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Hot Dry Rock Geothermal Energy Development Program

**Annual Report
Fiscal Year 1980**

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Hot Dry Rock Geothermal Energy Development Program Annual Report Fiscal Year 1980

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Over a period of several years, the first HDR energy system (the "Phase I" or "Research" system) has been constructed and operated successfully at Fenton Hill. In FY79 the injection well ("EE-1") of the Phase I system was reworked and a small hydraulic fracture previously made in its uncased bottom section was extended upward by fluid pressurization until it encountered the complex set of fractures from which heat had been extracted in earlier experiments. This refracturing permitted injection of cool water from EE-1 into an enlarged fracture system at a point about 200 m below the main entry point of fluid in the original circulation loop. Intensive investigation and extended flow testing of this enlarged Phase I heat-extraction system has been a major activity at Fenton Hill during FY80.

In the enlarged Phase I system, cool fluid pumped down EE-1 enters the extended hydraulic fracture system at a depth of 2930 m, rises through it, flows through part of the fractured volume cooled in previous experiments, and enters GT-2B (the production well) through several fractures in the vicinity of 2700 m. In "Run Segment 4," a 23-day recirculating flow experiment conducted in October and November 1979, the general behavior of the enlarged system was investigated. When steady state conditions had been established, an injection pressure of 9.65 MPa produced a flow rate of 6.0 kg/s against a back pressure of 1.1 MPa, and extracted heat from the rock at an average rate of 3 MW(t). Flow impedance through the fractured reservoir was $1.4 \text{ GPa}\cdot\text{s}/\text{m}^3$ and was concentrated at the exits from the fracture system into the production well. Although the initial rock temperatures at the entrance to the fracture system was 197°C and quartz geothermometry indicated contact of the circulating fluid with rock at about 190°C , cooling of the fluid as it passed through the old fractures reduced its temperature to 156°C as it entered well GT-2B-- and this did not change significantly during the 23-day test. Rate of fluid loss decreased continuously, to 1.3 kg/s at the end of the test, and quality of the recirculated fluid remained high, with less than 2000 ppm total dissolved solids. No seismic events from system operation could be detected at the surface, and there were no other observable environmental effects.

In the absence of measurable temperature drawdown, no estimate of effective heat-transfer area of the enlarged Phase I system could be made during Run Segment 4. To investigate this and other aspects of system behavior, a longer-term "Run Segment 5" was initiated in March 1980, under conditions similar to those established in Run Segment 4. At the end of FY80, 200 days

later, this run was still in progress. Temperature drawdown of 3 to 5°C had by then been observed, indicating an effective fracture area of approximately 40 000 to 60 000 m²--about five to eight times that of the Phase I system before enlargement. This is in reasonable agreement with a fracture volume eight to ten times that of the initial system, deduced from tracer experiments. Water-loss rate had declined to 0.6 kg/s, while flow impedance remained nearly constant at about 1.7 GPa·s/m³.

In May 1980, a skid-mounted 60-kVA binary-cycle electrical generator was installed in the Phase I surface system at Fenton Hill. In operation, 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 because of Freon leaks, electrical problems with the alternator and control circuit, and interruptions in the hot water supply to it, which was required by other experiments. However, during operating periods it reached its full rated capacity and slightly exceeded its overall design-cycle efficiency of 5.7%. Because it is designed to accept hot water at any temperature between 90 and 175°C, its efficiency should be higher with the hotter fluids that will be provided by the Phase II system, described below.

By combining the parameters obtained from pressure vs flow-rate data, dye-tracer experiments, thermal drawdown, and laboratory permeability measurements on core samples, approximate dimensions of the original Phase I fracture system (before enlargement) were determined and limits were set on permeating area and effective confining permeability. As has been noted, the fracture system has since been greatly enlarged, and downhole microseismic observations during Run Segment 4 indicated the occurrence of small acoustic events at much greater distances from the injection well than had previously been observed. The more remote of these events are evidently the result of fluid infiltration far beyond that part of the fracture system that contributes significantly to heat extraction. It is hoped that further experiments and analyses will elucidate the relationships among effective heat-transfer area, total fracture area accessible to fluid circulation, and formation volume affected by increased pore pressure.

