of six stations within 750 m (1/2 mile) of the site, five borehole stations located within 10 km of the site, and the Los Alamos National Laboratory regional net -- the nearest station of which is located at 10 km. The sensitivity of this surface array extended to local

Fig. 4-5.
Comparison of cumulative water loss
for Run Segments 2 and 5.

Fig. 4-6.
Uncorrected and corrected for buoyancy
impedances during Run Segment 5.

Fig. 4-7.
Computer model comparison with field
data with independent fracture model
for Run Segment 5.

Fig. 4-8.
Computer model comparison with field
data for multiple-fracture model.

Richter earthquake magnitudes of 0 to -1.5 and is limited by the nearly 3 km of vertical separation and the large seismic attenuation of the near-surface sediments and volcanics. The downhole geophone package consisted of 12 geophones, 4 each in the x-, y-, and z- directions. The sensitivity of the downhole package during most of Run Segment 5 extended to magnitudes as low as -6. During those periods when the geophones were in place, the drilling rig had to be idled; therefore, the downhole geophones were used only during selected periods. During the 286 days of flow, 13 microearthquakes ranging between -1.5 and 0.5 on the extrapolated Richter scale were recorded by the surface seismic array. These events were located about 200 m north of EE-2 at a depth of about 1 km. The events are not related to Run Segment 5 activities, but rather to the drilling of EE-3.

4.1.2. Stress Unlocking Experiment (SUE). On December 9 and 10, 1980, after 281 days of sustained heat extraction that took place during Run Segment 5, SUE was conducted. One purpose of SUE was to produce acoustic signals, that is, microseismicity from the cooled geothermal reservoir by releasing the accumulated thermal strains produced by 281 days of sustained heat extraction and rock cooling. At the time of the SUE experiment about 15 000 000 kWh of thermal energy had been extracted from the reservoir. The relaxation of thermal stresses was accomplished by pumping water into the reservoir injection well, EE-1, at high pressures, about 15 MPa (2200 psi). Because the reservoir production well, GT-2B, was shut-in, or also pressurized, nearly the entire reservoir was pressurized to high levels, and it was hoped that the normal forces that held the fracture faces together in frictional contact would be reduced, resulting in shear slippage and microseismicity. Monitoring of microseismic signals was performed with two downhole geophone packages, one stationed in GT-2B, the usual reservoir production well, and the other in EE-2, a recently drilled well, that served as an observation well for this experiment.

Other purposes were to reduce the fracture flow impedance as a consequence of the shear slippage of fracture faces and to increase the reservoir size.

4.1.2.1. Microseismic Results. Figure 4-9 presents the histories of the EE-1 and GT-2B well pressures and the measured rate of microseismic events. The events in question have magnitudes of between -4 and -2 on the extrapolated Richter scale. Figure 4-9 shows an increasing event

rate with time until the cessation of pumping into EE-1, at which time the rate drops sharply. Figure 4-10 plots these same event rates against the EE-1 pressure. Judging by the pressure at the commencement of activity and the pressure at the sharp increase in activity, this plot seems to indicate a threshold for seismic activity between 9.5 MPa (1400 psi) and 11.0 MPa (1600 psi), along with another apparent critical pressure of 15.0 MPa (2200 psi) at which seismic activity increases sharply. Examination of the EE-1 pressure history in Fig. 4-9 shows a constant pressure level at this last pressure, during the last 2 h of pumping, indicating the onset of further hydraulic fracturing. Additional fracturing was confirmed by the tracer experiments, which are described later.

Before presenting maps of the SUE microseismic results, we must first briefly discuss the complex relation between microseismicity, pressurization, and thermal stress. It is believed that most of the thermal-contraction strain during Run Segment 5 was "locked in" by frictional forces on the fracture faces. (Downhole operating pressures were well below the confining earth stress on average.) This belief is supported by observations from tracer studies, which showed that the measured volume increase of the reservoir was only 10% of that expected on the basis of free thermal contraction. However, these frictional forces could be eliminated by pressurization in excess of the local earth confining stress, which would "unlock" the thermal contraction. Unfortunately, such pressurization results in microseismicity on its own account, as has been shown during many past experiments. The question then is, how can one distinguish microseismicity caused by pressurization alone from that caused by thermal stresses abetted by pressurization? At the present time there appears to be no clear-cut answer; certainly there do not seem to be any distinguishing characteristics in the microseismic signals themselves. However, a partial and qualitative picture can be assembled by examining maps of the microseismic event locations from past experiments and comparing these with the SUE locations. A summary of this information is provided in Table 4-I. For each recent experiment in which microseismicity was measured, we have tabulated the total injection volume and injection rate, the maximum wellhead pressure, and the diameter of microseismic activity. This diameter is not meant to imply that the microseismic events define circular fractures, but is merely the length of the chord that passes through the

Fig. 4-9.
System pressures, pumping rates, and seismic event rates during SUE.

Fig. 4-10.
Seismic event rate as function of EE-1 wellhead pressure.

TABLE 4-I
SUMMARY OF MICROSEISMIC EXPERIMENTS

Experi- ment	Date	Injection Volume (m ³)	Max. Injec. Rate (m ³ /s)	Max. Inj. & Prod. Well Pressures (MPa)	Diameter of Microseismic Activity (m)
203	10/14/79	603	0.032	19.5/5.5	580
195	3/21/79	755	0.051	10.7/10.3	650
Run Seg. 4	10/30/79	5 000	0.025	17.0/10.0	920
SUE	12/8/80	1 000	0.040	15.5/13.0	250

bulk of the locations in a given experiment. In reviewing the operating conditions of Table 4-I, it can be seen that, although there are small variations of injection flow rate and pressures of the order of $\pm 50\%$ about the mean, the major difference occurs with injection volume. These injection volumes vary by nearly a factor of 10, from 600 m³ to 5000 m³, so as a first approximation, one would seek a correlation between the microseismic activity diameter and the injection volume. For the first three experiments, in which heat extraction and thermal contraction were insignificant (Expts. 203 and 195 lasted 1 day; microseismicity during Run Segment 4 was measured only 7 days from the start of heat extraction), it can be noted that the microseismic diameter indeed correlates with injection volume. Admittedly the variation is not a strong one -- the apparent diameter ranges only from about 600 m to 900 m despite a nearly 10-fold increase of injection volume. However, the SUE microseismicity is significantly different. Here the microseismic diameter is only 250 m, less than half the diameter measured during Expts. 203 and 195, despite the fact that the SUE injection volume was actually larger than that in either Expt. 203 or 195. During SUE, water penetrated the reservoir formation as far away from the injection well as it did during Expts. 203 and 195, but the microseismic activity in the regions unaffected by thermal drawdown was apparently diminished by the repeated injections prior to and including SUE. In other words, these regions were becoming aseismic to pressure variations. The SUE microseismicity is thus thought to be predominantly due to the released thermal stresses, and on this basis it may tentatively be concluded that the microseismic activity during SUE focused on thermal effects. However, we cannot exclude the possibility that some events due

primarily to pressure are still included in the population. Indeed, the comparison with heat-transfer-inferred geometries suggests that remaining pressure effects do distort the microseismic geometry somewhat. This distortion is unavoidable, even for reservoirs in nearly impervious rock. Because of the presence of natural joints, both filled and unfilled, and the finite, albeit low, permeability of the rock fabric, there will always be water losses to the rock surrounding the fracture system. Consequently, pressurization and microseismicity can occur not only in regions of the fracture not usually available for heat transfer in the continuous-circulation flow-through mode, but many of the events also stem from locations large distances away from and outside the plane of the fractures.

Figures 4-11 and 4-12 compare the locations of the microseismic events of SUE with the heat-transfer geometries discussed in 4.1.1.4. Figure 4-11 is a plan view, that is, looking vertically down; Fig. 4-12 is an elevation view, in which the reader is looking horizontally in approximately an east-west direction, perpendicular to the planes indicated in Fig. 4-11. In Fig. 4-11, the three upper fractures of the multiple-fracture model and the two fractures of the independent-fracture models are shown as lines. From these figures it can be seen that from one fracture extremity to the other the seismic activity takes place within a separation distance of about 250 m. This is in sharp contrast to the microseismic results of Run Segment 4, in which the microseismic diameter was over 900 m.

Referring now to the elevation view, Fig. 4-12, it is seen that if a circle is drawn around all the microseismic events, this circle has a radius of about 140 m and an area of about $60\,000\text{ m}^2$. In comparison, the largest of the parallel circular fractures of the independent-fractures model has an area of $35\,000\text{ m}^2$ per Table 4-I. The multiple-fractures model consisted of five fractures, three in the upper reservoir and two below. In the elevation view of Fig. 4-12, one would see one of each, and because the upper and lower fractures are connected in this model, one would see one long rectangle about 50 m wide and 300 m long in the vertical direction, a total area of about $15\,000\text{ m}^2$. In summary, the microseismic area from SUE is still considerably greater than the appropriate heat-transfer area, by a factor of 2 for the independent-fractures model and by a factor of 4 for the multiple-fractures model. As explanation for these discrepancies, we suggest the strong

Fig. 4-11.
Plan view comparing microseismic event locations with heat-transfer model geometries.

Fig. 4-12.
Elevation view (looking approximately from east to west) comparing microseismic event locations with heat-transfer model geometries.

possibility that the SUE microseismic events were not completely confined to the thermally affected region. Nevertheless, despite these numerical discrepancies, the rough qualitative agreement of the microseismic and heat-transfer model geometries is encouraging when the sharp differences in approach of the two methods are considered.

4.1.2.2. Impedance Reduction. Figure 4-13 shows the overall reservoir impedance history immediately before and after SUE. The total impedance involves a buoyancy correction that was calculated to be 2 MPa (300 psi). The entrance and exit impedances are derived from shut-in experiments on the dates shown. The techniques for determining entrance and exit impedances are based upon Muskat analysis of the wellhead pressures during shut-ins of EE-1 and GT-2B, respectively. Background discussion of this type of analysis is found in Ref. 32; details of all the Run Segment 5 shut-ins, before and after SUE, are presented in Ref. 33.

The results of the experiment are summarized in Table 4-II, which shows the percentage decrease in the impedance values.

Fig. 4-13.
Effect of SUE on impedances.

4.1.2.3. Reservoir Enlargement During SUE. To characterize the changes in fracture-system volume and flow distribution produced by the SUE experiment, radioactive $\text{NH}_4\text{Br}^{82}$ tracer experiments were conducted before and after SUE. In both cases, a 400-mCi pulse of tracer was injected and was monitored by logging with a downhole gamma counter in addition to counting at the production wellhead with a NaI crystal detector. Five pre-SUE tracer tests were run during the course of Run Segment 5 and the post-SUE tracer test was run on December 12, 1980.

Reservoir volumes can be inferred from the tracer experiments by multiplying the production flow rate by the time required for the tracer to pass through the reservoir. Because the tracer is dispersed and mixed in its passage, a single, discrete volume cannot be defined; instead one can define integral mean and modal volumes. These have been defined previously by Tester et al.³⁴ and for comparison purposes, we have found it most convenient to use the modal volume, in which the time from tracer injection to peak tracer concentration in the production well is used.

Figure 4-14 presents these modal volumes during Run Segment 5 as well as the post-SUE value. A rather large change in the modal volume is observed after the pressurization of the system during SUE. The high injection pressure of 15 MPa (2200 psi) was sufficient to increase the modal volume from 187 to 266 m^3 , a 43% increase in size. Comparison of the normalized residence time distributions for the last three tracer experiments (not presented here) shows no corresponding change in dispersion characteristics due to the SUE experiment. Apparently the volumes of the existing fractures were increased with no new fractures or other changes in flow paths being created.

Figure 4-14 also indicates a reasonably linear increase of fracture modal volume as heat was extracted; a total heat extraction, E , resulted in a volume increase, ΔV , of 37 m^3 . The energy E is related to the integral of the temperature decrease over the entire reservoir rock volume affected by thermal drawdown. If the rock is assumed to be a stress-free, freely contracting medium, then ΔV is also related to the same integral, and it can be shown that

$$\Delta V = \alpha_v E / (\rho c)_r ,$$

where α_v is the volumetric thermal expansion coefficient of the rock and $(\rho c)_r$ is its volumetric heat capacity. Using a typical value, $(\rho c)_r = 2.7 \times 10^6 \text{ J}/(\text{m}^3 \text{ } ^\circ\text{C})$, and the preceding values of ΔV and E , α_v can be estimated as $2.8 \times 10^{-6}/^\circ\text{C}$. This is only one-tenth the value typical of

TABLE 4-II
CHANGES IN IMPEDANCES CAUSED BY SUE

Type of Impedance	(a)		(b)		Percent Decrease (a-b)/a x 100
	Before, GPa s/m ³ (psi/gpm)		After, GPa s/m ³ (psi/gpm)		
Total	1.42	(15.5)	0.90	(9.8)	37
Entrance	0.16	(1.7)	0.06	(0.7)	61
Exit	0.90	(9.7)	0.50	(5.5)	43
Main Fracture	0.38	(4.1)	0.34	(3.7)	12

laboratory experiments with dense granite.³⁵ The large discrepancy is attributed to two causes: (1) the rock is actually under considerable tectonic stress, and much of the expected thermal contraction simply was consumed in relieving a part of these stresses; and (2) much of the thermal contraction may have been manifested as an increase in porosity that occurred far enough away from the main fracture system that the porosity increase was not detected by the tracer passing through the fracture system. It is interesting to note that SUE itself resulted in another ΔV of 78 m³, so that

Fig. 4-14.

Fracture modal volume increases due to Run Segment 5 heat extraction and high-pressure injection during SUE. The thermal energy referred to here is limited to that of the reservoir only -- it excludes the contribution from the injection and production wellbores. Thus the total energy during Run Segment 5 was 15×10^6 kWh.

the total volume increase was 115 m^3 , still only 30% of that expected if the reservoir was completely free to contract.

4.1.3. Electrical Generation Experiment. In May 1980, during Run Segment 5 (Expt. 217), an electric generating unit was added to the heat-extraction loop at Fenton Hill. The unit was designed, assembled, and evaluated by Barber-Nichols Engineering.³⁶ The design specification for the 60 kW(e) plant called for utilization of current technology, and required that the power module be skid-mounted and easily transported from one location to another. A resource temperature of 140°C was assumed for design purposes with an operating temperature range of from 110 to 180°C . Cooling water was unavailable at the site so ambient air was used for the sink. The annual average air temperature at Fenton Hill is 4°C .

Several cycles and working fluids were evaluated before Refrigerant 114 was selected for the Rankine-cycle power module.³⁷ The final cycle selected is shown in Fig. 4-15. The physical configuration of the R-114 system is shown in Fig. 4-16. The major components include a feed pump, preheater, boiler, turbine, condenser, hot well, and generator. The geothermal fluid, pressurized water, passes through the tubes of a pool-type boiler and then through a tube-in-tube preheater and back to the geothermal loop. The Rankine-cycle organic fluid, R-114, is boiled in the pool boiler after passing through the preheater and then expanded through the partial-admission single-stage axial flow turbine at 3600 rpm. The exhaust vapor is then condensed in air-cooled units and the liquid returned to the boiler via a hot well and multistaged centrifugal diffuser-type boiler feed pump. Efficiency for the generating cycle at design conditions is 5.7% with a source utilization efficiency of 24.7% and source production factor of 5.5 Wh/kg.

The installation of the skid-mounted unit was completed with the unit in parallel to loop heat exchangers and with the generated power being fed into the site secondary power system with safety shut-down provisions. Initial start-up of the unit was accomplished with very little difficulty. During operation it performed well. With geothermal fluid at 132°C and ambient air at design condition of 3.8°C , it produced 60-kW net output. This exceeds design cycle efficiency of 5.7%, partially due to still-clean heat-transfer surfaces. Although the unit had been carefully leak tested before delivery, instrumentation added at installation caused some continuing loss of refrigerant, and after running several weeks, the unit was shut down. When

Fig. 4-15.
Temperature-enthalpy diagram at design conditions.

Fig. 4-16.
R-114 60-kW(e) binary-fluid power cycle.

additional fluid was finally received, the unit was again operated until a short developed in the generator. Warranty covered repairs were slow, so a smaller generator (50 kW) was installed for the final weeks of Run Segment 5. The substitute unit worked satisfactorily to the end of the flow test. Overall, the results indicate the electric generating system was successful using R-114 as the working fluid and maintaining the geothermal fluid as superheated water for recirculation.

4.1.4. Summary of Research Reservoir Testing. The Research or Phase I reservoir was tested during Run Segments 2 through 5, conducted from 1978 through 1980. During these three years our understanding of reservoir behavior has steadily improved. In particular, numerical modeling evolved continuously, so that simplified models that were developed for Run Segment 2 were significantly modified by the time of Run Segment 5. Consequently, in 1980 we initiated a task to reassess, on a consistent basis, all previous tests with our latest models. The aim was to trace the growth of the reservoir with time, and identify those periods of growth caused by thermal fracturing as contrasted to pressure fracturing.

4.1.4.1. Growth of the Reservoir Heat-Transfer Area. As introduced in Section 4.1.1.4., heat-transfer modeling of the reservoirs has been performed with two numerical models. Both models use two-dimensional simulators in which heat is transported by conduction within the rock to the fractures. The most recently developed model, which we call the multiple-fracture model, assumes that the reservoir consists of three fractures, and idealizes these fractures as parallel rectangles in which the flow is distributed uniformly along the bottom of each fracture and uniformly withdrawn from the top of each fracture. The flow is thus one-dimensional and the streamlines are straight vertical lines. Consequently, fluid-dynamic considerations do not directly enter into the heat-extraction process -- the sweep efficiency is implicitly assumed to be 100%. However a rigorous two-dimensional heat-conduction solution is incorporated for the rock between the fractures, and this permits valid consideration of thermal-interaction effects between the fractures. In contrast, the older model, the independent-fractures model, assumes that the fractures (two in number) are circular (but other assumptions are permissible), and allows proper local positioning of the inlet and outlets, i.e., the point-like intersection of the injection well with the fracture can be modeled, as can the intersection of the main hydraulic

fractures and the slanting joints that provide the connections to GT-2B. However, as was cautioned earlier, while the fluid dynamic effects of the joints/outlets can be faithfully modeled, the heat-transfer effect of the joints cannot -- the area of the joints must be lumped with that of the main fractures. In view of this more faithful representation of inlet and outlets, and the fact that a complete two-dimensional solution to the Navier-Stokes fluid-dynamic equations is incorporated, the independent-fractures model results in a more realistic assessment of the effect of fluid dynamics and sweep efficiencies upon heat extraction. The penalty, however, is that in the present two-dimensional version of the code, thermal interaction as the temperature waves in the rock between fractures overlap cannot be realistically represented, as it is with the multiple fracture model.

4.1.4.2. Independent Fractures Modeling. The first application of the older model was to the early research reservoir, when only a small, single hydraulic fracture existed. This reservoir was tested extensively during Run Segment 2, the 75-day test, and is described in Ref. 28. Based upon spinner and temperature surveys in the production well, the depths of the intersections of the production well with the slanting joints were estimated as well as the flow rates communicated by each joint. In the calculations, the actual temporal variations of production and injection flow rates were utilized. The fracture-inlet temperature was estimated with a separate wellbore heat-transmission calculation.³⁸ With this information, estimates of the thermal drawdown were calculated with the model for various trial values of fracture radii and vertical position of the fracture inlet. It could not be assumed that the inlet was located at the center of the fracture because the earth stresses increase with depth, so that during its creation the fracture probably grew preferentially in the upward direction. A fracture radius of 60 m with an inlet located 25 m above the fracture bottom resulted in a good fit to the measurements, and, as shown in Fig. 4-17, the computed thermal behavior was in good agreement with the measured temperature. The temperature shown is the mixed mean reservoir-outlet temperature. That is, the mean outlet temperature is taken as the mean of the joint-outlet temperatures measured in the production well, averaged, or weighted, by the flow rate fraction in each joint. This mean outlet-temperature measurement is considered as the best measure of the overall thermal performance of the reservoir and is used, for this model, to describe not only the early reservoir, but

also below, the enlarged, two-fracture reservoir. However, as will be indicated later, one of the strengths of the newer, multiple-fracture model is that the temperatures of the individual joints, as well as the mean temperature, are also modeled realistically. A radius of 60 m, as indicated by the fit to the data in Fig. 4-17, implies a total fracture area (on one side) of $11\,000\text{ m}^2$; however, because of hydrodynamic flow-sweep inefficiencies, the net area effective in heat exchange was only 8000 m^2 during Run Segment 2. Unlike the newer model, we were unable, with the independent-fractures model, to obtain a clear-cut indication of thermal growth from the drawdown data of Run Segment 2. The very low rate of drawdown in the later period of the test prevented resolution of any potential area increase.