While the Fenton Hill Research system has provided a successful demonstration of the technical feasibility of creating and operating a hot dry rock energy system, it does not approach the wellhead temperature required for

efficient operation of an electrical power plant, the energy production rate that would support a power plant of commercial size, or the useful lifetime that would make such a plant economically attractive. Therefore, an Engineering (Phase II) system that should approach these commercial requirements has been designed and is being constructed concurrently at Fenton Hill. To achieve the desired temperature, the injection well for this system (borehole EE-2) has been drilled to a vertical depth of about 4500 m, where the rock temperature is approximately 320°C. To provide the heat-transfer area required for a long useful life at a high rate of heat extraction, it is projected that as many as 14 hydraulic fractures may be required, with fluid circulation through a vertical distance of the order of 360 m. To avoid premature thermal interference between these vertical fractures requires a horizontal separation of the order of 35 m. In order to permit this number and separation of fractures without drilling to excessive depths, the bottom 1000 m of hole EE-2 were drilled at an inclination of 35° to the vertical and in a northeasterly direction, approximately perpendicular to the northwesterly strike expected of the hydraulic fractures. Borehole EE-2 was completed on May 12, 1980.

It is intended that EE-3, the production well, be drilled similarly to EE-2 but that, in its inclined section, it be approximately 360 m vertically above EE-2. It was spudded in on May 22, 1980, at a location 46 m to the west of EE-2. At the end of FY80 the hole had been drilled to a depth of 3044 m, was inclined at 24° to the vertical, was directed 67° east of north, and directional drilling was continuing.

In the meantime, the design of the Phase II surface system was completed during FY80. It will provide a maximum flow rate of 63 kg/s, a reservoir inlet pressure up to 20.7 MPa, and a heat-rejection capability of 50 MW(t). A 19 000-m³ storage pond has been designed to hold the water required for hydraulic fracturing and system operations. The capability of the existing Fenton Hill water well and of the aquifer that it penetrates to provide the water required for these operations was being investigated at the end of FY80.

Six cores were taken during the drilling of EE-2, all at depths greater than those previously reached by boreholes GT-2 and EE-1. Chemical, petrographic, and x-ray-diffraction analysis of these cores, and of cuttings and junk-basket samples, indicate that a very complex geologic regime has been penetrated. Four of the cores contained both igneous and metamorphic units,

in some instances with very sharp contacts between the two. All showed ancient fractures, which in all but one were well sealed with secondary minerals, with a much lower abundance of calcite than in cores taken nearer the surface. One core showed two sets of vertical fractures with slickensided surfaces, representing an old fault system in the metamorphic rock. Analysis of the cuttings showed four extensively altered zones and eight moderately altered zones at depths below 3000 m. At least three of these contained illite-montmorillonite, a swelling clay. The effect of such zones on development and operation of an HDR reservoir is so far unpredictable, but may be significant.

Young's moduli of EE-2 core samples at room temperature were found to vary, at zero load, from about 4 to 15 GPa, and to increase by factors of 2 to 4 as uniaxial stress increased to 20 MPa. Poisson's ratio also increased with stress, from values typically less than 0.1 at low stress to the range of 0.1 to more than 0.4 at 20 MPa. Measurements on Berkeley granite, similar to the Fenton Hill reservoir rock, showed a marked orientation-dependence of both tensile modulus and fracture toughness, with a monotonic relation between the two. If this proves to be true also of the Fenton Hill rock, it could affect the orientation and surface nature of hydraulic fractures.

Monitoring of the recirculated fluid in a 75-day flow test, run before the Phase I system was enlarged, indicated that many of the dissolved species originated in an indigenous pore fluid, buffered by the rock. Plagioclase in the rock appears also to buffer the Na-K-Ca ratios in the circulating solution. A disproportionately low increase of Ca relative to Na suggests the formation of a Ca-bearing alteration product at depth, which agrees with results from a laboratory circulating system. Dissolution rates have been investigated by experiments in both the Phase I loop and, at 235°C and 275°C, in a laboratory autoclave. The rate constant for silica dissolution, in particular, remains in doubt, with a corresponding uncertainty concerning applicability of the quartz geothermometer to the Phase I reservoir.

A quite different type of geothermometer is now being investigated, which is expected to provide additional information on the thermal history of the Fenton Hill HDR reservoir. During examination of core samples it has been observed that pleochroic haloes have been formed in biotite around included zircon grains, by alpha-particle bombardment. In the laboratory, these have been shown to anneal out of the biotite progressively at temperatures between

134°C and 151°C, where they disappear completely. Their absence or presence and intensity in samples from known depths therefore provides a reference point in the geothermal history of the formation.

Room-temperature permeabilities have been measured as functions of effective confining pressure on six core samples from EE-2. In the 2- to 5-MPa range of pressures, permeabilities were 10^{-17} to 10^{-18} m²; near 30 MPa, they were 10^{-19} to 10^{-20} m². Most of the samples showed some foliation, but none were anisotropic in permeability. The reduction in permeability produced by pressurization in the laboratory was found to be irreversible.

Thermal stress cracking experiments have been conducted in the laboratory by water-cooling one face of preheated slabs of "Berkeley Blue" granite from Elberton, Georgia. Cracking history has been observed together with acoustic emissions from the cracking events, and near-surface principal tensile stress has been analyzed using the PORSAAS finite-element code, described below.

Environmental monitoring of the Fenton Hill site and its surroundings continued throughout FY80, in the following principal areas.

- Seismic Monitoring: Four new seismic stations were added to the Fenton Hill monitoring array during FY80, improving detection and location capability to the point at which microearthquakes as small as $M_L = -1.0$ can be detected and located at distances as great as 15 km from the site. In addition to a large number of natural microearthquakes well away from the site, six events with local magnitudes of -2.5 to -1.5 were located within 300 m south and east of GT-2 at depths of 2 to 3 km, caused by stress release during high-pressure experiments. Thirteen events with local magnitudes -1.5 to 0.5 were located about 300 m north of EE-2 during drilling of that hole, at about 1-km depth. These apparently were triggered by fluid injected near the sedimentary-Precambrian contact when about 9 million gallons of water were lost during a long period of drilling and remedial work accomplished without fluid return to the surface.
- Hydrology: No significant changes in the chemical quality of surface and ground waters have occurred in the vicinity of Fenton Hill during FY80.
- Microclimatology: A new meteorological tower was put on line at Fenton Hill during FY80, which makes and records observations at two

levels above ground. It continues to collect baseline data for environmental analysis of the Valles Caldera area in general.

- Biotic Monitoring: Recent studies have focused on the canyon area into which surplus water is occasionally released from the Fenton Hill site. This infiltrates into the valley alluvium within about 300 m from the discharge point. Soils within this limit show slightly elevated levels of cadmium and lithium. No effects on vegetation or mammals have so far been observed.

Aside from surface disturbance in the approximately 20 acres occupied by surface facilities, there have been no significant environmental effects from the Fenton Hill operation before or during FY80.

Technical support of the Fenton Hill Project has required the development of equipment, instruments, and materials not yet routinely available from commercial suppliers and service companies, both to withstand higher downhole temperatures than have normally been encountered elsewhere and to permit unusual experimental operations and types of measurements. This development has been done both at Los Alamos and, cooperatively or under subcontract, by other individuals and organizations. Major activities of this type during FY80 include the following.

- Two 13.7-cm-diam geothermal turbodrills, purchased from Maurer Engineering, Inc., were tested by drilling into granite blocks at the Drilling Research Laboratory in Salt Lake City, with support from Sandia Laboratory's DOE-sponsored Geothermal Drilling and Completions Program. They were subsequently tested in straight-hole drilling in borehole EE-2 at Fenton Hill, at a measured depth of 4.66 km and temperature of 317°C. Performance was satisfactory except for difficulty in controlling weight on the bits due to the extreme frictional drag on the drill pipe that resulted from the 35° inclination of the hole.
- An all-metal high-temperature turbodrill recently produced by the Dyna-Drill Division of Smith International was also tested at Fenton Hill, again with support from Sandia Laboratory. Both straight-hole and directional motors were tried, in borehole EE-3 at about 2.67-km depth and 170°C. Performance with a 12.25-in.-diam bit was marginal, but it appeared that satisfactory performance could be expected with an 8.75-in. bit.