Six months after the conclusion of Run Segment 2, Run Segment 3 (the high back-pressure experiment) was conducted in October of 1978. The purpose was to examine reservoir behavior under conditions of high mean fracture pressure. The test duration was short, less than 1 month, but the thermal drawdown suggested that, according to the independent-fractures model, the effective heat-transfer area was nearly the same. However, flow rate (spinner) surveys in GT-2 indicated that, because of the higher pressure level, most of the flow was entering GT-2B at positions that averaged 25 m deeper than during Run Segment 2. In effect the reservoir flow paths were shortened by 25 m, some 25%. A reduction of at least 25% in heat-transfer area would have been expected because this vertical shortening would also result in horizontal contraction of the streamlines, and yet the area estimated from actual drawdown was about the same. It was concluded that, while pressurization did indeed result in partial short circuiting of the streamlines, it also resulted in a notable decrease in impedance, which afforded better fluid sweep and bathing of the remaining area. This impedance change is described in more detail in a following section.

The reservoir was enlarged during the fracturing operations of 1979. For the independent-fractures model the enlarged reservoir is portrayed as two fractures, the old one operative in Run Segments 2 and 3, and a new and larger one. The enlarged reservoir was evaluated during Run Segment 4,³² and Run Segment 5.³⁰ To summarize the Run Segment 4 studies, it was found that the old fracture had an effective heat-transfer area (one side of the fracture) of $15\,000\text{ m}^2$ and the new fracture had an effective area of at least $30\,000\text{ m}^2$. We say at least because the heat-extraction period was only 23 days, far too

short to result in significant thermal depletion of the new fracture. The area determined in Run Segment 4 for the old fracture was at least twice that determined in Run Segment 2. This trend of increasing area, as observed in both Run Segments 3 and 4, is now attributed to thermal-stress-cracking effects.³⁹

Better estimates of the total effective heat-transfer area of both fractures were obtained in Run Segment 5, during which the thermal drawdown attained 8°C. This drawdown and the model predictions for several values of the combined areas are shown in Fig. 4-7. The data ranges shown should not be interpreted as error bars. Instead, the ranges merely reflect the differences that occur if the thermal decline is measured with respect to the initial mean reservoir-outlet temperature, or, instead, with respect to the highest mean outlet temperature observed. The mean outlet temperature actually increased slightly during the early portion of Run Segment 5. This temporary increase is due to transport of deeper, hotter water to the production well, as well as to some interaction of the fractures. For simplicity the effect was neglected in the independent-fractures model as it is fairly small, less than 2°C. As shown in Fig. 4-18, the data are fit very well by a model with a combined area of 50 000 m², some 5000 m² greater than the area tentatively estimated from the very small drawdown during Run Segment 4.

A summary of the heat-exchange areas determined with the independent fractures model is presented in Fig. 4-18. As can be seen, a steady increase, from 8000 to 50 000 m², is indicated. This trend is supported not only by the newer modeling discussed next, but also by reservoir tracer experiments presented in the following section.

4.1.4.3. Multiple Fracture Modeling. The mean reservoir outlet temperature as measured at 2620 m (8600 ft), in GT-2B during Run Segment 2, is replotted in Fig. 4-19, along with model fits that invoke an increasing heat-exchange area. The following procedure was used to fit the data.

- The measured GT-2B flow rate and estimated reservoir inlet temperature were programmed as functions of time.
- The initial fracture area was adjusted to obtain the best fit at early times.
- The fracture area was allowed to increase so as to provide a good fit to the remaining data. For computational simplicity, the area

increase was assumed to occur in discrete steps rather than in a smooth, say piece-wise linear, fashion.

The resulting step increases in the area necessary to fit the data are also shown in Fig. 4-19. As indicated earlier, the independent-fractures model was not able to detect any increase in the effective heat-transfer area during actual drawdown, but the multiple-fracture model indicates that the heat-transfer area increased by a factor of 2.

Similar modeling was carried out for Run Segments 3, 4, and 5 and Fig. 4-20 summarizes the growth of the heat-exchange area, according to the multiple-fractures model, throughout Phase I. The general similarity with the summary of the independent-fractures model, Fig. 4-19, is noted, but there are differences in detail. The initial area of 7500 m^2 in Fig. 4-21 was established by many pressurizations and some cooling. This area grew to $15\,000 \text{ m}^2$ in Run Segment 2. As indicated earlier the high back-pressure of Run Segment 3 caused a redistribution of flow resulting in fluid-dynamic short-circuiting. However, unlike the independent-fractures model, the new model indicates that the initial heat-exchange area was actually less than that of Run Segment 2, starting at 6000 m^2 ; but it then grew to $12\,000 \text{ m}^2$ during the 28-day test. The system was pressurized to high pressures several times during Expts. 203 and 155 (massive hydraulic fracturing experiments) and Run Segment 4, but no area or volume measurements were made until Run Segment 4. After Run Segment 4, the EE-1 temperature logs indicated that between 6000 and 9000 m^2 had been added to the lower part of the reservoir by the recementing and pressurization prior to and during Run Segment 4. This increased the measured heat-exchange area to between $21\,000$ and $24\,000 \text{ m}^2$. The area measurements during Run Segment 5 are somewhat uncertain. The best estimates are that the heat-exchange area was greater than $45\,000 \text{ m}^2$ at the end of the experiment.

4.1.4.4. Growth of the Reservoir Volume. Tracer tests and the reservoir volumes that can be derived from such tests were discussed in Section 4.1.2.3. As described there, the modal volume is used as a consistent basis for tracing the growth of the reservoir fracture volume.

A complete review of the tracer-test data from Segments 2 through 5 has revealed pertinent information regarding the growth of the reservoir due to heat extraction and pressurization effects. The reservoir growth due to heat extraction is, to be precise, really a thermal contraction effect -- as the rock surrounding the fractures shrinks, the fractures, and consequently, the

Fig. 4-17.

Computer model comparison with field data for a single fracture for Run Segment 2.

Fig. 4-18.

Heat-transfer area growth determined by the independent-fractures model in the Phase I reservoirs during Run Segments 2 through 5. Areas represent one side of the fracture only.

Fig. 4-19.

Computer model comparisons of field data with programmed increases in heat transfer area for Run Segment 2.

Fig. 4-20.

Heat-transfer area growth determined by model fits to drawdown data and well-bore temperature logs in the Phase I reservoirs during Run Segments 2 through 5.

measured volumes, expand. Figure 4-21 is a linear plot of modal volume increase (ΔV) as a function of net thermal energy extracted from the reservoir (ΔE). Essentially identical linear behavior is observed for the low back-pressure experiment, Run Segment 2, of the early research reservoir, and the low back-pressure experiment, Run Segment 5, of the enlarged system. In spite of nonlinear coupled effects of thermal contraction, pore and fracture inflation due to sustained pressurization, and local irreversibilities resulting in fracture propagation, a simple correlation between ΔV and ΔE exists. Furthermore, this simple relationship persists even in the presence of the confining stresses surrounding the active reservoir, which induce a constrained behavior. As indicated in Section 4.1.2.3., the slope of the line for low back pressure is only about 10% of what would be expected for free thermal contraction ($\Delta V = [\alpha_v / (\rho C)_r] \Delta E$) in a stress-free environment. Values of $\alpha_v = 2.8 \times 10^{-6} \text{K}^{-1}$, $c = 1000 \text{ J/kgK}$ and $\rho = 2700 \text{ kg/m}^3$ were used to represent the granite matrix. For practical purposes, the region between the low-pressure data and the free-thermal-volume lines defines an envelope of reservoir operating conditions. As stresses are relieved, for example during the SUE at the end of Run Segment 5, or the high back-pressure test of the original reservoir (Run Segment 3), or the high-pressure, hydraulic-fracturing stage at the beginning of Run Segment 4, one moves away from the normally constrained condition toward the free-thermal-expansion line.

Perhaps the most promising aspect of the tracer tests is their potential for estimating the effective heat-transfer surface area of a reservoir. This becomes clear when the modal volume (plotted vs time in Fig. 4-22) is compared to the corresponding heat-transfer area (plotted vs time in Figs. 4-19 and 4-21); the similarities of the growth of area and volume are quite striking. This can be quantified by considering the relationships between area, volume, and aperture (or effective fracture opening). The volume, V , is simply the product of the area, A , and the mean aperture, w :

$$V = A \cdot w$$

During heat-extraction and/or pressurization, the area and aperture can both vary; therefore the volume is a function of two variables rather than one. For constant aperture, the tracer volumes should scale directly with heat-transfer area. A suggestion of this behavior is seen in the data from Run Segment 2, shown in Fig. 4-23 where the modal volume vs area curve has an

Fig. 4-21.
Increase in tracer modal volume as a function of thermal energy extracted.

Fig. 4-22.
Growth of tracer modal volume in the Phase I reservoirs during Run Segments 2 through 5.

Fig. 4-23.
Preliminary correlation of increases in effective heat-transfer surface area with modal volume increase in the Phase I reservoir.

intercept that corresponds to a constant 1.7-mm aperture. Subsequent pressurization has apparently increased the aperture. Because only minimum estimates of the heat-transfer area are available for two of the measured volumes in Run Segments 4 and 5, not all of the tracer data can be used in this figure. It is likely that the data from Run Segment 5 would also fall upon a line of constant aperture, in which case, the mean fracture aperture would be roughly 4 mm. There is insufficient information available to provide upper bounds for the heat-transfer area from Run Segment 5, so the correlation between heat-transfer area and modal volume is inferred by analogy with Run Segment 2. Further development of this empirical correlation could provide a direct and independent method of determining reservoir heat-transfer area without requiring thermal drawdown, which is time consuming and expensive to obtain, particularly so for the larger Phase II reservoir under development.

4.2. Engineering (Phase II) System Design and Construction.

4.2.1. Reservoir Design. The Phase II Fenton Hill System is intended to serve as a demonstration of commercial viability of hydraulically fractured heat-extraction loops in low-permeability hot dry rock. It is of course difficult to specify requirements for reservoir performance to assure that such a demonstration will be convincing to potential commercial developers. Nevertheless, performance goals were set in Refs. 40 and 41. Basically these goals call for the production of thermal power at a nominal level of 35 MW(t) with no more than 20% drawdown in 20 yr. Temperature measurements in the first (EE-2) of the two wells completed for the Phase II reservoir indicate that the mean reservoir temperature will be about 260°C (500°F). Over the 10-yr evaluation period the average drawdown should be 10%, so the mean outlet temperature during this period will be approximately 235°C. Wellbore heat-transmission calculations show that, over a 10-yr period, the loss in temperature as the water travels to the surface will average less than 5°C. Currently the heat exchanger at Fenton Hill rejects heat so efficiently from the water produced from the Phase I reservoir that this water is reinjected at only 25°C. Assuming, however, that the increased flow rate intended for the Phase II reservoir results in lowered heat-rejection efficiencies, the Phase II reinjection temperature is conservatively assumed to be 50°C. The net change in the mean water temperature is thus 180°C, requiring a flow rate of 46 L/s (730 gpm) to yield 35 MW(t).

The effective heat-transfer area required to produce this thermal power can be estimated from one-dimensional heat-conduction theory.⁴² Using thermal-transport properties for Fenton Hill granites measured in situ,⁴³ it can be shown that an effective area of approximately 10^6 m^2 is required. (This area represents one side of a fracture only. Thus, if a fracture were circular with radius R , the area in question would be πR^2 .) This area requirement could be satisfied by a single fracture, or by several parallel fractures. In the latter case the fractures would have to be far enough apart so that significant thermal interaction between the fractures, which would diminish performance, could be avoided over the time span of interest, or else more fractures would be required to offset the diminished performance. A single fracture would require, if circular, a radius of 580 m (1900 ft), which is beyond established fracturing technology in HDR reservoirs. We have therefore adopted the conservative philosophy that the Phase II fractures will not be much larger than the fracture produced in enlarging our Phase I reservoir. This fracture, if judged by the inlet-to-outlet vertical separation distance of 300 m (1000 ft), would have a total area, if circular, of $70\,000 \text{ m}^2$, but due to inefficiencies of water-sweep patterns within the fracture, the effective heat-transfer area is only about $50\,000 \text{ m}^2$ (one side of the fracture only). However, this fracture was the result of the modest attempt in which only 1500 m^3 (400 000 gal) of water, without additives of any sort, were injected as the fracturing fluid. Our fracturing capabilities will be expanded for the Phase II reservoir, but even so, we plan, conservatively, to create fractures with an inlet-to-outlet separation of about 360 m (1200 ft). Assuming the same ratio of effective heat-transfer to circular areas as above, the estimated heat-transfer area of these fractures will be $75\,000 \text{ m}^2$ each, so that approximately 14 such fractures will be required to produce a total area of 10^6 m^2 .

Because the horizontal earth stresses at depth are usually considerably smaller than the vertical, or overburden, stress, the fracture planes are expected to be approximately vertical. In order, then, to accommodate 14 fractures with reasonable horizontal separation distances between fractures, it becomes necessary to deviate the wells from the vertical in the hot downhole region, as shown in Fig. 4-24. Whereas a perfectly horizontal well would be ideal for this purpose, and such wells have apparently been achieved in coal sedimentary formations, a well deviated too far from the vertical

(a)

(b)

Fig. 4-24.
Phase II wellbore system.

appears impractical in our situation. In addition to anticipated directional drilling problems, it becomes difficult to center and set casing, and even more difficult to run logging tools, if the angle from vertical exceeds about 45° . As a compromise, therefore, we have chosen 35° .

To avoid significant performance deterioration because of thermal interaction between the fractures, they must be horizontally separated by approximately two times the thermal diffusion distance, κt , where κ is the rock thermal diffusivity and t is time. For 10 yr the required separation

distance is 35 m (115 ft) which, for 14 fractures, requires a total horizontal distance of about 500 m (1600 ft). At a drilling angle of 35°, a reservoir with vertical height of 700 m (2300 ft) is thus required. For high-quality energy production purposes, reservoir temperatures in excess of 200°C are preferred, which, considering the geothermal gradients at Fenton Hill, corresponds to a minimum depth of 3 km (9850 ft). Thus, as shown in Fig. 4-25, our plan is to drill vertically to about 3 km and then directionally drill until a deviation of 35° from vertical is attained. Each hole will then be drilled straight ahead for an additional 1000 m (3300 ft), corresponding to a true vertical penetration of about 800 m (2600 ft), thus providing some margin of conservativeness over the 700-m requirement. During the drilling the wells would be maintained at a vertical separation of 360 m.

Details regarding drilling and completions of the first of the two wells, designated EE-2, appeared in our Annual Reports for FY79⁴⁴ and FY80,¹ and the drilling of the second well, EE-3, is discussed in the next sections. Final details regarding fracturing operations are still being considered. However, the fractures will probably be made with ordinary water, although it is possible that inexpensive additives will be included to reduce friction losses in the injection well and to decrease permeation losses from the face of each fracture as it is propagated. Our experience in the granitic formations at Fenton Hill indicates that, upon the cessation of pumping and fracturing, the fractures are "self-propped" due to asperity-to-asperity contacts on the fracture surfaces. Therefore proppants in the fracturing fluid have not been required, resulting in considerable saving over the usual fracturing job -- which typically requires hundreds of thousands of pounds of proppants, expensive fracture fluids, blending trucks, and pad and cleanup fluids. During the hydraulic fracturing operations of Expts. 195 and 203, which produced our current Phase I 300-m fracture, pumping rates of up to 0.05 m³/s (750 gpm), pressures of 200 bars (3000 psi), and total injection volumes of 1500 m³ (400 000 gal) of water were used. Currently we plan to have a pumping capacity of 0.08 m³/s (1300 gpm), 350 bars (5000 psi), and up to 4000 m³ (10⁶ gal) of water on hand for each of the Phase II fractures. Downhole fracturing locations will be selected from geophysical, temperature, televiwer, caliper, and tracer logs, focussing upon zones of potential rock weaknesses. Practical means of zone isolation, to produce appropriately spaced hydraulic fractures, are still being evaluated. Upon completion of the

(a)

(b)

Fig. 4-25.

(a) Plan view of EE-2/EE-3 well trajectories and tolerance band for EE-3 directional drilling. (b) Trajectories projected into west-east vertical plane showing EE-3 target inclination and vertical-separation tolerance. [kick-off point (KOP), total depth (TD), true vertical depth (TVD)].

fractures, metering of the flow rate into each fracture will probably be accomplished with downhole, wire-line-activated, flow-control equipment.

During construction of a surface system capable of handling and dissipating the ~35 MW(t), which the final Phase II System is designed to produce, an "interim" Phase II System will be constructed and operated. It will consist of approximately three parallel hydraulic fractures connecting the inclined sections of wells EE-2 and EE-3, whose combined thermal output should not exceed the 20 MW(t) capacity of the air-cooled heat exchangers already installed in the Phase I System. Construction of the interim underground loop will permit evaluation of hydraulic-fracturing techniques and problems in this demanding new environment, determination of fracture orientations and flow impedances, and investigation of flow distribution among parallel fractures.

4.2.2. EE-3 Well Drilling. The drill rig was skidded from the EE-2 wellhead 46 m (150 ft) to the west without lowering the derrick. A 76.2-cm (30-in.)-diam conductor pipe and the cellar had previously been emplaced for spudding in well EE-3. A new drilling-fluid reserve pit and an extension of the drill pad had also been prepared prior to skidding the rig. Drilling began on May 21, 1980, in volcanic and sedimentary rocks with 62.4-cm (26-in.)-diam bits. This continued to a depth of 577 m (1894 ft) without serious lost circulation problems, but at this depth loss of drilling-fluid circulation was complete. Two attempts were made to cement off the lost circulation zone by pumping plugs, 500 sacks of thixotropic cement, into the hole. The hole was drilled through the cemented zone after the first cementing attempt to 541 m (1775 ft). Considerable sloughing of the hole walls and bridging of the hole above the lost-circulation zone was experienced, and it was necessary to set the 50.8-cm (20-in.)-diam surface casing at 481-m (1580-ft) depth to continue drilling.

Drilling was started again below the cement with a 44.5-cm (17-1/2-in.) bit, and circulation was lost again at 567 m (1860 ft). One attempt was made to cement up this lost-circulation zone with a massive amount of cement (2500 sacks). This was unsuccessful. It was decided to drill on into the granitic formations without return of the drilling fluid. Drilling without returns was quite expensive because the water supply at La Cueva, 7.5 km (4.5 miles) away, was exhausted, and most of the water for this operation was hauled from Los Alamos, a distance of 45 km (27 miles) over mountainous roads.

Granite was encountered at 732 m (2404 ft), and drilling continued in granite to 783 m (2567 ft). A 34-cm (13-3/8-in.)-o.d. casing was then run into the hole and cemented in two stages. After this cement was set, the casing was tensioned with casing jacks to a load of $373 \times 10^4 \text{ N}$ (750 000 lb_f), which was done to prevent the occurrence of excessive compression loads in the casing when it is heated by hot fluid production after completion of the EE-2/EE-3 reservoir system. A delay of 5 days was incurred while waiting for suitable casing jacks to arrive. At this point, drilling operations had been underway for 39 days.

The first 31.1-cm (12-1/4-in.)-diam drilling assembly used a milled-tooth bit to drill out the cementing hardware (cementing sleeve, float collar, plugs, and shoe) and the cement below the shoe. The first 31.1-cm (12-1/4-in.)-diam carbide insert button bit and bottom-hole assembly (BHA) were then run in the hole and rotated very slowly (40 rpm) with a low weight on bit, $1.3 \times 10^4 \text{ N}$ (30 000 lb_f), to avoid casing and cement damage. This precaution was continued until the top reamer of the BHA was below the 34.1-cm (13-3/8-in.)-o.d. casing shoe.

Rotary drilling of the 31.1-cm (12-1/2-in.)-diam hole continued using a variety of tungsten-carbide button bits to a depth of 1964 m (6444 ft). The drilling sequence was plagued by occasional washouts of the drill collars and two short fishing jobs. This portion of the hole was surveyed approximately every 20 m (60 ft) and at this depth, the hole had an inclination of 10° to the vertical and the azimuthal direction was trending toward the northwest. To drill in the proper direction relative to the trajectory of Hole EE-2 it was now necessary to turn the wellbore to the northeast. Drilling and related operations for this portion of the hole took 26 days, and the system design now required the first directional drilling.

4.2.2.1. Directional Drilling to the Borehole Diameter Transition. The initial borehole trajectory elements at a depth of 1920 m (6431 ft) were $10^\circ \text{ N}63^\circ \text{ W}$ (10° inclination and an azimuth heading of 63° west of north). The first two directional-drilling runs below the 1994-m (6444-ft) depth were attempted using magnetic single-shot orienting tools to orient the downhole motor. The intention was to rotate the azimuth of the hole and build angle only slightly. However, a sharp angle build was experienced. The next several days were spent changing the hole azimuth to $\text{N}62\text{-}1/2^\circ \text{ E}$ over a drilled

section to 2280 m (7482 ft) using positive-displacement motors and continuous-readout steering tools.

Rotary drilling started again at 2300 m (7542 ft) on day 91 of drilling operations. Another sharp inclination increase from 7° to $14\text{-}1/4^{\circ}$ occurred and the azimuth angle rotated rapidly to the north, from $N83^{\circ}E$ to $N46^{\circ}E$. Therefore, directional drilling was resumed with downhole motors.

A sequence of eight motor runs was performed and hole trajectory was corrected to a survey reading $17\text{-}1/4^{\circ}$ - $N88^{\circ}E$ at a depth of 2576 m (8453 ft). A series of nine rotary bit runs was then completed to a depth of 3002 m (9850 ft) and the trajectory elements were changed to $25\text{-}1/2^{\circ}$ - $N67^{\circ}E$. The rotary drilling sequence was continued to 3653 m (10 017 ft) and trajectory survey results of 24° $N67^{\circ}E$ on day 110 of drilling operations. Directional drilling was then started again with a positive-displacement motor, but after two attempts (days 125 and 131) it was evident that temperatures were too high for the elastomer components of the motors. Therefore, on day 138, directional drilling was initiated with 19.7-cm (7-3/4-in.)-diam Maurer Engineering, Inc. (MEI) turbodrills.

Fiscal year 1980 ended on day 131 of the EE-3 drilling operations.

The original reserve pit had filled with cuttings by this time and required mucking with a dragline and disposal of the solids at a nearby dump. Drilling operations continued using the smaller reserve pit adjacent to the drill rig.

A reaming-and-build assembly, run on day 143, appeared to be building inclination angle too rapidly, so bit weight was reduced, but apparently too rapidly, which caused the inclination to drop sharply. During subsequent turbodrill runs, this drop in angle was rebuilt. However on day 145, the Scientific Drilling Controls (EYE) steering tool jammed and was left in the BHA. When inspected on the rig floor, it was discovered that the mule-shoe latch-in on the steering tool was jammed 170° away from the key pin in the orienting sub. This condition was due to wear of the components. The consequences of this misorientation were that two downward dips were introduced into the EE-3 trajectory.

Extremely tight hole conditions were experienced upon reaming to bottom, and the first reaming assembly -- with a six-point near-bit reamer -- had to be changed out for a three-point near-bit assembly. When very high torques occurred, a survey at 3128 m (10 262 ft) indicated that the trajectory had the

elements $26-3/4^{\circ}$ N 68° E, confirming that the second drop in inclination had occurred.

Reaming with a more-limber building assembly was in progress at 3157-m (10 357-ft) depth on day 150 when a twist-off of the 12.7-cm (5-in.)-diam drill pipe occurred. Four days were spent grappling and loosening the fish before it was finally recovered.

The hole was then reamed to a depth of 3175 m (10 417 ft) where a survey yielded results of $24-3/4^{\circ}$ N 66° E and verified again a considerable drop in inclination. Directional drilling continued in an effort to obtain the desired inclination and a more easterly directional trend. Very tight hole conditions continued to plague the directional-drilling operations and on day 159, a second drill-pipe twist-off occurred at about 2350 m (7070 ft). The BHA had fallen to bottom and the break was very jagged.

The drilling of EE-3 was interrupted for 44 days by a difficult fishing operation that did not retrieve the BHA, and the hole had to be sidetracked. The sidetracking was finally achieved using a permanent, cemented-in whipstock.

It was planned to sidetrack the fish by underreaming (increasing the borehole diameter locally) and placing cement plugs. To evaluate possible locations for underreaming, a caliper log was run (Dresser Atlas) on day 204. A zone at 2975 to 2979 m (9760 to 9775 ft) was selected to underream. The Tri-State Oil Tool Company underreamer (a three-arm tool, with carbide-insert buttons on the cones and especially designed for granite) was used.

Five cement plugs were placed, all of which failed to harden enough to allow sidetracking. It was conjectured that a core sample of the cement might indicate the nature of the problem with the plugs. A core was therefore taken from 2911 to 2915 m (9550 to 9565 ft). The cement in this core was hard and appeared to represent a fairly good-quality plug. However, drilling of the remainder of the plug indicated soft cement; that is, rate of penetration was about 20 m/h (1 min/ft) with 22.5×10^3 N (5000 lb_f) bit weight, to a depth of 3078 m (10 000 ft).

In all, three more cement plugs were placed and several special placement procedures were followed. The hole was especially well cooled to about 120°C (250°F). Water samples were analyzed, the hole preflushed, cement formulations changed to include 40% silica flour to replace the flour and sand mixture, and finally, the sixth through eighth cement plugs were cored and their compressive strengths determined. Placement with a 7.1-cm (2-7/8-in.)

centralized string on bottom and no retarder was attempted on the sixth plug. This plug drilled relatively slowly, 8 m/h (2-1/2 min/ft) with $44.5 \times 10^2 \text{ N}$ (10 000 lb_f) bit weight. Therefore, it was decided to attempt a sidetracking operation.

The attitude of the bit was established at 26°N 72°E, which meant that the motor was oriented to drill out east of the high side of the hole. However, repeated drilling above the underreamed interval starting at 2975 m (9760 ft) to below the bottom ledge gave no positive sidetracking indications. It was decided to set a whipstock above the fish at about 2800 m (9400 ft). The initial attempt was made with a 0.30-m (12-in.)-diam stock. The whipstock hung up at about 2194-m (7200-ft) depth and subsequent reaming of the hole and trimming off some of the metal still did not allow this whipstock to be run in the hole. It was decided to attempt another underreaming sidetrack while a smaller diameter whipstock was fabricated.

A cement plug was placed at 3011 m (9880 ft) and faced off to 2878 m (9500 ft). A gamma log was then run and an altered zone at 2856 to 2881 m (9370 to 9354 ft) identified. It was suggested that underreaming at that depth interval would provide a softer rock for the sidetrack drilling. Two underreamer runs were required to produce an enlarged section from 2833 to 2844 m (9293 to 9330 ft). A two-independent-arm caliper log was run and showed that a symmetric enlargement had been achieved. Another cement plug was placed and allowed to harden for 48 h.

This plug was cored and showed a fairly high compressive strength. Two motor runs were made with 22.2-cm (8-3/4-in.)-diam carbide-button-insert bits and two with special diamond sidetracking bits. A three-cone carbide bit was then run in on a downhole motor followed by another bit run with a 21.2-cm (8-3/8-in.) diamond bit. Cuttings showed considerable granite, and it was judged to have sidetracked.

However, after further drilling, it was concluded that the sidewall grooving had not actually resulted in a sidetrack. The cement was drilled out to a depth of 2896 m (9500 ft) and a 27.3-cm (10-3/4-in.)-diam whipstock was prepared to be cemented in.

On day 283, after a temperature survey and appropriate cooling program, the whipstock was run in with the wedge angle set to drill off at about 40°E of the high side of the hole. It was successfully cemented and anchored in place. On day 302, a rotary assembly drilled down the length of the whipstock

without problems. Magnet runs cleared the metal from the hole and the following build assembly run clearly indicated granite cuttings. On day 305, the sidetracking operations were completed after consuming 101 days.

The next 30 days were concentrated on orienting the EE-3 borehole properly above EE-2, establishing an inclination of 35° , and obtaining a target trajectory vector for the EE-3 borehole that would be parallel to that of EE-2. Two sequences of azimuth correction were successfully completed with the 13.7-cm (5-3/8-in.)-diam turbodrills. A third correction attempt failed due to steering-tool problems.

The following 93 days were spent drilling the hole at an inclination of 35° . This time interval was extended considerably due to several problems. The most troublesome was another fishing operation of 45 days duration. Clean-out operations consumed 9 days and drilling resumed on August 1, 1981. A packed-hole assembly was run in the hole and drilled to a depth of 4113 m (13 494 ft), where the drill string twisted off due to failure of a thread in a pin. Fishing this time occupied only one day because the bit was on bottom drilling when the twist-off occurred. Four days of steady drilling continued until the bit torqued up and stopped drilling at 4247 m (13 933 ft). This was the last bit run and the total depth of the EE-3 well, day 443, August 7, 1981.

A final single-shot survey was made at 4225 m (13 861 ft) and gave a trajectory element of $36-1/2^\circ\text{N } 63^\circ\text{E}$. The borehole had started to drift back to the east slightly and the projected horizontal total-depth position (extrapolated to the location of the total depth of EE-3) relative to EE-2, approximately 370 m (1200 ft) below it, was estimated to be 55 m (180 ft) north.

4.2.2.2. Cleaning, Casing Running, and Cementing. The final 18 days of EE-3 drilling operations were spent running the 24.4-cm (9-5/8-in.)-o.d. production casing, first-stage cementing, tensioning the casing, and cementing the second stage. And finally, drilling out cement, running cement-bond and neutron-gamma logs over the cased interval, and performing a flush and cleaning operation for the open-hole reservoir section of the hole.

A temperature survey, performed by the Los Alamos instrumentation group, at 3353-m (11 000-ft) depth was recorded as 197.81° with a recovery rate of 0.6°C/h .

At 6:00 am on August 25, 1981, the drill pipe had been laid down, the flow line cut off, the conductor pipe removed from the wellhead, and Brinkerhoff-Signal drill rig was released.

The final configuration of EE-3 is summarized in Fig. 4-25. The drill operations for EE-3 had extended for 461 days, or 330 days of FY81. Drilling history is summarized in Fig. 4-26.

4.2.3. Surface System Design.

4.2.3.1. Phase I. After the completion of Run Segment 5, the Phase I System was overhauled to the extent that financial constraints permitted. Some deterioration of components was observed and hence corrections to the system were initiated. Basically, however, the Phase I System will be unchanged for future experiments.

4.2.3.2. Phase II. The Phase II System design was completed in FY80 and has not been altered during FY81. All design efforts have instead been directed at the "interim system" (see Fig. 4-27). The interim system will be able to handle ~20 MW(t), with a pumping system capable of delivering 19 m^3/s (300 gpm) at 21 MPa (3000 psi). An endless variety of flow rates and pressures below these maximum numbers is achievable. However, the funding situation during FY81 was such that it was deemed prudent to wait until EE-3 was completed before funds were committed to surface facilities. Hence, little money was spent during the year for Phase II surface system hardware.

4.2.4. Water System Development. The Fenton Hill water-well pump, capable of 2.7 m^3/s (43 gpm), was replaced with a 6 m^3/s (100 gpm) pump.

An aquifer test was then made to determine the yield from the aquifer and to predict the amount of depletion that would occur with increased production during the period 1981-1985. A step-discharge test indicated that the aquifer would comfortably yield 6 m^3/s (100 gpm) without excessive water-level drawdown in the well. Drawdown-test results indicated that the average aquifer transmissivity and storage coefficient are $5.8 \text{ m}^3/\text{day/m}$ (5000 gpd/ft) and 0.07, respectively. Using these parameters, a drawdown was estimated to be at least 13 m (42 ft) at the pumping well due to a withdrawal of $6 \times 10^5 \text{ m}^3$ (500 acre ft) of water over 5 yr. However, the presence of groundwater boundaries indicates that the aquifer is of limited extent, and because of this, the water level decline would probably be much greater. Past water-level data indicate that there is little recharge of the aquifer and that the groundwater is being depleted.⁴⁴

Fig. 4-26.
EE-3 Drilling History.

Fig. 4-27.

Surface Loop, Phase II Interim System.

Production from this water-supply well (FH-1) increased from $18.4 \times 10^6 \text{ gal}$ ($4.86 \times 10^6 \text{ gal}$) in calendar year 1979 to $27.3 \times 10^6 \text{ gal}$ ($7.21 \times 10^6 \text{ gal}$) in 1980. Total production from the well since 1976 has been $76.5 \times 10^6 \text{ gal}$ ($20.2 \times 10^6 \text{ gal}$), with a decline in water level of about 2 m (6.5 ft). Monthly production during 1980 ranged from $0.07 \times 10^6 \text{ gal}$ ($0.02 \times 10^6 \text{ gal}$) in November to $5.8 \times 10^6 \text{ gal}$ ($1.5 \times 10^6 \text{ gal}$) in March. During the 10-day aquifer test in October, $4.9 \times 10^6 \text{ gal}$ ($1.3 \times 10^6 \text{ gal}$) were pumped. Analysis of water from the well shows that it is well within the limits for municipal or domestic use set by the U.S. Environmental Protection Agency and the State of New Mexico. It is, in fact, the domestic water supply for the Fenton Hill Site.

Late in the fiscal year the contract to construct a $19\,000 \text{ m}^3$ (5-million-gal) storage pond was issued. Construction began at the end of FY81 and completion is scheduled for early December 1981. In addition to the pond, the contract includes a pumping system consisting of:

- a 63 l/s (1000 gpm) electrically driven pump;
- a 6.3 l/s (100 gpm) gasoline-driven emergency pump; and
- associated piping to permit filling the pond from Water Well II and to connect the pond and the Phase II pumping area.

A formal request was issued to the DOE (Los Alamos Area Office) to secure a permit from the State Engineer's Office for $6 \times 10^5 \text{ m}^3$ (500 acre ft) over a 5-yr period.

4.3. Site Support Activities

4.3.1. Operations. The construction of the new Fenton Hill operations building was completed early in FY81. The machine-shop and welding facilities are located in this building along with office space and a conference room. The Fenton Hill warehouse, completed during FY80, was stocked with needed materials for site operations. A modular structure for the new data-collection facility became available for occupancy, in which all instrumentation except that required to operate the loop will be located. The installation of this instrumentation was approximately 50% complete at the end of FY81. The tower for EE-2, and its foundation, were completed.

4.3.2. Environmental Surveillance. Environmental monitoring of the HDR site at Fenton Hill has been continuous since 1976. In the past these efforts were directed primarily at establishing baseline information. Results from these studies appear in previous Annual Reports of the HDR Program.^{1,45-47}

Hydrologic, biotic, meteorologic, and seismic monitoring of the environment at Fenton Hill and in the Jemez Mountains surrounding it was continued during FY81. The only environmental effect of the Fenton Hill Operation that has been detected is an accumulation of minor amounts of trace elements in the stream channel immediately below the point at which excess water has occasionally been discharged from holding ponds on the site. This is discussed below under "Discharge Monitoring."

4.3.2.1. 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.⁴⁸⁻⁵⁶ Table 4-III summarizes the chemical quality of water for nine surface water stations, four water supply locations, two springs along the Jemez fault, one spring discharging from recent volcanics, and one abandoned well (Fig. 4-28). Water quality has varied slightly; however, the variations in quality are normal and are due to seasonal fluctuations.

4.3.2.2 Discharge Monitoring. Storage ponds at the Fenton Hill site contain water used in drilling operations and water circulated through fractures in the dry hot rock about 2900 m (9500 ft) below land surface. The

TABLE 4-III
CHEMICAL QUALITY OF WATER IN VICINITY OF FENTON HILL
(average of a number of analyses)

	<u>Surface Water</u>	<u>Water Supply</u>	<u>Springs (Jemez Fault)</u>	<u>Spring (Volcanics)</u>	<u>Abandoned Well</u>	<u>Fenton Hill (Pond Fluids)</u>
No. of stations and analyses ^a	9	4	2	1	1	4
Chemical (mg/l)						
SiO ₂	30 ± 6	71 ± 19	40 ± 8	48	65	90 ± 41
Ca	17 ± 11	19 ± 23	120 ± 61	14	26	31 ± 9
Mg	2 ± 1	4 ± 2	15 ± 14	2	8	4 ± 3
Na	13 ± 18	15 ± 5	518 ± 1022	11	112	465 ± 297
CO ₃	0 ± 0	0 ± 0	0 ± 0	0	0	0 ± 0
HCO ₃	42 ± 52	78 ± 46	807 ± 1168	54	326	622 ± 381
SO ₄	42 ± 186	<3 ± 9	34 ± 18	<1	22	112 ± 200
Cl	11 ± 22	5 ± 9	832 ± 1732	3	4	114 ± 51
F	0.4 ± 0.2	0.4 ± 0.3	2.8 ± 1.8	1.0	0.8	1.7 ± 0.6
NO ₃	<0.1 ± 0.1	1.5 ± 1.2	<0.1 ± 0.0	1.0	<1	<0.1 ± 0.0
TDS	159 ± 89	200 ± 73	2390 ± 4129	138	488	1873 ± 1036
Hard	52 ± 31	61 ± 67	363 ± 208	43	95	94 ± 27
pH	6.9 ± 2.2	7.3 ± 0.5	6.6 ± 0.7	6.5	6.9	7.4 ± 1.0
Conductance (mS/m)	18.5 ± 13.3	17.0 ± 10.9	369.0 ± 653.0	13.0	56.0	186.7 ± 93.5

^aSampling locations key on Fig. 4-28 as follows:

Surface waters - Locations F, J, N, Q, R, S, T, U, V.

Water supply - Locations JS 2-3, JS 4-5, FH 1, 4.

Springs (Jemez Fault) - Locations JF-1, JF-5.

Spring (volcanic) - Location 31.

Abandoned well - Location 27.

Fenton Hill (pond fluids) - Drilling fluids and circulation fluids from tests.

Fig. 4-28.

Water sampling locations in vicinity of Fenton Hill Geothermal Site.

water in the ponds is sometimes highly mineralized (e.g., 1870 mg/l of total dissolved solids). Certain elements present in the ponds are of particular interest because of monitoring requirements specified in the National Pollutant Discharge Elimination System (NPDES) permit. These are arsenic, boron, cadmium, fluorine, and lithium.

Discharges from the ponds into the canyon below the Fenton Hill Site began about 1974, and there were two such discharges during 1980, totalling 3000 m³ (8 x 10⁵ gal). Samples of vegetation and soil from the canyon bottom and bank of the channel have been collected semiannually since 1978. These samples are analyzed for the five elements listed above. Sample locations are about 100, 200, 400, and 1000 m down the small canyon leading into Lake Fork Canyon, plus an additional sample at the lower end of the small canyon -- at its junction with Lake Fork Canyon, and far beyond the section reached by the holding-pond discharges. These sample collections are designed to give some indication of whether there is any accumulation of the elements of interest with time and with progression down the canyon. Results obtained are shown in

Table 4-IV. Although these data are scanty, there is some indication in the lithium and boron data that there may be elevated concentrations in vegetation in the stream channel in the upper part of the canyon. This is consistent with the preliminary conclusion, using chloride as a tracer, that the discharge from the holding ponds sinks into the canyon alluvium within 400 m (440 yd) of the discharge point.

During FY81, additional soil samples collected in the stream channel below the site were studied. (This is the channel that receives liquid discharges from the holding ponds on site.) These new samples were taken to a

TABLE 4-IV
METAL ION ANALYSES OF VEGETATION AND SOILS IN POND RELEASE AREA AT FENTON HILL
(all values in ppm)

Sample Type	Channel											
	100 m			200 m			400 m			1000 m		
	Vegetation	Roots	Soil	Vegetation	Roots	Soil	Vegetation	Roots	Soil	Vegetation	Roots	Soil
Fall 78	---	---	---	---	---	---	---	---	---	---	---	2.4
As	---	---	0.9	---	---	---	---	---	---	---	---	---
B	---	---	---	---	---	---	---	---	---	---	---	0.0005
Cd	---	---	1.5 ^a	---	---	1.1 ^a	---	---	0.7 ^a	---	---	0.1 ^a
F	---	---	---	---	---	---	---	---	---	---	---	---
Fall 78	0.22	---	---	0	---	---	0.12	---	---	0.34	---	---
As	0	---	---	0	---	---	0	---	---	0	---	---
Cd	3.5	---	---	9.1	---	---	12.9	---	---	1.93	---	---
Li	---	---	---	---	---	---	---	---	---	---	---	---
Spring 79	0.7	---	---	0.7	---	---	0.7	---	---	0.7	---	---
As	150	---	---	286	---	---	350	---	---	26	---	---
B	0.17	---	---	0.15	---	---	0.15	---	---	0.16	---	---
Cd	46	---	---	109	---	---	239	---	---	2.6	---	---
Li	---	---	---	---	---	---	---	---	---	---	---	---
Fall 79	---	13	---	---	21	---	---	28	---	---	20	---
B	---	---	---	---	---	---	---	---	---	---	---	---
Spring 80	236	56	22	245	64	44	237	34	25	21	9	18
B	---	---	380	---	---	290	---	---	160	---	---	110
F	---	---	---	---	---	---	---	---	---	---	---	---
Fall 80	173	---	31	182	---	42	113	---	36	18	---	18
B	---	---	420	---	---	140	---	---	180	---	---	105
F	---	---	---	---	---	---	---	---	---	---	---	---
Sample Type	Bank											
	100 m			200 m			400 m			1000 m		
	Vegetation	Roots	Soil	Vegetation	Roots	Soil	Vegetation	Roots	Soil	Vegetation	Roots	Soil
Fall 78	0.13	---	---	0.14	---	---	0.06	---	---	0	---	---
As	0	---	---	0	---	---	0	---	---	0	---	---
Cd	1.93	---	---	1.93	---	---	0.69	---	---	1.00	---	---
Li	---	---	---	---	---	---	---	---	---	---	---	---
Spring 79	0.7	---	---	0.7	---	---	0.7	---	---	0.7	---	---
As	0	---	---	0	---	---	0	---	---	0	---	---
B	0.27	---	---	0.19	---	---	0.14	---	---	0.27	---	---
Cd	0.8	---	---	0.8	---	---	3.3	---	---	0.8	---	---
Li	---	---	---	---	---	---	---	---	---	---	---	---
Fall 79	---	14	---	---	0	---	---	9	---	---	8	---
B	---	---	---	---	---	---	---	---	---	---	---	---
Spring 80	21	9	16	14	0	19	13	13	15	11	0	25
B	---	---	100	---	---	110	---	---	100	---	---	200
F	---	---	---	---	---	---	---	---	---	---	---	---
Fall 80	32	---	---	30	---	13	9	---	19	9	---	23
B	---	---	---	---	---	80	---	---	95	---	---	160
F	---	---	---	---	---	---	---	---	---	---	---	---

^aExtractable

depth of 30.5 cm. Each sample was cut into three, 5-cm (2-in.) sections and analyzed for arsenic, cadmium, and lithium. These elements were found to occur in elevated concentrations at sampling stations along the receiving channel beginning at the fence below the lower pond.