- An instrumentation and data-acquisition system has been designed and installed in a well-logging truck (called a "wellside service unit"). This mobile unit provides great flexibility in well logging and other downhole observations and eliminates a great deal of downhole electronics from instruments used in the field.
- At this point the most critical remaining need with regard to downhole instrumentation systems is for a reliable high-temperature cable for signal transmission to the surface. A cable-test program has been initiated in which 340-m lengths of prototype cables of several designs were purchased from a number of manufacturers to be tested under a variety of temperature and pressure conditions at Southwest Research Institute, Sandia Laboratories, and Los Alamos. The goal is a cable, preferably containing a coaxial conductor, which will survive temperatures of at least 275°C and pressures up to 58.6 MPa over a usefully long service life. In the meantime, a 7-conductor cable manufactured by Vector Cable Co. has performed well for short residence times in borehole EE-2 at temperatures up to 320°C. It uses PFA Teflon insulation on the individual conductors in a TFE Teflon tape-wrapped outer jacket.
- Under contract to the HDR Program, L'Garde, Inc., produced elastomeric O-rings for high-temperature seals, made from their GEM 267 EPDM elastomer, and also provided that compound to Kemlon Products who molded connector boots from it. In laboratory autoclave tests at temperatures up to 340°C, pressures up to 55.16 MPa, and times up to 5 days, one O-ring failed by separation along the mold line, and all others were deformed but maintained a seal. In downhole tests in borehole EE-2 at hydrostatic pressure and temperatures to 317°C, used as seals on a cablehead, the connector boots failed and were replaced with Viton boots; all GEM 267 O-rings maintained good seals, but were permanently deformed and had to be replaced between runs.
- High-temperature geophones in a triaxial array have been used quite successfully in a downhole sonde to detect and locate the sources of acoustic signals produced by fracturing events in the reservoir rock. However, the moving-coil geophone suspension is unsuitable for use at inclinations greater than 20° to its intended orientation. Therefore, for acoustic measurements in the lower sections of the Phase II

boreholes (which are inclined at 35° to the vertical), the geophones will be replaced by accelerometers, which are insensitive to orientation. An accelerometer package, including amplifiers and a multiplexer, has been designed, packaged, and tested successfully at the surface.

- As a backup for commercial directional-drilling tools and also for independent use, a borehole-survey instrument has been designed, built, packaged to withstand temperatures to 300°C and pressures to 68.95 MPa, and calibrated. It contains a fluxgate magnetometer to measure borehole azimuth (slant-angle bearing) and tool rotation about its axis, and an inclinometer servo-drive system to measure borehole inclination (slant angle).

Support of the Fenton Hill operation has also involved development of models of several kinds to describe and attempt to explain the behavior of the Phase I system and to develop a predictive capability that can be applied to future systems.

- The REX (Rock Energy Extraction) computer code has been developed and used to study heat extraction as a function of time as fluid flows through a single hydraulic fracture, and the effect on it of the lateral cracks that may form as a result of thermal contraction of the adjacent reservoir rock.
- During the early part of FY80, the TSAAS finite-element code (Thermal Stress Analysis of Axisymmetric Solids) was used to calculate thermal stresses in granite blocks cooled on one surface, with results that agreed well with those of the laboratory experiments described above. The PORSAAS code (Porous Flow Stress Analysis of Axisymmetric Solids) was used to study porous elastic diffusion from pressurized fractures, and to simulate formation permeation during the 75 days of Run Segment 2 of the Fenton Hill Phase I system. The two codes were then coupled to analyze more complicated porous-thermoelastic problems, including the opening and closing of fractures during Run Segment 2.
- The ADINA code (Automatic Dynamic Incremental Nonlinear Analysis) was investigated initially as a means to calculate stress-intensity factors for a single crack, using linear-elastic fracture-mechanics theory. The numerical calculations gave results that agreed closely with those from analytic solutions.

- Development of a geochemical model of the Phase I system continued, leading to a general mathematical description of changes in the chemical composition of the circulating fluid as a result of both mineral dissolution and displacement of indigenous pore fluid. Application of the model to Run Segment 4 of the Phase I loop indicates that the assumption of two parallel flow paths, on one of which (through fractures) dissolution predominates while pore-fluid displacement from the rock matrix predominates in the other, adequately describes the geochemical behavior of the recirculated heat-extraction fluid.

Under contract to DOE, Plains Electric Generating and Transmission Cooperative, Inc., has undertaken a 1-yr study of the feasibility of constructing and operating a 5- to 10-MW(e) electrical generating plant at Fenton Hill utilizing heat from the Phase II heat-extraction loop. If results are favorable, a proposal will be made by Plains Electric for engineering design of such a plant.

Away from Fenton Hill, the HDR Program includes a broad evaluation of the commercial HDR energy potential of the United States, identification of areas that appear particularly promising for future HDR development, and detailed characterization of those that may be appropriate locations for a second energy extraction demonstration of the Fenton Hill type.

Resource evaluation, being conducted in conjunction with the U.S. Geological Survey (USGS), includes consideration both of high-grade regions characterized by high temperatures at shallow depths (and therefore potentially suitable for generation of electricity) and broad regions with moderately elevated geothermal gradients (which may be suitable for direct thermal applications). During FY80, resource investigations have continued in the following regions.

- Eastern Region: On the Atlantic Coastal Plain, the best prospects appear to be buried granitic plutons containing unusually high concentrations of radioactive minerals whose slow decay locally supplements the relatively low regional heat flow. Geothermal gradients up to $45^{\circ}\text{C}/\text{km}$ have been measured in shallow (300-m) holes, representing heat flows up to $79 \text{ mW}/\text{m}^2$. In the Appalachian Highlands, the highest heat-flow values found to date in the eastern United States were measured in the Conway granite of the White Mountain batholith, where they were determined to be 82 to $92 \text{ mW}/\text{m}^2$ --although, because of relatively high thermal conductivity, gradients were only 27 to $29.9^{\circ}\text{C}/\text{km}$. On the

Interior Plateaus, gravity lows in New York are found associated with geothermal gradients up to $41.2^{\circ}\text{C}/\text{km}$ and heat flows up to $81 \text{ mW}/\text{m}^2$. Slightly elevated gradients and heat flows have also been encountered in Ohio, Pennsylvania, and West Virginia.

- Midcontinent: Geophysical and geochemical anomalies have indicated the possibility of higher-than-normal heat flow in areas of western Nebraska, the Mississippi embayment (primarily in Arkansas), and eastern Michigan. These and a deep "well of opportunity" in Illinois are being investigated for the HDR Program by a university consortium.
- Rocky Mountains: Here the highest regional heat flow is associated with the youngest volcanism and tectonism, and occur in the Yellowstone Park area, the Colorado Mineral Belt, the San Juan Mountains, and the Rio Grande Rift. Intersections of linear tectonic features tend to localize geothermal areas. In the Northern Rockies, the Boulder (Montana) Batholith is a positive HDR target. In the Middle Rockies, the Yellowstone Park area is withdrawn from exploration, but the Yellowstone-Absaroka-Jackson area has extensive young volcanism and is probably underlain by a large HDR thermal resource. The Southern Rockies have great geothermal potential, particularly in the Rio Grande Rift and the San Juan volcanic field, although the southern part of the province has high geothermal gradients everywhere. The Colorado Plateau in Colorado also has above-normal heat flow and thermal gradients, locally above $100 \text{ mW}/\text{m}^2$ and $50^{\circ}\text{C}/\text{km}$.
- Southwestern States: In New Mexico, the Rio Grande Rift probably has the greatest HDR potential, especially in the areas of the Jemez Mountains, Socorro Peak, San Diego Mountain, and Mirage. However, there are also promising areas along the Jemez lineament, extending from the Springerville volcanic field in Arizona through the areas of the Zuni Pueblo, Mt. Taylor, and the Jemez Mountains. In Arizona, central Maricopa County west of Phoenix, eastern Pima County south of Tucson, west-central Yuma County, and the Aquarius area, are all very attractive.
- California, Nevada, and Utah: These states offer many promising high-grade geothermal areas for HDR exploration. Of particular interest are The Geysers-Clear Lake, Long Valley Caldera, and Salton Trough

areas in California; the Battle-Mountain heat flow high in northern Nevada; and the Roosevelt Hot Springs area in Utah.