The decreasing concentration with increasing distance was expected. However, from the graphs in Fig. 4-29 the decline in concentrations at 250 m is followed by an upswing at the 500-m station. As this trend is consistent for all three elements, it would seem that the effect is real although unexplainable at this time.

At the end of 1980 soil samples were again taken in the stream channel and on the adjacent bank at the same stations. Each soil sample was taken to a depth of 90 cm in 15-cm sections. Samples have been submitted for neutron-activation analysis for 30 elements. Results from these analyses will be correlated with the routine sampling effort described above.

4.3.2.3. Microclimatologic Monitoring. A tower-based meteorological observation and cassette-recording system provide data for the Fenton Hill site. In addition to wind speed, wind direction, and temperature at two levels (4 m and 20 m), precipitation, humidity, and pressure are recorded hourly on magnetic-tape cassettes. Then monthly weather summaries are distributed to HDR personnel. The meteorological sensors on the tower were operational approximately 80% of the time during FY81 except for the relative-humidity sensor that was operational only 50% of the time.

4.4. Laboratory and Analytical Support.

4.4.1. Theoretical Modeling Efforts/Incorporation of Permeations and Fracture Interaction Effects in HDR Reservoir Models. The present conception of the HDR fluid reservoir at Fenton Hill is one of a highly fractured rock matrix with very complicated flow paths. In addition the flow rate in these paths is highly pressure dependent as evidenced by high-back-pressure experiments. This made it desirable to develop a finite-element code that could solve for the flow and temperature distributions in the fractures and for permeation into the adjacent rock, and then use this information in calculating the stress distribution in the reservoir. In contrast to the GEO⁵⁷ and REX⁵⁸ codes developed in previous years, the fluid flow in the fractures in the present code, FEHM (Finite Element Heat and Mass), is modeled in a simpler but still realistic way. In previous codes the full set of equations governing fluid behavior was solved. In the present FEHM code, a

Fig. 4-29.
Element concentrations along stream channel.

nonlinear flow law is incorporated that includes many of the features of the complete governing equations. The code is characterized by strong numerical stability and is capable of modeling multiphase flows. The code will handle fully three-dimensional problems, although in many problems the geometry is considerably simpler. For the numerical details of the code and the presentation of example problems, see Ref. 59.

4.4.2. Rock Mechanics. Activities centered on material-properties measurements. Work has focused on two topics: (1) studies of rock samples recovered from the bottom portion of EE-2, which supports other efforts to model and understand the Phase II reservoir, and (2) studies of the mechanical properties of some cements, which supports various drilling and completion activities in EE-3.

The studies of rocks from EE-2 include measurements of Young's modulus, Poisson's ratio, bulk modulus, and thermal expansion at temperatures to about 250°C (490°F), confining pressures of about 34.5 MPa (5000 psi), and pore-fluid pressures of about 33 MPa (4800 psi). These conditions are near the

horizontal stress and temperature conditions deep in EE-2. On the samples tested so far, bulk moduli have ranged from 30 to 50 GPa (4.35×10^6 to 7.25×10^6 psi), Young's moduli range from 7 to 15 GPa (10^6 to 2.2×10^6 psi), and linear-thermal-expansion coefficients range from 7.5 to $14 \times 10^{-6}/^\circ\text{C}$. This variation in properties among the different rocks that will occur in the reservoir is significant. It may, for example, lead to enhanced thermal-stress cracking at some of the interfaces between different rocks. Testing of additional EE-2 samples is continuing.

Characterization by mechanical-properties testing of cements used in EE-3 was begun when difficulties were experienced in sidetracking the hole. Cements used for sidetracking plugs as well as those used to set casing have been tested for compressive strength, Young's modulus, tensile strength, and, in some cases, conjunction with certain chemical and mineralogical characteristics (discussed below). Casing cement used in EE-3 shows very good properties. It has compressive strength in excess of 27 MPa (3900 psi), tensile strength of 8.8 MPa (1270 psi) or more, and Young's modulus of at least 6.6 GPa (960×10^3 psi).

By the standard compressive-strength criterion, properly formulated cements used for sidetracking plugs were good cements. Many had strengths of 41 MPa (6000 psi) and more. The difficulties experienced in trying to sidetrack off these plugs into the granite show the need to investigate nonstandard cements for future sidetracking needs.

4.4.3. Reservoir Geochemistry Studies. A major portion of the 1981 fiscal year was dedicated to the completion of Run Segment 5.³⁰ The remaining part of the year was spent updating procedures and instrumentation for future Phase II experiments.

Samples of the geothermal fluid for Run Segment 5 were collected at regular intervals from the GT-2B wellhead, the EE-1 wellhead, and at the makeup pump, which provided the water from reserve pits to replace the down-hole water loss. Samples of both noncondensable gases and radon were collected at less-frequent intervals. Fluid samples were analyzed for pH, Eh (oxidation-reduction potential), conductivity, SiO_2 , Na^+ , K^+ , Li^+ , Ca^{++} , Mg^{++} , Sr^{++} , Mn^{++} , Fe^{+2} and $+3$, B, $\text{SO}_4^{=}$, Cl^- , HCO_3^- , F^- and total suspended solids (TSS).

4.4.3.1. Variation in Concentrations With Time. Typical results of the fluid and gas analyses from the GT-2B wellhead are presented in

TABLE 4-V

SELECTED ANALYSES OF PRODUCED AND MAKEUP FLUID FROM RUN SEGMENT 5
(Analyses are reported in ppm unless otherwise noted.)

Sample No.	Date	Time	pH	Eh mv	Ca	Mg	Na	K	Cl	SO ₄	HCO ₃	SiO ₂	Fe	Li	Mn	F	B	Conductivity μ mho/cm
<u>Produced Fluid</u>																		
G-2	3/10/80	15:00	6.57	284	83	3.0	1490	110	1750	341	538	267	nd	nd	nd	8.7	42.3	7500
G-3	3/11/80	00:30	5.95	336	61	2.3	1110	90	1220	290	513	245	5.55	17.0	0.17	10.6	33.1	5600
G-4	3/11/80	07:00	6.05	333	42	1.6	855	75	921	248	493	232	5.83	14.0	0.15	15.3	25.0	4500
G-8	3/14/80	10:00	6.33	305	26	0.8	750	53	583	227	400	214	1.00	9.5	0.09	16.5	14.5	3100
G-15	3/21/80	10:30	7.33	249	28	0.6	554	48	528	260	471	214	0.64	8.8	0.09	11.2	13.5	2900
G-22	3/28/80	10:30	6.78	290	24	0.5	485	46	422	241	455	209	0.38	7.8	0.07	14.1	12.0	2500
G-29	4/04/80	10:30	7.31	253	24	0.5	470	47	387	222	483	211	0.42	7.6	0.07	14.4	10.9	2400
G-36	4/11/80	14:00	6.15	56	27	0.6	490	48	381	245	477	226	0.44	7.9	0.08	15.8	11.4	2500
G-50	4/25/80	10:00	6.13	34	24	0.5	485	47	412	258	454	227	0.30	7.8	0.07	14.6	11.2	2500
G-63	5/09/80	06:00	6.27	288	25	0.5	475	48	420	256	448	233	0.30	7.8	0.07	13.3	11.2	2500
G-76	5/30/80	10:30	6.14	61	28	0.6	535	48	485	286	450	233	0.39	8.6	0.06	17.0	13.4	2900
G-94	6/20/80	10:00	6.28	17	25	0.6	490	46	380	229	490	228	0.23	7.8	0.06	13.0	11.8	2400
G-104	7/11/80	10:00	6.37	-15	21	0.5	402	39	314	190	471	211	0.20	6.8	0.04	12.6	9.8	2300
G-114	7/25/80	11:10	6.37	4	19	0.5	398	39	351	205	467	225	0.21	7.1	0.04	13.0	10.9	2300
G-175	10/31/80	10:45	6/26	66	19	0.5	360	35	305	180	346	204	0.38	6.0	0.04	17.2	8.7	2000
G-183	11/21/80	11:45	6.26	-39	20	0.5	405	38	302	208	434	199	0.36	6.3	0.04	20.3	0.2	2000
<u>Makeup Fluid</u>																		
M4	3/11/80	07:00	7.67	271	23	3.0	13	3	9	8	79	62	0.22	0.0	0.02	0.7	0.0	205
M36	4/11/80	13:15	7.65	132	38	4.4	13	5	15	8	166	69	0.04	0.0	0.00	0.0	0.0	290
M63	5/09/80	05:45	7.87	265	37	3.7	12	6	15	7	166	72	0.03	0.0	0.00	0.1	0.0	280
M94	6/20/80	09:15	7:44	201	6	2.7	5	1	0	4	50	35	0.10	0.0	0.01	0.1	0.0	76
M114	7/25/80	09:55	7.38	124	7	3.2	4	1	2	2	53	43	0.04	0.0	0.01	0.1	0.0	90
M175	10/31/80	11:20	6.72	220	17	2.0	125	8	130	82	259	108	2.88	2.32	0.11	8.0	3.4	1030
M183	11/21/80	11:00	6.79	43	14	1.7	300	27	228	134	388	144	5.73	4.34	0.16	14.0	6.7	1650

Table 4-V and Table 4-VI. Some of these results are plotted vs time in Figs. 4-30 through 4-36. As was observed in the closed-loop portion of the Run Segment 4 test,³² steady-state levels of species concentrations were established rapidly. During Run Segment 5, however, a gradual decline in dissolved-species concentration started at about day 100.

There are several very sharp perturbations on the graphs in Fig. 4-30 through 4-34 at days 102-110 and 230-234. These periods show the chemical response of the reservoir to a step change in inlet-fluid composition caused by switching the operational mode from closed-loop to fully open-loop. This type of perturbation experiment is termed "fresh-water flush."

The predominant noncondensable gas results shown in Fig. 4-35 indicate that CO₂ is highly enriched while O₂ is depleted relative to N₂, as in Run Segment 4. However, the much higher CO₂ fraction in Run Segment 5 (~78%)

TABLE 4-VI
ANALYSES OF NONCONDENSIBLE GAS AND RADON SAMPLES

Sample No.	Date	Time	CO ₂ (%)	O ₂ (%)	N ₂ (%)	H ₂ (%)	H ₂ S (ppm)	Rn (nCi/L)
G4	3/11/80	10:00	80.9	15.7	2.6	0.8	145	4.7
G8	3/14/80	10:30	71.4	2.3	25.9	0.4	350	3.6
G15	3/21/80	11:30	78.0	0.7	20.8	0.1	265	7.2
G22	3/20/80	13:00	77.2	0.9	21.9	-- ^a	360	nd ^b
G29	4/4/80	14:30	78.4	0.7	20.9	--	660	9.5
G35	4/10/80	10:30	73.5	1.5	24.8	0.2	660	9.6
G50	4/25/80	13:15	74.4	1.3	24.2	0.1	350	8.0
G62	5/8/80	20:00	75.6	1.2	21.3	1.9	nd	8.8
G76	5/30/80	11:30	78.6	0.8	20.6	--	850	9.3
G93	6/19/80	11:30	78.4	0.8	20.8	--	820	9.8
G104	7/11/80	04:00	73.1	1.7	25.2	--	725	10.1
G114	7/25/80	12:55	76.0	0.3	23.7	--	1050	10.2
G187	12/4/80	11:00	nd	nd	nd	nd	nd	8.4
G187	12/4/80	11:00	nd	nd	nd	nd	nd	9.2

^a-- indicates below detection limit.

^bnd indicates not determined.

Fig. 4-30.
Variation of silica concentration
with time.

Fig. 4-31.
Variation of sodium concentration
with time.

Fig. 4-32.
Variation of potassium concentration
with time.

Fig. 4-33.
Variation of chloride concentration
with time.

Fig. 4-34.
Variation of boron concentration with time.

Fig. 4-36
Variation of radon activity with time.

Fig. 4-35.
Variation of noncondensable gas fraction with time.

compared to Run Segment 4 (55%) was due to dilution effects in the latter. Radon analyses (Fig. 4-36) showed a gradual increase to a steady-state value of 9 to 10% nCi/l. Minor concentrations of H_2 and H_2S were also observed.

4.4.3.2. Geochemical Behavior of the Reservoir. Arguments based on the constant ratios among soluble ions for the previous (Run Segment 4) test were used to infer the presence of an indigenous fluid within the connected pores and microfractures in the granodiorite reservoir rock. This pore fluid has been in intimate contact with the reservoir rock for a very long time, hence the ratios among cations such as Na^+ , K^+ , and Ca^{++} are fixed by equilibrium with reservoir minerals even though the absolute concentrations of these species far exceed the solubilities of the reservoir minerals. This pore fluid is slowly displaced by fresh water and, under conditions of long-term recirculation, the pore fluid should eventually be replaced by fresh water.

The degree to which the ratios among the dissolved species Na^+ , K^+ , Cl^- and B are constant is shown in Fig. 4-37 where the nondimensional concentrations for these species are plotted vs time. The nondimensional concentration, $\langle C \rangle$, is defined as

$$\langle C \rangle = \frac{C_{\infty} - C(t)}{C_{\infty} - C_m}$$

where C_{∞} is the pore-fluid concentration, C_m is the makeup concentration and $C(t)$ is the produced-fluid concentration of a given species at time t . As was observed for these species in Run Segment 4, the ratios are constant over long periods of time, and the pore-fluid concentrations, C_{∞} , used in this normalization are very close to those used in Run Segment 4.³²

The flow rate at which the pore fluid enters the circulating system can be calculated by considering the increase in concentration of the circulating fluid as it passes through the downhole system. The reservoir can be treated as consisting of two parallel flow paths: Path 1 is the fracture-dominated flow path that includes all of the heat-extraction surfaces discussed thus far, while Path 2 is a very low flow-rate path consisting of the connected microfractures and pores in the rock surrounding the heat-extraction portion of the reservoir. Path 1 has a short residence time; the mean residence time is approximately 12 h. Therefore, on the scale of tens of days, the fluid originally in this flow path is completely replaced with the injected fluid that has a characteristic composition of C_{EE-1} ($C_{injected}$). Path 2, on the

other hand, has a very long mean residence time so that the fluid displaced from this path is, for long times, pore fluid that has a composition denoted by C_{∞} . This model is shown in Fig. 4-38. If we presume that the concentration of the pore fluid is constant, a mixing relationship between the fluids entering the GT-2 wellbore from Path 1 and from Path 2 is

$$C_{EE-1}(\dot{q}_1) + C_{\infty}(\dot{q}_2) = C_{GT-2} ,$$

where $\dot{q}_1$ and $\dot{q}_2$ are the flow fractions in Path 1 and Path 2. Because $\dot{q}_1 + \dot{q}_2 = 1$, we can easily solve for $\dot{q}_2$. A plot of $\dot{q}_2$ vs time calculated in this manner from chloride, boron, and sodium data is shown in Fig. 4-39. The points shown are the mean values and the bars show the maximum and minimum values. For most of the points, the range is small and, except for the initial transient, the mean value for $\dot{q}_2$ is ~ 2 to 5% of the flow rate at the GT-2B wellhead.

Because this analysis presumes that the pore-fluid concentration is constant, the small variation in $\dot{q}_2$ in the last 240 days of the experiment indicates that no breakthrough of fresh water occurred in the secondary flow path. The slight decline observed in chloride, sodium, potassium, boron, and other-species concentrations after day 100 of the experiment correlates with a decline in the injected-fluid concentrations as a result of increased dilution of the produced fluid with makeup water prior to reinjection. If the residence time of the secondary flow path is greater than 280 days at ~ 5 gpm, the total volume of this path is in excess of 6800 m^3 (1.8×10^6 gal). If the volume of the secondary flow path is contained in microfractures, it is apparent that a very large fracture system is connected hydraulically to the main flow path through a large impedance.

4.4.3.3. Geothermometry. The quartz geothermometer⁶⁰ and the Na-K-Ca geothermometer⁶¹ temperatures were calculated for the fluid produced during Run Segment 5 and compared to measured downhole temperatures. There was a measureable decline in downhole temperatures in Run Segment 5, which was observed in the quartz geothermometer but was not seen in the Na-K-Ca geothermometer. Also the Na-K-Ca system was affected significantly less during open-loop operation than the quartz geothermometer. This insensitivity of the Na-K-Ca geothermometer was due to the constant Na/K ratio in the secondary flow-path pore fluid, which was fixed by equilibrium with feldspars at the initial rock temperature (~ 195 to 198°C). Dilution of this pore fluid with fresh water of very low Na and K concentrations did not significantly affect

Fig. 4-37.
Comparison of nondimensional concentrations for several reservoir species.

Fig. 4-38.
The two-path reservoir used for modeling the chemical behavior of the reservoir

Fig. 4-39.
Calculated pore flow from two-path model.

the Na/K ratio in the produced fluid. The Na-K-Ca geothermometer reflected initial rock temperature rather than changes in reservoir temperature.

The quartz geothermometer had a fast response to temperature changes and was influenced by both temperature changes in the main flow path and changes in inlet fluid composition. The constant differences observed between measured downhole temperatures and those predicted by the quartz geothermometer were largely due to the slight influx of pore fluid saturated with quartz at higher temperature zones.

4.4.3.4. Fresh-Water Flush. To resolve questions about how the quartz geothermometer applies to the Phase I reservoir, an experiment was designed to perturb the steady-state chemical interactions within the system. This experiment called for the sudden change from recirculating or closed-loop operation to open-loop operation where the injected fluid was either 100% fresh water or 50% fresh water. The intent was to determine the flux of silica into solution as a result of quartz dissolution in the main flow path.

Two fresh-water-flush experiments were performed during the course of Run Segment 5 operations. For the first experiment, approximately 950 m³ (250 000 gal) of fresh water were injected into the system while the fluid produced at GT-2 was vented. The concentrations of dissolved species such as silica and chloride in the produced fluid declined in response to the fresh-water injection (Figs. 4-30 through 4-35). After 2 days of closed-loop operation, the second experiment was started. In this, 50% of the injected flow was fresh makeup water and the other 50% was produced (GT-2) fluid. This mixture gave an injected-fluid composition intermediate to those of the normal closed-loop operation and the open-loop fresh-water-flush operation. Here, the concentrations of silica and chloride declined; however, the decline was slightly less steep than was observed in the first experiment (Figs. 4-30 through 4-35). After the second experiment was completed, the silica and chloride concentrations in the produced fluid recovered to their pre-fresh-water-flush values.

For the second experiment, 475 m³ (125 000 gals) of fresh water were injected after which the system was returned to closed-loop operation.

Two methods of analyzing the response of the reservoirs to the fresh-water-flush experiments were considered. The first involved solving a mass-balance equation for a series of control volumes at different temperatures along the fracture surface. This method was difficult because knowledge of

quartz-dissolution kinetics was needed. The second method predicted the amount of quartz dissolved in the main fracture path and could be used to determine the maximum temperature in the fracture without requiring quartz-dissolution kinetics.

The second approach was developed by considering the changes in output concentration during a fresh-water flush in a system of two parallel flow paths, as shown in Fig. 4-38. By controlling the concentration of a dissolved species in the main reservoir loop during a fresh-water-flush experiment, the influence of pore fluid from the secondary loop could be determined through mathematical calculations involving residence times determined from tracer studies.