- Pacific Northwest: Here the most promising areas for HDR development are the margins of the Snake River plain in Idaho and eastern Oregon, the Brothers Fault Zone in Oregon, and possibly some of the Mesozoic or Tertiary granitic plutons in Washington. Because much of the Northwest is underlain by stratified volcanic or metasedimentary rocks in which there is no experience with hydraulic fracturing or fluid containment, its true HDR potential remains to be determined by field experiments.

Data from all of the above regions have been collected, analyzed, and assembled into a preliminary geothermal gradient map of the United States, a necessary first step in estimating the HDR resource base of the conterminous United States. Only data from series of measurements down the borehole in a clearly conductive environment were used, so that many productive hydrothermal areas do not appear on the map. There are also many broad areas in which no reliable gradient measurements have so far been made in deep holes, and it is intended to update and improve this map annually as new data are collected.

The HDR resource base of the United States is distributed between relatively small, high-grade geothermal areas generally associated with igneous systems and broad regions of the type identified on the gradient map where the conductive geotherm gradient is greater than normal ($>30^{\circ}\text{C}/\text{km}$). To a depth of 10 km and for heat content above 15°C , it is estimated that the HDR resource base in young igneous systems in the conterminous 48 states is at least 33 000 quads. In regions where the conductive gradient is $>30^{\circ}\text{C}/\text{km}$, again to 10-km depth, the heat content above 15°C is estimated to be approximately 6 000 000 quads.

During FY80, five areas have been studied specifically as possible locations for HDR Experimental Site 2. These are

- Mountain Home, Idaho: An area of 400 km^2 east of Mountain Home, on the northern margin of the western Snake River Plain, has been investigated intensively by Harding-Lawson Associates. Geologic, geophysical, hydrologic, and water-chemistry studies were performed. Evaluation of the prospect area has not been completed, but it appears to be very promising for HDR development.

- Roosevelt Hot Springs, Utah: A high-temperature hydrothermal area in the Milford Valley just west of the Mineral Mountains in southwestern Utah is now being developed as an energy source for commercial electrical power generation. Several hot dry wells have been drilled on the periphery of the hydrothermal field, particularly in the valley west of the north-south-trending Opal Mound fault. Three of these wells, which bottom in low-permeability granite and gneiss, show conductive thermal gradients of 55 to 60°C/km. This area appears extremely attractive for HDR development by the general method developed at Fenton Hill.
- The Geysers-Clear Lake Region, California: The highly developed natural steam field at The Geysers in California is separated by the northwest-trending Collayami fault from a large and intense geothermal area that has proved to be relatively unproductive of natural fluids. Here, in an area of about 150 km² covered by the Clear Lake volcanic field, ten or more deep wells have been drilled by various energy companies, most of which have reached temperatures of at least 200°C at depths of 2000 m. Only one of them has encountered a significant production of fluid--which in that case was hot water rather than steam. The area is of special interest for an HDR experiment because the reservoir rock would be a metamorphosed graywacke quite unlike the basement rock at Fenton Hill.
- Wallops Island, Virginia: D'Appolonia Consulting Engineers have been investigating an area between Crisfield, Maryland, and Wallops Island, Virginia, as a possible region in which HDR systems might be developed to produce relatively low-temperature heat for direct use. The study has included drilling and logging of heat-flow holes, aeromagnetic surveys, a controlled-source time-domain electromagnetic survey, and seismic-reflection surveys. In conjunction with earlier Los Alamos fracturing and pressurization studies in DOE's Crisfield well, results appear promising for eventual low-temperature HDR development in the basement rock underlying the Eastern coastal plain.
- West-Central New York: Led by Dennis Hodge of the State University of New York at Buffalo, an exploration is in progress of geothermal possibilities in western New York. Well-defined geothermal-gradient anomalies have been found southeast of Buffalo (East Aurora), southeast of

Rochester (near Auburn), and east of Elmira. Although the geothermal gradient near Elmira is slightly higher than that near Auburn, depth to basement is much less near Auburn--which is considered the best prospect for HDR development so far discovered in New York.

An "Industrial Assessment of the Economic Feasibility of HDR Geothermal Systems" was undertaken by Bechtel National, Inc., and its subcontractors--GeothermEx, Republic Geothermal, and Intercomp. Its major purpose was to determine what combination of factors would be required to make HDR energy systems commercially viable by the year 2000. Unfortunately, because of budget constraints, it was necessary to terminate this study near the end of the fiscal year. Another economic study, undertaken by Los Alamos, was an examination of a potential cogeneration application of an HDR system at Crown Zellerbach's pulp and paper mill at Camas, Washington. With the assumptions made, it appears that an acceptable after-tax rate of return on the investment in such a system would be possible if a conductive gradient of not less than $37^{\circ}\text{C}/\text{km}$ can be found in an HDR reservoir within 40 km of the mill. Such reservoirs are believed to exist there.

During FY80, program personnel met on several occasions with advisory and review bodies and technically interacted with complementary and parallel programs in the United States and in several other countries.

The Fenton Hill Project International Steering Committee, currently consisting of representatives of the U.S. Department of Energy and of the Kernforschungsanlage-Jülich GmbH, met twice during the year. At its first meeting, in Los Alamos on January 17, 1980, it reviewed the status of the Fenton Hill Project and discussed details of West German participation in it. The second meeting, in Washington on July 19-20, 1980, focussed on planning for the Phase I and Phase II work at Fenton Hill.

The Executive Committee of the National HDR Program Development Council (PDC) met at Los Alamos on April 16, 1980. All major Program activities were reviewed, its financial position and funding projections were considered, and the fifth draft of the DOE's HDR Program Plan was discussed, commented on, and recommendations were made for its next revision. The PDC Technical Committee on Reservoir Engineering met at Los Alamos on November 27, 1979. This was a workshop at which discussions were concerned primarily with reservoir-rock properties, the geostress environment, and reservoir-testing and modeling techniques. The PDC Site Selection Committee met at Los Alamos on January 28-29,

1980. Sixteen areas considered promising for HDR development were discussed in depth. Of these, The Geysers-Clear Lake region in California was assigned first priority as the next area to be investigated in detail as a possible location for HDR Experimental Site 2.

On April 3, 1980, in Denver, Colorado, Program personnel reviewed the status and objectives of the HDR Program for a Geothermal Panel of the Energy Research Advisory Board (ERAB), which reports to the U.S. Secretary of Energy. There was general agreement by the Panel that Program goals and objectives were appropriate, that balance and pace of the HDR Program were satisfactory, and that recent experiments had been successful. Integration of the HDR Program with other related geothermal programs was considered weak but improving. The Panel specifically recommended that Site 2 be located at a shallow, high-temperature thermal resource, to demonstrate the economics of an HDR system in a relatively favorable thermal and geologic environment of potential interest to commercial energy companies.

A table of units and conversion factors used in this report is presented Appendix A.

2. INTRODUCTION

2.1. The HDR Concept

In the context of geothermal energy, HDR is naturally heated crustal rock that is not productive of natural steam or hot water at commercially useful rates. At varying depths, HDR exists everywhere 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 hot dry rock. Its principal objectives, therefore, are to confirm that the potential HDR resource is indeed large and accessible; to develop a commercializable 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 water is returned to the first well to be recirculated and reheated.

2.2. Synopsis of the HDR Program Through FY79

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. This enlarged Phase I system was flow-tested extensively during FY80, as is discussed in detail below.

Drilling the first well, EE-2, of a second circulation loop began at Fenton Hill in April 1979 and continued through the rest of the fiscal year. Its completion during FY80 is described below. 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, also began in FY80.