Initial calculations using this method were done using chloride ion because of its solubility, and results from the chloride calculations were extended to the more complex silica situation. Once the silica contribution from the secondary loop was determined, the silica dissolution in the primary loop could be determined by chemical analysis of the output fluid.

Data obtained in these experiments indicated that future fresh-water-flush experiments can be used to adjust the silica geothermometer to within a few degrees Celsius of temperatures actually measured downhole. Much of the uncertainty could be eliminated by continuing such an experiment to the steady-state condition before returning to closed-loop operation. In addition, knowledge of the temperature dependence of quartz-dissolution kinetics and of the rate of removal of silica by mechanisms such as precipitation of secondary silica phases, would increase the level of detail observable by this type of experimentation.

4.4.3.5. Dissolved Gases. Throughout much of Run Segment 5, the HCO_3^- levels were 10 to 20% above the steady-state HCO_3^- levels observed in Run Segment 4. The higher CO_2 fraction in the gas phase observed in Run Segment 5 when compared to Run Segment 4 was probably due to the higher HCO_3^- concentrations in aqueous solution.

The depletion of oxygen relative to nitrogen is an indication that oxidation is occurring within the reservoir. Two likely mechanisms are (1) the oxidation of the steel casing and (2) the oxidation of pyrite (FeS_2) in the rock to produce hematite or magnetite and sulfate ions in solution. The high sulfate concentration in the fluid (Table 4-V) could be explained by the second mechanism, while the presence of free hydrogen could result from the

hydrolysis of water by either of these mechanisms. Equilibria among sulfur and iron species in geothermal systems often depend on iron-bearing alteration phases in the reservoir rock, such as epidote and chlorite,^{62,63} for which thermodynamic data are sparse or unavailable. However, the presence of these species in the core samples⁶⁴ suggests that the requisite alteration phases could be participating in reactions. Within the scatter of the gas analyses, gas concentrations appear to be constant with time (Fig. 4-35).

4.4.3.6. Radon Analyses. Radon (^{222}Rn) is the radioactive daughter of radium (^{226}Ra) decay by alpha emission. The emanation of radon from rock depends very strongly on the surface area of rock exposed to the fluid.⁶⁵ Radon analyses were performed during Run Segment 5 to look for changes in fracture permeability⁶⁶ and changes in rock surface area attributed to thermal-stress cracking.⁶⁷

Results of radon analyses performed during Run Segment 5 are shown in Fig. 4-36. Although there is wide variation in the data, several observations can be made: first, the initial radon concentration was low and increased with time; second, the radon reached steady-state levels of around 9-10 nCi/l; and finally, during the fresh-water flush episodes the radon concentrations decreased. Analysis of the radon data makes it apparent that new heat-transfer surface created in the fractured portion of the reservoir will not be observed from radon data obtained during closed-loop operation.

4.4.3.7. Comparison with Previous Experiments. Run Segment 5 was basically a continuation of the low-back-pressure portion of Run Segment 4. The results of these two tests are understandably quite similar. As was concluded in Run Segment 4 (and also in Run Segment 2) pore-fluid displacement was the single most important process involving the fluid chemistry and, as has been briefly described in this section, the pore-fluid contribution to the fluid chemistry determines the temperature predicted by the Na-K-Ca geothermometer and interferes with the temperature prediction in the fracture flow paths based on the silica geothermometer. These points were not clear from Run Segment 4 data; however, they are as valid for Run Segment 4 as for Run Segment 5. Another interesting feature of the Run Segment 5 results is the suggestion developed in Fig. 4-39 that the pore fluid was displaced at a constant rate and composition throughout most of the test. The volume of displaced pore fluid is in excess of 6800 m^3 (1.8×10^6 gals). A calculation

Using a microfracture porosity of 0.01 shows that the volume of rock affected by fluid flow and pressurization is $680\,000\text{ m}^3$.

The completion of a fresh-water-flush experiment during this test is an important step toward using geochemical data in determining the temperature distribution within a fracture. Significant development remains to be done in modeling and interpreting this experiment; however, it is hoped that a fresh-water-flush type of experiment may be useful in predicting Phase II reservoir temperatures before measurable thermal drawdown occurs.

Preliminary analysis of the radon data suggests that interpretation of changes in fracture area by radon-transient analysis could be misleading in the same way that interpretation of the quartz and the Na-K-Ca geothermometers could be misleading. Apparently only the heat extraction is confined to the fracture system; the results of the fluid chemistry analyses indicate that the affected rock volume is significantly larger.

4.4.4. Fluid Flow and Tracer Studies.

4.4.4.1. Fluid Flow in Rough-Walled Hydraulic Fractures.

Efficient operation of hot dry rock geothermal reservoirs requires a better understanding of fluid mechanics in fractures than now exists. Typically the apertures (i.e., the smallest dimensions) of hydraulic fractures are only of the order of 1 mm (0.04 in.) so that reasonable energy production rates require fairly large flow velocities within the fracture, which often result in non-Darcian flow. The problem is compounded by the fact that in a "self-propped" fracture, the roughness asperities, which prop the fracture faces open, must be as large as, or nearly as large as, the fracture aperture itself. The Phase I reservoir was operated in the self-propped mode during Run Segments 2, 4, and 5. In a self-propped fracture the roughness ratio (ratio of roughness asperity to flow-channel diversion) approaches 1.0, whereas in conventional flow situations the ratio hardly ever exceeds 0.01, even in very rough pipes. To investigate the effects of such large roughness ratios, the laboratory apparatus pictured in Fig. 4-40 was designed, fabricated, and operated.

In this study air was used as the working fluid whereas, in the in situ case, water is used. The results are nevertheless valid because of the principles of hydrodynamic similitude. Air was drawn in at the top of the apparatus from the room between two parallel, sawtooth-roughened plates, through the transition shown near the bottom of Fig. 4-40, which smoothly

guides the flow from the vertically mounted test section to the horizontal circular tube shown in the lower right-hand corner. Although not shown in the photo, this circular tube ducts the air flow to a laminar-element flow meter, control valves, and eventually to a reversed blower where air is exhausted back to the room. One of the test section plates is aluminum and the other is Plexiglas. The aluminum plate has pressure taps so that pressure gradients can be measured in the flow direction. The plates are both 684.8 mm in the vertical or streamwise direction and 152.4 mm in the horizontal, or span, direction (27 in. x 6 in.). Both plates are corrugated in a sawtooth manner, idealizing the condition of a rough surface found in a hot dry rock geothermal reservoir. The corrugations are symmetrical right-angle triangular prisms with a 6.35-mm base (0.250 in.), a 3.17-mm height (0.125 in.), and a length that stretches the entire span (width) of the flow.

Fig. 4-40.
Experimental flow apparatus.

In addition to the plate spacing, the other variable that can be changed in the apparatus is the phase angle. The phase angle can be changed by displacing one of the plates relative to the other as shown in Fig. 4-41. Thus, data for peak-to-peak runs ($\phi = 0^\circ$), peak-to-valley runs ($\phi = 180^\circ$) and other phase angles can be obtained. In this study the following phase angles were used: 0° , 60° , 120° , 180° , and 360° . The $\phi = 360^\circ$ geometry is the same as $\phi = 0^\circ$, and provides a convenient check on the experimental measurements. The most extensive experimentation was done when the corrugations were out of phase, $\phi = 180^\circ$.

Following the usual treatment of flow in both smooth and rough ducts, we summarize our flow measurements in terms of friction factors, Reynolds numbers, and relative roughness. The friction factor f_1 is defined as the wall shear stress, c , (derived from the pressure gradient) divided by the dynamic pressure $PV_d^2/2$ where P and V_d are density and mean velocity. The Reynolds number Re is defined in terms of the equivalent hydraulic diameter D_{eq} , which is defined as four times the flow-passage area divided by the wetted perimeter. For fractures, D_{eq} is nearly two times the fracture aperture. Finally, the relative roughness ratio is the projection of the roughness into the flow shear, R , divided by D_{eq} .

When the phase angle is 180° (see Fig. 4-41) and the plate spacing is greatly reduced, the relative roughness can easily exceed 1.0. In cases such as this the flow channel resembles a sequential chain of disjointed, but individually smooth, miniducts. Each miniduct is turned 90° from its preceding and following ducts.

Some typical function-factor results are presented in Fig. 4-42. Here the phase angle is 180° , so that the peaks and valley of the opposing roughness corrugations are aligned. Note that unlike typical pipe flows, in which f_1 is of the order of 10^{-2} , for a rough fracture f_1 is typically 1 to 10. Additional results are summarized in Table 4-VII and are discussed as follows: (1) that region of each curve where the friction factor depends upon the inverse of the Reynolds number, indicating a linear, or Darcy, flow regime in which pressure loss is linearly related to either velocity or flow rate; (2) that area where f_d is approximately constant, the fully rough regime, in which pressure loss scales with the square of either velocity or flow rate; and (3) the transition Reynolds number at which the change from linear to nonlinear flow occurs.

As the relative roughness becomes larger, one would expect, in the fully rough regime, that the friction factor should increase. Table 4-VIII indicates that this is the case as the relative roughness increases from 0.26 to 0.43. Thereafter f_d actually decreases, indicating that the flow is beginning to act more as flow in a series of disjointed but individually smooth miniducts, as previously described. Values of the transition Reynolds number show a similar effect. At low $k/D_{eq,d}$ laminar flow is sustained to larger values of Re_d , in the range 250 to 700; at intermediate $k/D_{eq,d}$ the flow is more disturbed and transition occurs at Re_d as low as 30; but at very

Fig. 4-41.
Phase angles.

Fig. 4-42.
Friction factor results for cases where peaks and valley aligned, $\phi = 180^\circ$.

high k/D_{eq} the microscopic viewpoint applies and transition is deferred to higher Re_d again. Final corroboration is seen in the laminar slopes. At the highest relative roughness, $k/D_{eq,d} = 1.26$, the flow is actually so smooth, corresponding to the microscopic view of flow through a series of miniducts, that $f_d = 50/Re_d$, quite close to the relation expected for perfectly continuously smooth ducts: $f_d = 48/Re_d$. At intermediate $k/D_{eq,d}$ the constant of proportionality increases from 50 to as high as 140, and at lower relative roughnesses, the proportionality constant decreases again.

4.4.4.2. Br^{82} Tracer Studies. The study of the movement and dispersion of radioactive tracers through the EE-1/GT-2B fracture system continued to be of great value in detecting and measuring changes in the reservoir occurring in Run Segment 5. The method, described in detail in earlier reports,^{44-46,67-69} consists simply of injecting a small sample of NH_4Br solution containing a few hundred millicuries of the Br^{82} isotope. This isotope, with a conveniently short half-life (~ 35 h) and strong gamma-ray strength (≥ 1 Mev) provides an almost perfect tracer for following the movement of fluid, both in the wellbore and behind the casing, with the use of gamma-radiation logging tools. The results from a sequence of five different Br^{82} tracer surveys run during Run Segment 5 provide information about flow

distribution and the residence-time distributions of both individual fractures and the entire fracture system.

Details of the surveys are given in Table 4-VIII. The increase in source strength after the first survey greatly improved the resolution obtainable in the dispersion studies, while still staying well below designated safe radiation levels in the returning fluid.

A sequence of these logging scans follows the movement of the location of the maximum value of the pulse as it moves down through the casing and into the open-hole section of EE-1. Movement of the tracer into several fractures is detected by changes in the pulse velocity. Figure 4-43 shows the reduction in activity with time in the open-hole section along with later growth in

TABLE 4-VII
SUMMARY OF RUNS AT $\phi = 180^\circ$

Relative Roughness $k/D_{eq,d}$	Spacing, $2t_d$ (mm/in.)	Approximate Transition Re_d	Fully Rough f_d	Laminar Slope
0.26	6.35/0.250	250-700	0.4	$89/Re_d$
0.32	5.08/0.200	300-600	1.5	$140/Re_d$
0.43	3.81/0.150	30-60	4.0	$65/Re_d$
0.51	3.18/0.125	30-100	2.6	$65/Re_d$
0.64	2.54/0.100	75	1.5	$65/Re_d$
1.26	1.27/0.050	250	0.5	$50/Re_d$

TABLE 4-VIII
DETAILS OF TRACER SURVEYS INDICATING SOURCE STRENGTH AND GAMMA-RAY TOOLS

Survey Number	Date	Source Strength (mCi)	Use of Gamma-Ray Tools	
			EE-1	GT-2B
1	5/8/80	40	Yes	Yes
2	9/4/80	400	Yes	Yes
3	9/24/80	400	Yes	No
4	12/2/80	550	No	Yes
(Pre-SUE)				
5	12/12/80	400	Yes	Yes
(Post-SUE)				

activity at several locations higher in the casing. Each of these locations shows a growth of activity followed by subsequent decay. This behavior is interpreted as movement of the tracer through numerous individual fractures crossing the EE-1 wellbore. These observations again indicate the unique value of this wellbore as an observation well, providing information complementary to that obtained from temperature-recovery logs.

The fracture intersections with EE-1 that accept fluid can be located by measurement of the velocity changes obtained from sequential logging runs through the downward-moving tracer pulse, as shown in Fig. 4-44. This technique provides very sensitive detection of flows, some too small to be measured with the spinner tool, and will be used in the Phase II System.

The tracer moving through the complex system finally starts to appear in the GT-2B wellbore. A sequence of logging scans in GT-2B follows the arrival and subsequent growth of activity in the flows from the several fractures mapped in the temperature/spinner surveys. Figure 4-45 shows such a sequence, with changes in activity caused both by the amount of flow and the level of activity. The activity reaches a maximum and then slowly dies away. The arrival of the tracer in the GT-2B wellbore is complex in that the tracer activity results from the mixing of individual streams of fluid, each with a different activity history. However, using the relative values of flow

Fig. 4-43.
Variation of activity with time in the EE-1 borehole.

Fig. 4-44.
Movement of tracer in EE-1 on 9/27/80.

obtained from spinner surveys, the activity is measured at the several fracture locations, and applying the principle of mass conservation, the level of activity of each individual flow with time can be determined.

Radioactive tracer analysis has become a valuable tool in the determination of fracture geometry and aided in the formulation of the multiple-fracture heat-transfer model described in Sec. 4.1.1.4.

4.4.5. Cementing Technique Studies. The successful completion of geothermal wells depends on successful cementing operations. Casings and liners must be cemented in, plugs must be set for isolation of sections of the wellbore for various purposes including fracturing and sealing of lost circulation zones, and cement may be needed for sidetracking.

Cements must have certain properties if they are to be useful. For example, casing cements must have sufficient strength to hold the casing in place. They should be resistant to attack by well fluids over the life of the well; they should be resistant to thermal shock, and of course, they must be capable of being placed in the annulus between the casing and the wellbore. On the other hand sidetracking cements must be strong and hard and must bond well with the wellbore. Each cement must have properties appropriate for its special use.

Fig. 4-45.

Variation of activity with depth in GT-2 from logging through the tracer pulse.

At the present time Portland and closely related cements are the only ones in common use. There are several reasons for this: the chemistry and physics of placement, setting, curing, and aging are fairly well known especially for low-temperature use; the technology of formulating, mixing, and placing of Portland cements is well developed, at least for oil-field work; and Portland cement is relatively inexpensive and readily available. However, the properties of Portland cements are often marginal and new cements should be investigated.

During the past year a laboratory capable of investigating cements has been established. Several problems have been attacked.

A program for the development of new geothermal cements was organized by Brookhaven National Laboratory and carried out by six independent laboratories in the U.S. (DOE Contract TID-4500). These laboratories produced a number of cements. The microstructure and microchemistry of these cements was studied and attempts were made to correlate microstructure and microchemistry with the properties of the cements. This program is continuing but at a reduced level of effort.

In December of 1980, sidetracking operations were started in EE-3. Five formulations of cement were placed, but none of them proved adequate for sidetracking. At this point an investigation of the reasons for failure was begun. Cuttings from the plugs were studied microscopically and by x-ray-diffraction techniques. The fifth plug was also cored, its properties

measured and its structure and chemistry investigated. It was shown that insufficient SiO_2 resulted in the formation of weak and friable phases in the cement. The next plug had the correct composition and it was shown by coring that the properties were as good as could be expected from the formulation placed.

The physical properties of the well-formulated and set cements proved inadequate for sidetracking and finally a whipstock was set and used to sidetrack EE-3.

As a result of these experiences an autoclave was set up to test cement formulations before placement in a well. This autoclave was set up so that the temperature profiles encountered by cements in the wellbore could be duplicated in the laboratory. The autoclave can also subject the cements to pressures up to 5000 psi.

Using the autoclave all cement formulations placed in EE-3 were tested before placement. The effects of impurities and different temperature profiles were investigated before the cements were put into the wells.

The Laboratory now possesses facilities for fairly comprehensive studies of cements to be used in geothermal wells.

a) For microstructural and microchemical studies there are light and electron microscopes.

b) For phase compositions x-ray diffraction facilities are available.

c) For chemistry there is an x-ray fluorescence unit.

d) There are facilities for measuring the physical and mechanical properties of the cement samples.

e) For exposure of cement samples to geothermal well conditions there are several facilities; the autoclave mentioned above, several smaller autoclaves useful for long-term exposure of samples to well conditions, a test facility capable of taking large specimens and subjecting them to high temperatures and pressures, and finally samples can be placed in the geothermal wells at Fenton Hill.

4.5. Instrument Development and Support

4.5.1. Downhole Instrumentation for Drilling Support. Four new wireline tools were designed and fabricated for use during the drilling of EE-3. Each tool was required for a specific application, including remedial work in the wellbore when drilling problems occurred. Accumulated experience

and expertise in the development of high-temperature borehole instrumentation packages, including high-temperature explosive devices for use in the hot dry rock geothermal boreholes, made possible the immediate design and fabrication of these new tools.

A shaped-charge high-explosive device was designed to rubblize a bell-shaped cavity in the granitic formation at a specific location to sidetrack the EE-3 wellbore. This tool was fabricated for use as a backup should the whipstock method fail in sidetracking the borehole. The entire system is rated for operation at borehole temperatures above 260°C (500°F) with a downhole residence time in excess of 10 h. The downhole firing unit uses a capacitive discharge system (charged from the surface after insertion) to fire the high-temperature detonators. A dual-firing unit is used for redundancy. The firing unit is housed in a Laboratory-designed Dewar flask of the type incorporated in many of our high-temperature instrument packages to protect sensitive electronics (see Fig. 4-46).

A drill-pipe cutoff tool was designed to sever the drill-pipe string just above the bottom-hole assembly that was stuck in the EE-3 wellbore at a depth of 3048 m (10 000 ft). This instrument also uses a high-temperature high-explosive shaped charge, a high-temperature detonator, and a Dewared firing unit. The detonators and firing units were developed for the HDR Program by the Reynolds Corporation. The shaped charge is designed to cut the drill pipe leaving a clean circumferential edge (Fig. 4-47).

Extensive use of Torque-Trim as a drilling lubricant in the inclined portions of the EE-2 and EE-3 boreholes resulted in a layer of "gunk" caked to the walls. Samples of the materials at various depths in the wellbores -- corresponding to various temperatures along the temperature gradient -- were required for chemical analysis and testing to find a satisfactory detergent for cleaning the boreholes. A sidewall sampler (Fig. 4-48) was fabricated to run on a wireline. The tool was quite simple in concept and proved to be very effective in retrieving the desired samples.

A downhole tool for introducing fluid tracers, such as chemicals, radioactive solutions, or fluorescent dyes, at predetermined depths in boreholes with high-temperature gradients, is shown in Fig. 4-49. The temperature-activated fluid injector releases the fluid by matching depth-vs-temperature-log data to the melting temperature of a fusible alloy plug. (Over 75 alloys are commercially available with melting ranges from 38°C [100°F] to 250°C

1. NOSE PIECE AND SINKER BAR	14. COMPRESSION SPRING TO MAINTAIN FORCED CONTACT BETWEEN DETONATOR AND HE (High Explosive)
2. CUSHION	15. CONNECTOR, FIRING CIRCUIT TO WIRELINE CABLE HEAD
3. HE BILLET 3.970" DIAM. x 4.250" lg. (14 each)	16. CORK PLUG IN OPEN END OF DEWAR
4. HOUSING FOR HE AND FIRING CIRCUIT SYSTEM	17. FIRING CIRCUIT NO. 1
5. HE BILLET 2.970" DIAM. x 2.125" lg. (17 each)	18. FIRING CIRCUIT NO. 2
6. HE BILLET 2.470" DIAM. x 2.125" lg. (9 each)	19. VACUUM DEWAR FOR THERMAL PROTECTION OF FIRING CIRCUIT SUPPORT
7. SPACE RING	20. FIRING CIRCUIT SUPPORT CUPS
8. O-RING PRESSURE SEAL	21. SUPPORT SPACER FOR CLOSED END OF DEWAR
9. HE BILLET 3.970" Diam. x 4.250" lg. (1 each)	22. SUB TO WIRELINE CABLE HEAD
10. DETONATOR NO. 1	23. CONNECTOR TO CABLE HEAD
11. DETONATOR NO. 2	
12. DETONATOR SUPPORT CUP	
13. GROUND STRAP	

Fig. 4-46.

High-explosive package-rubblizing explosive, 5.0 in. o.d. x 250.0 in. long, pressure limit 10 000 psi, temperature limit 500°F.

[483°F].) The fluid chamber is connected to the temperature probe that monitors the downhole temperature. The alloy disk melts at the proper borehole temperature (therefore at the predetermined depth) and the tool is retracted. Ports in the temperature housing provide a flushing action to inject the fluid into the wellbore. The volume of fluid injected is variable depending on the size of the fluid chamber.

Fig. 4-47.

Explosive cut-off tool, 2.5 in. o.d. x 95 in. long, pressure limit 10 000 psi, temperature limit 600°F.

4.5.2. High-Temperature Instrumentation Cable. Four high-temperature coaxial cables have been tested at the Laboratory's Cable Test Facility to evaluate their physical and electrical characteristics in water over the temperature range 20°C to 350°C and pressure range 0 to 17.24 MPa (2500 psi). The cables were supplied by four manufacturers to meet Laboratory specifications, which, briefly, called for a coaxial core similar to RG-58 that would be used in an armored instrumentation cable that would function at 275°C. The cables will be referred to in this report as Cable A, B, C, or D, and a description of each cable is given in Table 4-IX.

The Cable Test Facility comprises a 25-ft long, horizontal autoclave with the necessary heaters, sensors, valves, and plumbing to allow the temperature and pressure to be controlled remotely from an adjacent control room. The autoclave is electrically heated, and the internal pressure is

Fig. 4-48.
Sampler side wall scraper, 5.0 in. o.d. x 7 ft 8 in. long.

Fig. 4-49.
Temperature activated fluid injector, 110 in. long, 5.5-in.-diam chamber, 1130 in.³ maximum fluid volume. Fusing temperature is varied by fusible alloy selection.

TABLE 4-IX
DESCRIPTION OF COAXIAL CABLE CONSTRUCTION

<u>Cable</u>	<u>Description</u>	<u>Thickness</u>
A	Conductor -- 19/0.008 in. Ni Plated Cu	0.99 mm (0.039 in.)
	Dielectric -- 0.040 in. TFE Sintered	3.02 mm (0.119 in.)
	Braid Shield -- Ni Plated Cu	3.58 mm (0.141 in.)
	Jacket -- 0.20 in. TFE	4.59 mm (0.181 in.)
B	Conductor -- 19/0.008 in. Ni Plated Cu	1.02 mm (0.400 in.)
	Dielectric -- TFE Sintered Tape Wrap	2.89 mm (0.114 in.)
	Braid Shield -- #36 Ni Plated Cu	3.45 mm (0.136 in.)
	Jacket -- TFE Tape with Teflon Finish Glass Braid	5.08 mm (0.200 in.)
C	Conductor -- Ni Plated Cu over Teflon Filament	1.45 mm (0.057 in.)
	Dielectric -- TFE Tape	
	Braid Shield -- Ni Plated Cu Flat Braid	3.81 mm (0.150 in.)
	Jacket -- TFE Tape/Polymide Tape	4.32 mm (0.170 in.)
D	Conductor -- 19/0.008 in. Ni Plated Cu	0.99 mm (0.039 in.)
	Dielectric -- 0.040 in. TFE Sintered	3.02 mm (0.119 in.)
	Braid Shield -- Ni Plated Cu	3.58 mm (0.141 in.)
	Jacket -- 0.015 in. Polyetheretherketone (PEEK)	4.34 mm (0.171 in.)

adjusted with bleed valves and a high-pressure pump to allow fluid (water) temperatures up to 350°C and pressures to 26.8 MPa (3000 psi) to be achieved. The cable conductors and shields are brought out of the pressure vessel at either end through high-pressure feedthrough connectors allowing some electrical measurements to be made on the cables during the test. The cable test parameters as recorded were DC resistance from the center conductor to the shield, resistance of the center conductor, Hi-Pot resistance from the center conductor to the shield, and the cable capacitance.

Measurements were made on each cable sample at ambient temperature and pressure, both in air and in water. Measurements were also made at ambient temperature and pressure after the autoclave test.

Results of the autoclave tests are summarized in Table 4-X for Cables A, B, and C. Each measurement was made one hour after reaching the given temperature and pressure plateau. The DC resistance from the center conductor to the shield at ambient temperature and pressure is recorded within the range of the ohmmeter. The Hi-Pot resistance of center conductor to shield has a much greater measurement range.

TABLE 4-X

AUTOCLAVE TEST RESULTS

Test Conditions			D.C. Resistance			Center Conductor to Shield			Capacitance		
Temp °C	Pressure MPa	(Psig)	Ohm meter mΩ			Hi Pot mV/volts			nf		
			A	B	C	A	B	C	A	B	C
20	0	0 Dry	>20	>20	>20	$25 \times 10^3/500$	$25 \times 10^3/500$	$25 \times 10^3/500$	4.0	3.6	4.1
20	0	0 Water	>20	>20	>20	$15 \times 10^3/500$	$15 \times 10^3/500$	$4 \times 10^3/500$	3.9	3.6	4.1
20	1.72	(250)	11	>20	short	6/500	$3 \times 10^3/500$	short/50	3.7	3.7	---
100	6.89	(1000)	11	5	short	1/500	0.2/500	short/50	3.6	2.1	---
200	6.89	(1000)	5	3	short	0.9/500	0.4/100	short/50	3.5	2.2	---
300	10.34	(1500)	7	5	short	9/100	short/50	short/50	3.5	1.5	---
325	13.79	(2000)	2	0.8	short	0.5/100	short/50	short/50	3.7	2.1	---
350	17.93	(2600)	0.7	0.8	short	0.2/100	short/50	short/50	3.1	2.7	---

Cable D was similar in construction to Cable A except for the jacket material polyetheretherketone (PEEK) used on Cable D for the electrical insulation. A separate series of tests was performed on this cable to determine the effectiveness of the PEEK jacket as a fluid-intrusion barrier as well as an electrical insulator. The cable was cycled through several excursions in the autoclave from ambient temperature and pressure in steps of 300°C and 13.8 MPa (2000 psi), 325°C and 13.8 MPa (2000 psi), and 340°C and 17.2 MPa (2500 psi) where the cable failed. Similar cyclic tests were performed on Cable A for comparison.

Cable A proved to give the best overall performance, maintaining usable electrical properties up to 350°C. The early failure of Cable C was attributed to the unsintered TFE tape wrap that allowed water to penetrate the insulation under low pressure conditions. The failure of Cable D at 340°C was caused by the melting and shrinkage of the PEEK material used for the outer jacket (see Fig. 4-50). Further tests are required on Cable D to determine the maximum temperature for which the PEEK jacket will not degrade.

4.5.3. Multiplex Systems for Downhole Data Transmission. The Phase II Energy Extraction System now planned for the Fenton Hill Test Site will encounter bottom-hole wellbore temperatures in excess of 300°C and pressures exceeding 69 MPa (10 000 psi). It is imperative that the geophysical parameters be monitored and the dimensions and orientation of the Phase II fracture reservoir be measured in order to optimize the fluid-flow and heat-transfer properties. The most severe limitations to the use of measuring

equipment in the geothermal well are associated with the high-temperature and high-fluid-pressure effects on the downhole instrumentation cable. To ensure the development of a usable armored instrumentation cable for the near-term use in the Phase II system, the Laboratory initiated the cable test program (described above). The result of the cable tests and subsequent studies have led to the conclusion that the most practical cable for logging in this environment would be an armored coaxial cable with TFE Teflon used for the electrical insulating material. This type of cable has the best mechanical and electrical performance properties for this environment available today.

The use of a coaxial cable demands a multiplexed instrumentation system for transmission of downhole data to the surface recording station.

Many system constraints and parameters had to be considered in the design of this system. Downhole power requirements, component size, shock,

Fig. 4-50.
Cable sections before and after test.

and heat dissipation were major factors. Our downhole measurements have a wide variance in data bandwidth, accuracy, and signal-conditioning requirements. System constraints on the quality of data transmission had to be considered. Different multiplexing techniques were compared. Universally accepted standards and availability of components are very important. Careful consideration also had to be given to the large investment we currently have in data-acquisition equipment and associated software.

After considerable research, it was decided to design this downhole multiplex system around standards and components that are readily available for airborne or space-telemetry applications. This approach provides equipment and component manufacturers that are governed by IRIG Standard 106-77. This assures us of compatibility between manufacturers, compatibility between downhole components and surface recording equipment, and compatibility with future expansion and design changes. It also provides us with a suite of manufacturers that produce micro-miniature components for space applications. These components are generally small in size, low in power consumption, operate from a universal, unipolar, 28-V power supply, and can withstand severe shock.

FM is the most common analog technique used in telemetry. When data bandwidth and time correlation between channels is important, a constant-bandwidth FM system is optimum.

PCM is a digital multiplex technique that will be used for data that has a lower bandwidth but requires measurement accuracy better than 1% of full scale. Accuracy in a PCM system is much improved over FM for slow-response analog signals. PCM also has an advantage over FM when a noisy transmission link results in a low signal-to-noise ratio. A PCM system can also handle a much larger channel capacity and, because of its digital form, it lends itself well to digital data processing.

Another factor in the choice of using these two techniques is that they can be integrated to form a hybrid system. PCM can be multiplexed together with FM to form a very versatile multiplexed telemetry system.

It is important to tailor the multiplexing technique to hardware that best fits a particular measurement application, whether it be FM, PCM, or both. This allows us to optimize the amount of hardware for multiplexing and signal conditioning. A downhole tool can be designed for maximum power efficiency, maximum signal transmission, minimum power dissipation, and minimum

size. One disadvantage to this approach, however, is economics. A larger amount of downhole hardware will be required to cover a variety of applications. Downhole components include micro-miniature PCM encoders, high-level and low-level subcarrier oscillators, and airborne-type charge amplifiers for accelerometers. Associated surface equipment includes FM discriminators, PCM decommutators, and associated hardware for computer interfacing.

The low-level subcarrier oscillators are intended to be used for acoustical measurements, i.e., geophones and accelerometers. The unit has a built-in amplifier for signal gain. This will eliminate the need for additional amplifiers now needed in the acoustical packages and also simplify power-supply requirements. To date, all ordered components for downhole use operate on a unipolar, 28-V power supply.

Using a prototype FM multiplex system it has been possible to multiplex geophones and accelerometers through both a long coaxial cable and through the seven-conductor, logging cable. The seven-conductor cable presents more problems than the coax due to impedance characteristics, but its use is possible.

The design to power the downhole electronics and run motors on the same conductor that carries the multiplexed signal has been accomplished. At this time, it is hoped that all downhole batteries can be eliminated. This can be done with the use of passive high- and low-pass filters. The motor is controlled by an SCR and appropriate gate firing circuits.

The system design provides not only a downhole multiplex system, but a complete telemetry system, the transmission link being a logging cable. Even with the seven-conductor cable now on site, a much higher frequency can be recorded from geophones and accelerometers. The rolloff in the cable is no longer a major factor in the recording of the data. The frequency rolloff only affects the magnitude of the carrier frequency, not the data; and the logging cable is the transmission link, not part of the measurement. Downhole logging tools such as the proposed six-arm caliper tool now become realistically possible.

The system as designed is compatible with our existing computer-controlled data acquisition system. However, other possibilities exist. The multiplexed data could be recorded in its raw form on a reel-to-reel tape recorder for playback into a computer system at a later date. Another possibility is the transmission of this multiplexed data with a VHF/UHF

transmitter to another site; for example, Fenton Hill to TA-33 or from the logging truck at a remote site. This could result in great savings in the future in the cost of data-reduction and data-processing equipment required in the field.

A block diagram of the FM multiplex system for use with the downhole acoustic detectors is shown in Fig. 4-51. The results of a system test in which the triaxial geophone outputs were multiplexed and the composite signal transmitted over 4572 m (15 000 ft) of armored coaxial cable are shown in Fig. 4-52. The composite FM signal is discriminated and fed into the Biomation Digitizer where the data is transferred to floppy disc for storage and on-line plotting. Figure 4-53 shows the output of data taken from the triaxial accelerometer system under the same conditions. The higher frequency response of the accelerometers is evident in the output plots.

4.5.4. Industrial Support

4.5.4.1. Instrument Sonde Test Facility (ISTF). In addition to component and instrument-sonde testing for HDR equipment, the ISTF has been

Fig. 4-51.

FM multiplex system for use with the downhole geophone acoustic detectors.

Fig. 4-52.

Results of FM multiplex system test in which triaxial geophone detector outputs were multiplexed over 15 000 ft of armored coaxial cable.

Fig. 4-53.

Results of FM multiplex system test in which triaxial accelerometer detectors outputs were multiplexed over 15 000 ft of armored coaxial cable.

used to test a number of commercial seals, instrument pressure housings, packers, and cements. Two stainless-steel instrument chambers, each 2.74 m (9 ft) long by 101.6 mm (4 in.) in diameter, were tested in a saturated steam environment at a temperature of 285°C and a pressure of 6.89 MPa (1000 psi). The instrument chambers were tested as part of a cooperative industrial (Union Oil Company)/Laboratory program for use in a geothermal-well-stimulation experiment. The chambers leaked during the first test due to O-ring failure. Both pressure chambers were modified and retested. The test temperature was set at 275°C and the external fluid pressure was set at 6.89 MPa (1000 psi). The test was continued for 20 h followed by a cooldown to below boiling while maintaining pressure on the system to avoid loss of any water that might have leaked into the chambers. No leakage was found at the conclusion of the test.

Several Bakerline float-valve seals made from EPDM Compound No. 130-42 were tested in the ISTF for 30 h in water at 280°C temperature and 10.34 MPa (1500 psi) fluid pressure. No serious deterioration of these float seals was observed. A set of Viton float seals was also tested under the same conditions. When the autoclave was opened only a few fragments of the Viton float seals were left and they were extremely hard and brittle.

Three wiper plugs were tested for 1 h in the ISTF with the autoclave temperature set at 275°C and the fluid pressure set at 41.4 MPa (6000 psi). The wiper plugs were made of a Teflon-based proprietary material supplied by

Dowell Company. The three plugs were 114.3 mm (4-1/2 in.) diam. The top plug disintegrated into particle sizes of less than 12.7 mm (1/2 in.). The other two plugs showed a 10% increase in durometer readings and had numerous cracks in the elastomeric material around the central metal core. All materials were returned to Dowell for evaluation.

A downhole detonator-firing instrument system was tested for Union Geothermal. The instrument package included an electronic firing system, a timer, and several detonators. The entire system survived the 1-h exposure to the simulated geothermal environment and the test detonators fired properly during the timing sequence.

4.5.4.2. Baca Site Acoustic Test. On Sunday, March 22, 1981, the Union Geothermal Company performed a well-stimulation experiment in a recently drilled well (Baca No. 23). A cooperative industrial-DOE experiment using the Laboratory's downhole-geophone acoustic detector was performed. Republic Geothermal Company, Union Geothermal Company, and the Laboratory participated in a joint effort to map the hydraulic fractures using microseismic technology similar to that developed for the Phase I SUE previously conducted at Fenton Hill. Figure 4-54 shows the field equipment at the Baca Site.

The geophone sonde was positioned at a depth of 304.8 m (1000 ft) in the Union Well Baca No. 10 about 400 m (1300 ft) southwest of Well No. 23. A number of microseismic events were recorded that were caused by the hydraulic fracturing experiment. These events had emergent S-waves and a very slow P-wave coda decay, quite similar to the SUE events recorded in GT-2 at Fenton Hill. It was difficult to obtain orientation of the locked-in geophone from the internal inclinometers, due to the near-vertical borehole. The event locations projected to a plane running 26° east of north. The preliminary data analysis is described in Ref. 70.

The successful results of this test encouraged the planning of a future massive hydraulic fracture experiment at the Baca site.

4.5.4.3. ORE-IDA No. 1 Flow Test. A cooperative industrial/DOE well-stimulation experiment was conducted in ORE-IDA No. 1 exploratory geothermal borehole. The borehole was drilled to a total depth of 3064 m (10 054 ft) into the hot basalts underlying the ORE-IDA Foods, Inc. facility at Ontario, Oregon. It was intended to produce hot water for food processing and to heat the processing plant, but the well was found to produce no

Fig. 4-54.
Logging truck and other field equipment at the Baca Site.

significant amount of geothermal fluid. However, the temperature at 3000 m (9840 ft) was about 190°C and there were some indications of permeability at several horizons. Accordingly, the DOE Idaho Operations Office and ORE-IDA Foods, Inc., with assistance from EG&G and Los Alamos National Laboratory, undertook a well-stimulation experiment there in May 1981. The well had been cased to 2493 m (8180 ft) and the bottom 570 m (1870 ft), below the casing, had been completed with a slotted liner hung from 2402 m (8142 ft) to 3060 m (10 038 ft). It was intended, by pressurizing the well, to attempt to open natural fractures in the basalt section behind the slotted liner.

The first pumping test indicated that no pressure significantly above hydrostatic could be developed in the well, and it was then discovered that the casing had been perforated above 2347 m (7700 ft). Los Alamos temperature and spinner (flow-velocity) logs demonstrated that most of the injected water left the well through the uppermost set of perforations, at 1825 m (5985 ft).

Attempts to plug the perforations with "perf balls" were unsuccessful, and the well-completion hardware could not be removed or packers set without bringing in a large workover rig, which available funding did not permit.

Further, the lower part of the well was found to be filled with a viscous substance presumably representing lignosulfate drilling mud that had drained back into the well from natural fractures in the basalt. This probably prevented any of the injected water from entering those fractures. Equilibrium bottom-hole temperature was determined to be 189.5°C.

The Los Alamos temperature and spinner surveys demonstrated that most of the injected flow left the wellbore through the uppermost set of casing perforations between 1823 m (5980 ft) and 1829 m (6000 ft). A time-averaged temperature of 150.2°C was measured at 2134 m (7000 ft) and indicated no downward flow past this depth. Figure 4-55 shows the Laboratory's logging truck and other service equipment at the ORE-IDA wellhead.

Reference 71 describes the operations and results of this experiment.

Fig. 4-55.
Los Alamos National Laboratory's logging truck and other
service equipment at ORE-IDA wellhead.

4.5.4.4. Shallow-Hole Geophone Station. A triaxial geophone sonde was designed for permanent installation in a shallow hole, i.e., 670 m (2200 ft), for continuous monitoring of near-surface seismic signals at the Fenton Hill site. This package houses the geophones and associated line-driver electronics and is lowered into place with an armored seven-conductor wireline (Fig. 4-56). The output signals are multiplexed at the surface and transmitted via radio telemetry to the central recording station at Fenton Hill. The surface equipment is battery powered and incorporates a solar-panel charging system.

This system package has recently been used at the Nevada Test Site in another DOE program. The results of preliminary tests have led to an expansion of the program to incorporate a number of the geophone devices to be cemented in the bottoms of 914-m (3000-ft) boreholes. The geophone system,

Fig. 4-56.

Slimline geophone tool, 5.5 in. o.d. x 16 ft 3.38 in. long, pressure limit 10 000 psi, temperature limit 85°C.

although not a high-temperature system, is a direct spinoff from the HDR equipment-development program.

5.0. INSTITUTIONAL ISSUES ANALYSIS

5.1. Environmental Studies

During FY81, environmental studies were confined to continuing surveillance of the Fenton Hill geothermal site and its surroundings in the Jemez Mountains of northern New Mexico. As has been discussed in Sec. 4.3.2., the only environmental effect of the Fenton Hill operation that has been detected is the accumulation of minor amounts of trace elements in the stream channel immediately down grade from the lowest water-storage pond. This occurs within a few hundred meters of the point at which fluids from drilling operations and circulation experiments have occasionally been discharged. No detectable contamination of surface or groundwaters has resulted.

5.2. Legal and Regulatory Studies

Due to funding limitations, there was no significant activity in this area during FY81.

5.3. Public Relations

The Third Annual Hot Dry Rock Information Conference was held in Santa Fe, New Mexico, on October 28-29, 1980. It provided an overview of the progress, problems, results, and current situation of the HDR Program. After 1 1/2 days of technical sessions, the last half-day was devoted to a technical tour of the Fenton Hill HDR experimental site. Approximately 250 attendees participated in the Conference, representing energy and industrial companies, investment interests, research and development organizations, service companies, government agencies, and the energy interests of several foreign countries. The agenda of the Conference appears in Appendix B.

Formal papers on various aspects of the HDR Program were presented at a number of national conferences during FY81, including the National Rural Electric Cooperative Association meeting in October 1980; the Houston Energy Technology Conference and Exposition in January 1981; the Rocky Mountain Groundwater Conference in May 1981; and the Electric Power Research Institute's Conference on Geothermal Energy in June 1981.

As has been true for several years, there have been many visitors to the HDR Program during FY81, both at the Laboratory and at Fenton Hill, and from a

number of foreign countries as well as the United States. These have included representatives of energy companies, service companies, electric-power producers, direct-heat users, research and development organizations, universities, domestic and foreign government agencies, interested individuals, newspaper and magazine reporters and science writers, and radio and television crews.

6.0. COMMERCIAL FEASIBILITY ASSESSMENT

6.1. Preliminary Economic System Study

Plains Electric Generation and Transmission Cooperative of Albuquerque, New Mexico, with support from the U.S. Department of Energy, has completed a preliminary study of the feasibility of constructing and operating a 10 MW(electrical) generating station at Fenton Hill using energy supplied by the Phase II HDR heat-extraction system. Their study assumes that Los Alamos will have successfully demonstrated that the Phase II loop can produce heat at the temperature and rate and over the lifetime required to support such a power plant, and that, upon completion of the HDR Program's experiments there, Plains Electric can acquire the Fenton Hill Site -- specifically including the boreholes and underground circulation loop -- from the U.S. Forest Service and the U.S. Department of Energy.

With these assumptions, a draft version of the Plains Electric report estimates a capital cost of \$13 537 000 (in 1981 dollars) for construction of the 10 MW(e) power plant including structures, turbine-generators, and a contingency allowance of \$1 720 000. At \$1354 per installed kW of generating capacity this is significantly higher than the present cost of a conventional fuel-fired plant and, in view of the relative simplicity of a geothermally fueled plant, it appears conservative. Staffing requirement is estimated at 18 persons at an annual cost of \$330 000, and fixed annual charges -- including power-loss charges -- could range from \$312 000 to \$482 000 per year, depending upon which of seven alternative transmission schemes was selected. However, with no fuel costs beyond maintenance of the fluid-circulation loop, the study concludes that the HDR generation system is feasible and would be an economical producer of electrical power.

For comparison, a Los Alamos economic study estimates a cost of \$62.5 million (also in 1981 dollars) for the surface facilities of a 75 MW(e) HDR generating station, or \$833 per installed kW of generating capacity.

Including exploration, site acquisition and development, well drilling and completion and hydraulic fracturing, the Los Alamos estimate is \$154 million for the entire facility (\$2060 per installed kW). The cost breakdown appears in Table 6-I. Assumed drilling costs are based on actual cost experience with wells EE-2 and EE-3 -- which can probably be improved on in future drilling -- and represent precisely one-half of the total cost of the complete system. Assumed annual finance charge is 17%, and the break-even cost of producing electricity is estimated at 44 mills/kWh at the plant bus bar.

In Table 6-II, the estimated capital cost and levelized bus bar cost of electricity from an HDR system are compared with those for generation using conventional energy sources. With the assumptions made, it is concluded that the cost of electricity from the HDR resource is somewhat higher than that from coal-fired plants or from light-water reactors, but significantly less than that from oil-fired steam plants. With regard to capital costs, it is important to note that the entire HDR system -- energy source and power plant -- is included as a self-contained unit, whereas the capital costs of coal and uranium mines, petroleum and natural gas fields, and fuel-transportation systems, are all concealed in the fuel costs of conventional power plants.

At the end of FY81, a study of the economics of direct-heat use of HDR geothermal energy was in progress.

6.2. Economic Program Model Development

In FY81 some housekeeping-type changes were made to the HDREM economic model. This code constitutes a dynamic programming model of an HDR-powered electric-generator plant. Utilizing a net-present-value (NPV) analysis approach, this program continually optimizes the system design and management strategy through each time step. The principal change this year was converting the code for use with the CDC 7600 machine. In so doing, however, considerable cleanup was accomplished that resulted in factors of 2 to 3 improvement in execution time.

In addition, a new, simplified (non-dynamic programming) code, called HDRCST, was written and checked out. This code performs an NPV analysis of a specified direct application of HDR-derived thermal energy for space or process heating. Well-costing methodology has been updated over that used in the HDREM code by incorporation of both

o recently completed algorithms developed from the FY80 Republic Geothermal drill-cost study; and

TABLE 6-I
CAPITAL COSTS OF 75 MW(e) HDR POWER STATION, 1981 DOLLARS

<u>Item</u>	<u>Total Cost (millions of \$)</u>	<u>Cost per kW(e) \$</u>	<u>Fraction of Cost</u>
Geophysical Exploration	4.4	59	0.03
Site Acquisition & Development	0.5	7	--
Dry Cooling Heat Rejector	7.5	100	0.05
Other Surface Plant Costs	55.0	733	0.36
Well Drilling and Completions	77.0	1,030	0.50
Fracturing	<u>10.0</u>	<u>130</u>	<u>0.06</u>
Total	154.0	2,060	1.00

TABLE 6-II
COMPARISON OF ELECTRICITY GENERATING COSTS IN LEVELIZED, CONSTANT 1981 DOLLARS

<u>Type of Generating Station</u>	<u>Application</u>	<u>Capital Cost (\$/kW of Capacity)</u>	<u>Fuel Cost</u>	<u>Levelized Bus Bar Cost(¢/kWh)</u>
Hot Dry Rock Geothermal	Baseload	\$2060	None	4.4
Coal Fired Steam	Baseload	975	\$25/ton \$40/ton	3.2 3.9
Oil Fired Steam	Baseload	645	\$34/BBL \$50/BBL	6.9 9.6
Nuclear LWR	Baseload	1335	\$25/lb U ₃ O ₈ \$75/lb U ₃ O ₈	3.2 3.6
Gas Turbine	Peaking	202	\$2.72/mcf \$5.00/mcf	4.2 7.2
Diesel Electric	Peaking	300	\$34/BBL \$50/BBL	8.4 11.9

o a modification of Battelle's GEOCOST methodology.

The HDRCST code is being used to perform a case study of a fuel-source change for space heating at the NASA Wallops Island, Virginia, facility from No. 6 oil to an HDR source.

7.0. PROGRAM MANAGEMENT

7.1. HDR Program Development Council

The Executive Committee of the National HDR Program Development Council (the "PDC") met in Albuquerque on March 26, 1981. Present were C. M. Swinney, Chairman; G. Bodvarsson; W. Dolan; B. Greider; L. J. P. Muffler; and ex-officio members W. P. Grace, G. J. Nunz, and M. C. Smith. B. DiBona represented DGE/DOE, and H. Keppler represented KFA-Jülich, the Federal Republic of Germany. Progress, problems, and plans of the HDR Program were reviewed and discussed. Principal recommendations of the Committee were: (1) to continue background experiments in the existing Phase I system; (2) to install heavier casing in Well EE-3 than was originally planned; (3) to initiate hydraulic-fracturing experiments in EE-2 near the bottom of the open-hole section; (4) to proceed with selection of HDR Experimental Site 2 as soon as possible; (5) to organize a technical committee on equipment technology concerned primarily with downhole instrumentation and equipment.

7.2. Fenton Hill Steering Committee

In accordance with the terms of an International Energy Agency (IEA) agreement to which the KFA, NEDO, and DOE are parties, an International Steering Committee has been established to formulate and review the broad planning of the Fenton Hill HDR Project. The DOE members have, as technical advisors, two representatives from the Los Alamos National Laboratory, and the KFA and NEDO members are advised by their respective scientist-assignees to the Fenton Hill Project (who are in residence at Los Alamos). The Committee meets regularly twice each year and on an ad hoc basis when required. In FY81, the Committee met thrice.

First, an ad hoc meeting was held in Washington, D.C. on November 25-26, 1980 at which the KFA and DOE -- then the only members -- met with Japanese negotiators to finalize details of a modified agreement under which NEDO could join on an equal footing with KFA. The negotiations, which were concerned primarily with the legal aspects of patent and payment-schedule provisions,

were successfully completed. NEDO formally signed the agreement at IEA headquarters in Paris on February 23, 1981, with its membership retroactive to the beginning of FY80 (for parity with KFA).

The third regular Committee meeting, which now included all three partners, was held in Washington, D.C. on May 26-27, 1981. Some minor legal matters that had been tabled were resolved, and the major part of the meeting was devoted to reviewing the Fenton Hill Project's status and the proposed planning and budgetary projections for the balance of FY81 and all of FY82. The Committee was made aware of the unexpected difficulties in drilling EE-3 and their severe impact on the FY81 schedule and budget, and of how these impacts might propagate into FY82. Los Alamos presented several proposals to the Committee that would modify the Project in ways that would ameliorate these impacts. The Committee felt it did not have sufficient data or time to evaluate and reach final decisions on the proposals. Instead, they were tabled to the next regular meeting, which was scheduled sooner than would normally have been the case. Los Alamos was instructed to provide appropriate supporting-data packages to the members for detailed consideration in the interim.

The fourth regular Committee meeting was held on August 4-5, 1981 at Los Alamos with all members present. Los Alamos staff presented an update on technical status and budget, and on the then-current versions of the FY81 and FY82 Annual Operating Plans. The Committee unanimously agreed to drop the Deep Wellbore Equipment Test Station from the Project. After considerable discussion, the Committee also approved conduct of a proposed Run Segment 7, "high-buoyancy heat production," in the Phase I system early in FY82 providing that it did not significantly interfere -- either technically or budgetarily -- with the completion of, and fracturing operations in, the Phase II reservoir. A decision on another proposed Phase I test (Run Segment 6) was deferred as it could not be conducted until FY83 in any case. The Committee directed that the Annex of the IEA Agreement be updated to conform to current planning. It concluded its deliberations with some further discussions concerning financial-contribution schedules for KFA and NEDO. The next Committee meeting is tentatively scheduled in the spring of 1982.

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REFERENCES

1. G. M. Cremer, ed., "Hot Dry Rock Geothermal Energy Development Program Annual Report FY1980," Los Alamos National Laboratory report LA-8855-HDR (July 1981).
2. A. Kron and G. Heiken, "Geothermal Gradient Map of the Conterminous United States," Los Alamos National Laboratory map LA-8476-MAP (August 1980); Geotherm. Res. Coun. Trans., V. 4, pp. 69-71 (September 1980).
3. M. Guffanti and M. Nathenson, "Preliminary Map of Temperature Gradients in the Conterminous United States," Geotherm. Res. Coun., Trans., V. 4, pp. 53-56 (September 1980).
4. R. G. Luedke and R. L. Smith, "Map Showing Distribution, Composition, and Age of Late Cenozoic Volcanic Centers in Arizona and New Mexico," U.S. Geol. Surv. Map, No. I-1091-A (1978).
5. M. J. Aldrich, Jr. and A. W. Laughlin, "Location, Age, and Rock Type of Volcanic Rock Younger than 5 Myr Old in Arizona and New Mexico," Los Alamos National Laboratory report LA-8820-MS (April 1981).
6. M. E. Ander, "Geophysical Study of the Crust and Upper Mantle Beneath the Central Rio Grande Rift and Adjacent Great Plains and Colorado Plateau," Univ. of New Mexico Ph.D. dissertation, Los Alamos National Laboratory report, LA-8676-T (December 1980).
7. M. E. Ander, "Magnetotelluric Exploration in Arizona and New Mexico for Hot Dry Rock Geothermal Energy using SQUID Magnetometers," in SQUID Applications to Geophysics, H. Weinstock and W. C. Overton, eds., Soc. Exploration Geophys., pp. 61-65 (1981).
8. C. L. V. Aiken and M. E. Ander, "A Regional Strategy for Geothermal Exploration with Emphasis on Gravity and Magnetotellurics," J. Volcan. and Geotherm. Res., V. 9, (1981).
9. J. T. Gutmann, C. L. V. Aiken, M. E. Ander, and R. T. Laney, "Preliminary Geological and Geophysical Evaluation of the Castle Dome HDR Geothermal Prospect, Southwestern Arizona," Geotherm. Res. Coun., Trans., V. 4, (September 1980).
10. C. L. V. Aiken and M. E. Ander, "Batholithic Complex Beneath the Castle Dome Area, Southwestern Arizona: A Geophysical Study," Abst., EOS, Trans., Am. Geol. Union, V. 62, No. 17, p. 384 (1981).
11. M. E. Ander, R. Goss, D. Strangway, C. Hillebrand, A. W. Laughlin, and C. Hudson, "Magnetotelluric/Audiomagnetotelluric Study of the Zuni Hot Dry Rock Geothermal Prospect, New Mexico," Geotherm. Res. Coun., Trans., V. 4, (September 1980).

12. M. E. Ander, R. Goss, D. Strangway, and A. W. Laughlin, "AMT/MT Study of the Jemez Lineament, New Mexico," Abst., IAGA Scientific Assembly Symposium on Audiofrequency Magnetotellurics and Crustal Studies using ELF Wave Propagation, Program and Abstracts, Edinburgh, Scotland, p. 137-138 (1981).
13. M. J. Aldrich, M. E. Ander, and A. W. Laughlin, "Geological and Geophysical Structures of the Jemez Lineament: A Reactivated Precambrian Structure," Abst., 4th International Conf. on Basement Tectonics, Program and Abstracts, Oslo, Norway (1981).
14. T. J. Shankland and K. A. Kariya, "Upper Bounds on Crustal Temperatures Inferred from Electrical Conductivity," IAGA Scientific Assembly, Program and Abstracts, Edinburgh, Scotland, p. 133 (1981).
15. M. E. Ander, "Lithosphere Thinning Below the Rio Grande Rift and Adjacent Colorado Plateau in New Mexico," Abst., EOS, Trans., Am. Geol. Union, V. 62, No. 17, p. 390 (1981).
16. M. E. Ander, G. Heiken, J. Eichelberger, A. W. Laughlin, and S. F. Huestis, "Geologic and Geophysical Investigations of the Zuni-Bandera Volcanic Field, New Mexico," Los Alamos National Laboratory report LA-8827-MS (May 1981).
17. M. E. Ander, W. D. Kennedy, C. L. V. Aiken, "Complete Bouguer Gravity Anomaly Map of the Socorro 1°X2° Quadrangle, New Mexico," Los Alamos National Laboratory map LA-8679-MAP (March 1981).
18. M. E. Ander and S. P. Huestis, "Mafic Intrusion Beneath the Zuni-Bandera Volcanic Field, New Mexico," submitted to Geol. Soc. Am. Bull. (1981).
19. M. E. Ander and S. P. Huestis, "Recent Mafic Intrusion Beneath the Lucero Uplift, New Mexico and Its Possible Structural Relationship to a Northeast-Trending Precambrian Shear System," submitted to Geol. Soc. Am. Bull. (1981).
20. J. S. East, "Hot Dry Rock Geothermal Potential of Roosevelt Hot Springs Area: Review of Data and Recommendations," Los Alamos National Laboratory report LA-8751-HDR (June 1981).
21. W. E. Glenn, J. B. Helen, and D. L. Nielson, "A Comprehensive Study of Los Alamos National Laboratory Well C/T-2, Roosevelt Hot Springs KGRA, Utah, and Applications to Geothermal Well Logging," Los Alamos National Laboratory report LA-8686-MS (February 1981).
22. D. Gambill, "Hot Dry Rock Geothermal Potential of Long Valley Caldera, California," Los Alamos National Laboratory report LA-8710-HDR (March 1981).
23. D'Appolonia Consulting Engineers, Inc., "Evaluation of Hot Dry Exploration Techniques in the Atlantic Coastal Plain: A Test Site on the Delmarva Peninsula of Maryland and Virginia," Los Alamos National Laboratory report LA-8800-MS (April 1981).

24. P. H. Osberg, R. Wettevauer, M. Rivers, W. A. Bothner, and J. W. Creasy, "Feasibility Study of the Conway Granite as a Geothermal Energy Resource," U.S. Dept. Energy Tech. Info. Center, Oak Ridge, Tennessee Tech. report C00-2686-1 (1978).
25. James Browning, "Flame-jet Drilling in Conway, New Hampshire, Granite, Final Report," prepared for the Los Alamos National Laboratory by Browning Engineering Corporation, P.O. Box 863, Hanover, NH 03755, Order No. 4-L10-2889R-1, November 4, 1981.
26. J. T. Gutmann, "Geologic Framework and Hot Dry Rock Geothermal Potential of the Castle Dome Area, Yuma County, Arizona," Los Alamos National Laboratory report LA-8723-HDR (February 1981).
27. C. R. Shearer, "A Regional Terrestrial Heat Flow Study in Arizona," Thesis, New Mexico Institute of Mining and Technology, Socorro, New Mexico, (1979).
28. J. W. Tester and J. N. Albright, eds., "Hot Dry Rock Energy Extraction Field Test: 75 Days of Operation of a Prototype Reservoir at Fenton Hill," Los Alamos Scientific Laboratory report LA-7771-MS (April 1979).
29. H. N. Fisher and J. W. Tester, "The Pressure Transient Testing of a Man-Made Fractured Geothermal Reservoir: An Examination of Fracture Versus Matrix Dominated Flow Effect," Los Alamos Scientific Laboratory report LA-8535-MS (September 1980).
30. G. A. Zyvoloski, R. L. Aamodt, R. R. Aguilar, D. A. Counce, H. N. Fisher, T. A. Grant, C. O. Grigsby, R. H. Hendron, C. E. Holley, Jr., R. G. Lawton, H. D. Murphy, C. Pearson, R. M. Potter, and P. E. Trujillo, Jr., "Evaluation of Second Hot Dry Rock Geothermal Energy Reservoir: Results of Phase I, Run Segment 5," Los Alamos National Laboratory report LA-8940-HDR (September 1981).
31. Z. V. Dash, H. D. Murphy, and G. Cremer, eds., "Hot Dry Rock Geothermal Reservoir Testing: 1978 to 1980," Los Alamos National Laboratory report LA-9080-SR (November 1981).
32. H. D. Murphy, ed., "Preliminary Evaluation of the Second Hot Dry Rock Geothermal Energy Reservoir: Results of Phase 1, Run Segment 4," Los Alamos Scientific Laboratory report LA-8354-MS (May 1980).
33. R. L. Aamodt, "Distributed Impedances in the EE-1/GT-2B Circulation System During Run Segment 5 (Phase 1, Experiment 217) as Determined from Shut-In Experiments," Los Alamos National Laboratory internal tech memo 1, ESS-4, January 23, 1981.
34. J. W. Tester, R. M. Potter, and R. L. Bivins, "Interwell Tracer Analyses of a Hydraulically Fractured Granitic Geothermal Reservoir," paper SPE 8270 presented at 54th Annual Mtg. of Soc. Petr. Engrs. of AIME, Las Vegas, Nevada, September 23-26, 1979.
35. B. J. Skinner, "Thermal Expansion," in Handbook of Physical Constants, S. P. Clark, Jr., ed., Geol. Soc. Am., New York (1966).

36. K. E. Nichols, "60-KW Geothermal Power Module: Design and Performance Evaluation," presented at Energy Sources Tech. Conf., New Orleans, Louisiana, February 1980.
37. R. G. Olander, K. E. Nichols, and J. W. Tester, "Utilization of Hot Dry Rock Geothermal Energy: Power plant Design Considerations," 3rd National Congress, Pressure Vessel and Piping Division, ASME, paper 79-PVP-38, June 1979.
38. G. Zyvoloski, "Bottom-Hole Temperatures and Pressures for Experiment 217," Los Alamos Scientific Laboratory, tech memo 11, G-5, (November 7, 1980).
39. H. D. Murphy, "Thermal Stress Cracking and the Enhancement of Heat Extraction from Fractured Geothermal Reservoirs," *Geotherm. Energy* 7, p. 22-29 (1979).
40. J. W. Tester, G. E. Morris, R. G. Cummings, and R. L. Bivins, "Electricity from Hot Dry Rock Geothermal Energy: Technical and Economic Issues," Los Alamos Scientific Laboratory report LA-7603-MS (January 1979).
41. R. G. Cummings and G. E. Norris, "Economic Modeling of Electricity Production from Hot Dry Rock Geothermal Reservoirs: Methodology and Analyses," Electric Power Research Institute report EPRI-EA-630 (September 1979).
42. H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids, 2nd Ed., Oxford Univ. Press, London, p. 396 (1959).
43. H. D. Murphy and R. G. Lawton, "Downhole Measurements of Thermal Conductivity in Geothermal Reservoirs," *J. Pres. Ves. Tech*, 99, pp. 607-611 (1977).
44. N. M. Becker, W. D. Purtymun, and W. C. Ballance, "Aquifer Evaluation at Fenton Hill, October and November 1980," Los Alamos National Laboratory report LA-8964-MS (October 1981).
45. G. M. Cremer, R. B. Duffield, M. C. Smith, M. G. Wilson, "Hot Dry Rock Geothermal Energy Development Program, Annual Report, Fiscal Year 1979," Los Alamos Scientific Laboratory report LA-8280-HDR (August 1980).
46. M. C. Brown, R. B. Duffield, C. L. B. Siciliano, and M. C. Smith (compilers), "Hot Dry Rock Geothermal Energy Development Program, Annual Report, Fiscal Year 1978," Los Alamos Scientific Laboratory report LA-7807-HDR (April 1979).
47. Los Alamos Scientific Laboratory HDR Project Staff, "Hot Dry Rock Geothermal Energy Development Project: Annual Report Fiscal Year 1977," Los Alamos Scientific Laboratory report LA-7109-PR (February 1978).
48. W. D. Purtymun, "Geology of the Jemez Plateau West of the Valles Caldera," Los Alamos National Laboratory report LA-5124-MS (February 1973).

49. W. D. Purtymun, F. G. West, and R. A. Pettitt, "Geology of Geothermal Test Hole GT-2, Fenton Hill Site, July 1974," Los Alamos Scientific Laboratory report LA-5780-MS (November 1974).
50. W. D. Purtymun, W. H. Adams, and J. W. Owens, "Water Quality in Vicinity of Fenton Hill Site, 1974," Los Alamos Scientific Laboratory report LA-6093 (December 1975).
51. W. D. Purtymun, W. H. Adams, A. K. Stoker, and F. G. West, "Water Quality in Vicinity of Fenton Hill Site, 1975," Los Alamos Scientific Laboratory report LA-6511-MS (September 1976).
52. W. D. Purtymun, W. H. Adams, and A. K. Stoker, "Water Quality in the Vicinity of Fenton Hill Site, 1976," Los Alamos Scientific Laboratory report LA-7307-MS (June 1978).
53. W. D. Purtymun, A. K. Stoker, W. H. Adams, and J. W. Owens, "Water Quality in Vicinity of the Fenton Hill Site, 1977," Los Alamos Scientific Laboratory report LA-7468-PR (September 1978).
54. W. D. Purtymun, R. W. Ferenbaugh, A. K. Stoker, W. H. Adams, and J. W. Owens, "Water Quality in the Vicinity of Fenton Hill Site, 1978," Los Alamos Scientific Laboratory report LA-8217-PR (January 1980).
55. W. D. Purtymun, R. W. Ferenbaugh, A. K. Stoker, W. H. Adams, and J. W. Owens, "Water Quality in the Vicinity of Fenton Hill Site, 1979," Los Alamos Scientific Laboratory report LA-8424-PR (June 1980).
56. W. D. Purtymun, R. W. Ferenbaugh, and W. H. Adams, "Water Quality in the Vicinity of Fenton Hill Site, 1980," Los Alamos National Laboratory report LA-9007-PR (September 1981).
57. R. B. Demuth and F. H. Harlow, "Thermal Fracture Effects in Geothermal Energy Extraction," Los Alamos National Laboratory report LA-7963 (November 1979).
58. R. B. Demuth and F. H. Harlow, "Geothermal Energy Enhancement by Thermal Fracture," Los Alamos National Laboratory report LA-8428 (December 1980).
59. G. A. Zyvoloski, "Finite Element Methods for Geothermal Reservoir Simulation," International J. Numerical and Analytical Methods in Geomechanics, (in press).
60. G. W. Morey, R. O. Fournier, and J. J. Rowe, "The Solubility of Quartz in Water in the Temperature Interval from 25°C to 300°C," *Geochimica et Cosmochimica Acta* 26, pp. 1029-1043 (1962).
61. R. O. Fournier and A. H. Truesdell, "Chemical Indicators of Subsurface Temperature, Part 2: Estimation of Temperature and Fraction of Hot Water Mixed with Cold Water," *J. Res. U.S. Geol. Surv.* 2, pp. 263-270 (1974).
62. W. F. Giggenbach, "Geothermal Gas Equilibria," *Geochimica et Cosmochimica Acta*, 44, pp. 2021-2032 (1980).

63. W. F. Giggenbach, "Geothermal Mineral Equilibria," *Geochimica et Cosmochimica Acta*, 45, pp. 393-410 (1981).
64. A. W. Laughlin and A. Eddy, "Petrography and Geochemistry of Precambrian Rocks from GT-2 and EE-1," Los Alamos Scientific Laboratory report LA-6930-MS (August 1977).
65. J. N. Andrews and D. F. Wood, "Mechanism of Radon Release in Rock Matrices and Entry Into Groundwaters," in Institution of Mining and Metallurgy Transactions/Section B, 81, No. 792 (November 1972).
66. A. Stoker and P. Kruger, "Radon in Geothermal Reservoirs," Proc. of the 2nd U.N. Symp. on the Development and Use of Geothermal Resources, San Francisco, California, 1975.
67. P. Kruger, G. A. Cederberg, and L. Semprini, "Radon Data - Phase I Test, Los Alamos Scientific Laboratory Hot Dry Rock Project January 28-April 27, 1978," Stanford Geothermal Program technical report SGP-TR-27 (1978).
67. D. W. Brown, "Dresser-Atlas Iodine Tracer logs - Experiment 116," Los Alamos National Laboratory internal memo, Q-11, (November 17, 1976).
68. R. Potter, "The Use of Radioactive Tracers in HDR Reservoir Studies," Los Alamos National Laboratory tech memo 5, G-3, (March 14, 1979).
69. M. C. Brown, G. J. Nunz, G. M. Cremer, and M. C. Smith, "Hot Dry Rock Geothermal Energy Development Program: Semiannual Report October 1, 1978-March 31, 1979," Los Alamos Scientific Laboratory report LA-7959-HDR (September 1979).
70. C. F. Pearson, "Baca Hydrofrac Event Locations," Los Alamos National Laboratory internal memo, ESS-3 (May 22, 1981).
71. D. Brown, "ORE-IDA Flow Tests," Los Alamos National Laboratory internal memo, ESS-4 (June 16, 1981).

APPENDIX A

PUBLICATIONS AND PRESENTATIONS

- Aiken, C. L. V., and M. E. Ander, "A Regional Strategy for Geothermal Exploration with Emphasis on Gravity and Magnetotellurics," J. Volcan. and Geotherm. Res., V. 9, (1981).
- Aiken, C. L. V., and M. E. Ander, "Batholithic Complex Beneath the Castle Dome Area, Southwestern Arizona: A Geophysical Study," Abst., EOS, Trans., Am. Geol. Union, V. 62, No. 17, p. 384 (1981).
- Aki, K., Michael Fehler, R. M. Potter, et al., "Interpretation of Seismic Data from Hydraulic Fracturing Experiments at the Fenton Hill, New Mexico Hot Dry Rock Geothermal Site," Geophys. Res. (May 1981).
- Albright, J., C. Pearson, F. Homuth, J. Bridwell and R. Potter, "The Relationship Between High Pore Pressures and Seismicity at the Fenton Hill, New Mexico Hot Dry Rock Geothermal Site," EOS, v. 61, no. 46, p. 1051, (November 11, 1980).
- Aldrich, M. J., M. E. Ander, and A. W. Laughlin, "Geological and Geophysical Structures of the Jemez Lineament: A Reactivated Precambrian Structure," Abst., 4th International Conf. on Basement Tectonics, Program and Abstracts, Oslo, Norway (1981).
- Aldrich, M. J., and A. W. Laughlin, "Age and Location of Volcanic Centers 3.0 Myr Old in Arizona, New Mexico, and the Trans-Pecos Area of West Texas," Los Alamos National Laboratory map LA-8812-MAP (April 1981).
- Ander, M. E., G. Heiken, J. Eichelberger, A. W. Laughlin, and S. F. Huestis, "Geologic and Geophysical Investigations of the Zuni-Bandera Volcanic Field, New Mexico." Los Alamos National Laboratory report LA-8827-MS (May 1981).
- Ander, M. E., W. D. Kennedy, C. L. V. Aiken, "Complete Bouguer Gravity Anomaly Map of the Socorro 1°x2° Quadrangle, New Mexico, Los Alamos National Laboratory map LA-8679-MS (March 1981).
- Ander, M. E., "Geophysical Study of the Crust and Upper Mantle Beneath the Central Rio Grande Rift and Adjacent Great Plains and Colorado Plateau," Univ. of New Mexico Ph.D dissertation, Los Alamos National Laboratory report, LA-8676-T (December 1980).
- Ander, M. E., "Magnetotelluric Exploration in Arizona and New Mexico for Hot Dry Rock Geothermal Energy using SQUID Magnetometers," in SQUID Applications to Geophysics, H. Weinstock and W. C. Overton, eds., Soc. Exploration Geophys., p. 61-65 (1981).
- Ander, M. E., R. Goss, D. Strangway, C. Hillebrand, A. W. Laughlin, and C. Hudson, "Magnetotelluric/Audiomagnetotelluric Study of the Zuni Hot Dry Rock Geothermal Prospect, New Mexico," Geotherm. Res. Coun., Trans., V. 4, (September 1980).

- Ander, M. E., R. Goss, D. Strangway, and A. W. Laughlin, "AMT/MT Study of the Jemez Lineament, New Mexico," Abst., IAGA Scientific Assembly Symposium on Audiofrequency Magnetotellurics and Crustal Studies Using ELF Wave Propagation, Program and Abstracts, Edinburgh, Scotland, p. 137-138 (1981).
- Ander, M. E., "Lithosphere Thinning Below the Rio Grande Rift and Adjacent Colorado Plateau in New Mexico," Abst., EOS, Trans., Am. Geol. Union, V. 62, No. 17, p. 390 (1981).
- Ander, M. E. and S. P. Huestis, "Mafic Intrusion Beneath the Zuni-Bandera Volcanic Field, New Mexico," submitted to Geol. Soc. Am. Bull. (1981).
- Ander, M. E. and S. P. Huestis, "Recent Mafic Intrusion Beneath the Lucero Uplift, New Mexico and Its Possible Structural Relationship to a Northeast-Trending Precambrian Shear System," submitted to Geol. Soc. Am. Bull. (1981).
- Arney, B., D. Brown, and R. Potter, "The HDR Alternative in the Cascades," Geotherm. Res. Coun., Portland, Oregon (January 19-23, 1981).
- Becker, N. M., W. D. Purtymun, and W. C. Ballance, "Aquifer Evaluation at Fenton Hill, October and November 1980," Los Alamos National Laboratory report LA-8964-MS (October 1981).
- Charles, R. W., C. O. Grigsby, C. E. Holley, J. W. Tester, and L. A. Blatz, "Experimentally Determined Rock-Fluid Interactions Applicable to a Natural Hot Dry Rock Geothermal System," in Process Mineralogy in Extractive Metallurgy, Mineral Exploration and Energy Resources, O. M. Hansen and W. C. Park, eds., The Metallurgical Society of AIME, 1981 (originally published as TMS Paper A80-8, 1980).
- Cremer, G. M., Update, Los Alamos National Laboratory newsletter, LASL-80-7, V. 3 and 4 (February 1981).
- Cremer, G. M. and M. Wilson, Eds., Update, Los Alamos National Laboratory newsletter, LALP-81-66 (December 1981).
- Cremer, G. M., Ed., "Hot Dry Rock Geothermal Energy Development Program, Annual Report, Fiscal year 1980," Los Alamos National Laboratory report LA-8855-HDR (July 1981).
- D'Appolonia Consulting Engineers, Inc., "Evaluation of Hot Dry Exploration Techniques in the Atlantic Coastal Plain: A Test Site on the Delmarva Peninsula of Maryland and Virginia," Los Alamos National Laboratory report LA-8800-MS (April 1981).
- Dash, Z. V., H. D. Murphy, and G. M. Cremer, "Hot Dry Rock Geothermal Reservoir Testing: 1978 to 1980," Los Alamos National Laboratory report LA-9080-SR (November 1981).
- Demuth, R. B. and F. H. Harlow, "Geothermal Energy Enhancement by Thermal Fracture," Los Alamos National Laboratory report LA-8428 (December 1980).

- East, J. S., "Hot Dry Rock Geothermal Potential of Roosevelt Hot Springs Area: Review of Data and Recommendations," Los Alamos National Laboratory report LA-8751-HDR (May 1981).
- Fisher, H. N. and J. W. Tester, "The Pressure Transient Testing of a Man-Made Fractured Geothermal Reservoir: An Examination of Fracture Versus Matrix Dominated Flow Effect," Los Alamos Scientific Laboratory report LA-8535-MS (September 1980).
- Gambill, D., "Hot Dry Rock Geothermal Potential of Long Valley Caldera, California," Los Alamos National Laboratory report LA-8710-HDR (March 1981).
- "Geothermal Resources Council Annual Meeting Preprints," Houston, Texas, October 25-29, 1981, Los Alamos National Laboratory, LALP-81-48.
- Glenn, W. E., J. B. Helen, and D. L. Nielson, "A Comprehensive Study of Los Alamos National Laboratory Well C/T-2, Roosevelt Hot Springs KGRA, Utah, and Applications to Geothermal Well Logging," Los Alamos National Laboratory report LA-8686-MS (February 1981).
- Goff, F. E. and C. O. Grigsby, "Valles Caldera Geothermal Systems, New Mexico, USA," J. Hydrology (1981).
- Grigsby, C. O., J. W. Tester, P. E. Trujillo, D. A. Counce, J. Abbott, C. E. Holley, and L. A. Blatz, "Rock-Water Interactions in Hot Dry Rock Geothermal Systems: Field Investigations of In-Situ Geochemical Behavior," submitted to J. Volcanology Geotherm. Res. (1981).
- Grigsby, C. O., P. E. Trujillo, Jr., D. A. Counce, and R. E. Aguilar, "Geochemical Behavior of the Second Hot Dry Rock Geothermal Reservoir at Fenton Hill, New Mexico," presented at the 6th Annual Workshop on Geothermal Reservoir Engineering at Stanford University, Stanford, California (December 16-18, 1980).
- Gutmann, J. T., "Geologic Framework and Hot Dry Rock Geothermal Potential of the Castle Dome Area, Yuma County, Arizona," Los Alamos National Laboratory report LA-8723-HDR (February 1981).
- Gutmann, J. T., C. L. V. Aiken, M. E. Ander, and R. T. Laney, "Preliminary Geological and Geophysical Evaluation of the Castle Dome HDR Geothermal Prospect, Southwestern Arizona," Geotherm. Res. Coun., Trans., V. 4 (September 1980).
- Heiken, G., H. Murphy, G. Nunz, R. Potter, and C. Grigsby, "Hot Dry Rock Geothermal Energy," Am. Scientist, p. 400-407 (July-August 1981).
- Heiken, G. and F. Goff, "HDR Geothermal Energy in Igneous Systems - I. Large Calderas," submitted to J. of Volcan. and Geotherm. Res. (1981).
- Murphy, H. D., J. W. Tester, C. O. Grigsby, and R. M. Potter, "Energy Extraction from Fractured Geothermal Reservoirs in Low-Permeability Crystalline Rock," J. Geophys. Res. (1981).

Murphy, H., Ed., "Relaxation of Geothermal Reservoir Stresses Induced by Heat Production," Los Alamos National Laboratory report LA-8954-MS (August 1981).

Murphy, H. D., J. W. Tester, and R. M. Potter, "Comparison of Two Hot Dry Rock Geothermal Reservoirs," presented at the 6th Annual Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California (December 16-18, 1980).

Potter, R., "Permeability Testing for Geothermal Application in Granite," Repository Sealing Field Testing Workshop of the Office of Nuclear Waste Isolation, Santa Fe, New Mexico (September 18-19, 1980).

Purtymun, W. D., R. W. Ferenbaugh, and W. H. Adams, "Water Quality in the Vicinity of Fenton Hill Site, 1980," Los Alamos National Laboratory report LA-9007-PR (September 1981).

Shankland, T. J. and K. A. Kariya, "Upper Bounds on Crustal Temperatures Inferred from Electrical Conductivity," IAGA Scientific Assembly, Program and Abstracts, Edinburgh, Scotland, p. 133 (1981).

Stix, J., "Seasat Satellite Investigation of the Structure of Western Nebraska and Its Application to the Evaluation of Geothermal Resources," Proc. Intern. Symp. of Remote Sensing of Environment, Ann Arbor, Michigan (May 1981).

"Summary of Talks, Third Annual Hot Dry Rock Geothermal Information Conference," Santa Fe, New Mexico, October 28-29, 1980, Los Alamos National Laboratory report LAL-81-22 (May 1981).

Zyvoloski, G. A., R. L. Aamodt, R. R. Aguilar, D. A. Counce, H. N. Fisher, T. A. Grant, C. O. Grigsby, R. H. Hendron, C. E. Holley, Jr., R. G. Lawton, H. D. Murphy, C. Pearson, R. M. Potter, and P. E. Trujillo, Jr., "Evaluation of Second Hot Dry Rock Geothermal Energy Reservoir: Results of Phase I, Run Segment 5," Los Alamos National Laboratory report LA-8940-HDR (September 1981).

Zyvoloski, G., "Finite Element Models for Heat and Mass Transfer in Porous Media," Symposium on Computer Use by Engineers, Livermore, California (October 22-24, 1980).

Zyvoloski, G. A., "Finite Element Methods for Geothermal Reservoir Simulation," International J. Numerical and Analytical Methods in Geomechanics (in press).

APPENDIX B

THIRD ANNUAL HOT DRY ROCK GEOTHERMAL INFORMATION CONFERENCE AGENDA

Tuesday, October 28, 1980

SESSION I

Harry Hoyt, LASL, Presiding

8:45	Call to Order	H. Hoyt
8:50-9:00	Greeting	L. Kehoe
	Secretary, NM Dept. Energy & Minerals	
9:00-9:15	Welcome and Conference Keynote	D. Kerr
9:20-9:50	Geothermal Energy Development Overview	C. Carwile, DOE/DGE
9:50-10:15	HDR Program Review	G. Nunz
10:15-10:20	Preview of the Conference	H. Hoyt

... Break ...

SESSION II

A. Jelacic, DOE/DGE Presiding

10:50-12:20	Fenton Hill Project: Research Reservoir Heat Extraction Results	
10:50-11:20	(a) MHF and Evaluation-Phase I	J. Tester
11:20-11:50	(b) Long Term Drawdown Tests	H. Murphy
11:50-12:20	Engineering Reservoir Progress and Plans	R. Spence

... Lunch ...

SESSION III*

Porter Grace, DOE/ALO, Presiding

1:30-2:00	HDR Resource Evaluation	G. Heiken
2:00-2:30	Candidates for Site Two	F. Goff
2:30-2:50	HDR Resources in New England	J. Maxwell
2:50-3:15	The Delmarva Peninsula HDR Prospect	C. Schubert, D'Appolonia

SESSION IV*

Susan Prestwich, DOE/TDOO, Presiding

3:30-3:50	Downhole Instrumentation	B. Dennis
3:50-4:10	Drilling Technology	E. Hoover, SLA
4:10-4:45	Commercialization of HDR Energy	HDR Energy Development, Inc.

... Close First Day Session ...

5:30-7:00 No Host Cocktail Reception
 7:00-9:00 Banquet
 Advanced Geothermal Technology: The Rough Road Ahead

Sweeney Center
 Sweeney Center
 Dr. H. Tsvi Meidav
 Consultant

Wednesday, October 29, 1980

SESSION V*

Larry Germain, LASL, Presiding

8:00-8:25	Status of HDR at Falkenberg/FRG	O. Keppelmeyer, FRG
8:25-8:45	Hydraulic Experiments in Artificially Created Fractures	R. Jung, FRG
8:45-9:05	Pressure Pulse Experiments for Determination of Hydraulic Properties of Fractures	H. Keppler, FRG
9:05-9:30	In Situ Determination of Thermal Conductivity of Cased Holes	H. Villinger U. of Berlin
9:30-9:45	Environmental Monitoring and Studies	E. Wewerka
9:45-10:00	Seismic Investigations	J. Albright
10:00-10:15	Geochemistry	C. Grigsby

... Break ...

SESSION VI*

Mort Smith, LASL, Presiding

10:30-11:00	HDR in the United Kingdom	A. Batchelor, UK
11:00-11:15	The 60-kVA Binary Demonstration System	R. Hendron
11:15-11:30	Preview of Fenton Hill Tour	R. Hendron

... End Technical Sessions ...

12:30 Fenton Hill Bus No. 1 - Leaves Sweeney Center
 1:30 Fenton Hill Bus No. 2 - Leaves Sweeney Center
 1:30-3:30 Work Sessions, Sweeney Center, Discussions Among Participants and HDR Specialists

* A room will be available for discussions with speakers and contributors from previous sessions.

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