Progress of the Los Alamos National Laboratory HDR Project was sufficiently encouraging so that, at the beginning of FY79, the Division of Geothermal Energy of the U.S. Department of Energy (DOE/DGE) 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 by a Program Manager at the Los Alamos National Laboratory and an Associate Program Manager from DOE's Albuquerque Operations Office (DOE/AL00). 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 FY79, 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; an intensified 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 International Energy Agency (IEA) agreement, direct participation in the Fenton Hill Project by KFA-Jülich, the energy research agency of the Federal Republic of Germany, began in FY79. 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 the Government of Japan continued throughout FY79, as did cooperation with ENEL, the Italian National Energy Agency (under a bilateral agreement) and informal cooperation with individuals and organizations from other countries.

2.3. Objectives and Plans for FY80

Planning of the principal elements composing the HDR Program included the following major activities and objectives for FY80.

Program Management. Further revision of the long-range HDR Program Plan was to be undertaken to accommodate the changes in management structure imposed by the IEA agreement described above and the expected technical and funding position of the Program.

Determination of Resource Potential. Geological, geophysical, and heat-flow studies of geothermal areas throughout the U.S. were to be expanded, leading to publication of the first of a series of conductive geothermal gradient maps and preliminary estimates of the HDR resource base, accessible resource, and potentially economic resource.

Site Characterization and Selection. Detailed investigations were to be completed of two promising candidates for selection as HDR Experimental Site 2 and a similar investigation was to begin in a third geothermal area. Available data were also to be collected and evaluated on other possible Site 2 locations, including dry holes drilled in hydrothermal explorations and for other purposes.

Fenton Hill (Site 1) Project. Flow testing of the enlarged Research (Phase I) System was to continue for up to about 6 months to characterize it with regard to effective heat-transfer area, volume, flow paths and flow impedance, dispersion and mixing, rate of water loss, composition of the recirculated fluid, temperature drawdown, induced microseismicity, and changes in these with time. A skid-mounted 60-kVA Freon-114 binary cycle turboalternator was to be installed and operated on a bypass from the Phase I loop. Construction of the Engineering (Phase II) System was to continue through FY80 with completion of injection well EE-2 at a depth of about 4400 m (14 500 ft) and a rock temperature of about 275°C, drilling of production well EE-3 along a trajectory about 350 m (1200 ft) above it, and initiation of construction of the associated surface system.

Materials, Equipment, and Instrument Development. Existing downhole instruments were to be modified to withstand operating temperatures up to at least 275°C. A prototype downhole magnetostrictive acoustic transceiver was to be completed by a subcontractor and tested at the Los Alamos National Laboratory. Components for a downhole television camera (the Borehole Optical Survey System, or "BOSS") were to be tested by the subcontractor responsible for its design. Test specimens of commercially fabricated samples of a variety of high-temperature instrument-cable designs were to be investigated in a joint program among the Los Alamos National Laboratory, Sandia Laboratories, and the U.S. Geological Survey (USGS). The prototype Instrument Sonde Test Facility (ISTF) was to be tested and put into service for testing assembled instrument packages under realistic downhole conditions.

Analytical and Laboratory Support. Continued development of techniques for reservoir investigation and evaluation was planned, together with continuous improvement of mathematical and physical models representing the information derived from them. Laboratory studies of the chemical, mineralogical, physical, and mechanical characteristics and behavior of the reservoir rock were to continue. On-line monitoring of the chemistry of makeup and recirculating fluids was scheduled for all flow tests of the Phase I system, with development of models to describe chemical interactions in the underground loop.

Environmental and Institutional Activities. Seismic and ecological monitoring of the Fenton Hill area was to continue through FY80, and the Fenton

Hill environmental analysis was to be revised to include consideration of the drilling of EE-3 and the construction of a water-storage pond. Investigations of environmental, legal, regulatory, and institutional constraints on geothermal development were to continue, with special attention to HDR systems, water-rights legislation, and comparison of environmental residuals from HDR with those from other energy systems.

Precommercialization. Fiscal year 1980 was to be the first year of a planned 2-yr "Industrial Assessment of the Economic Feasibility of Hot Dry Rock Geothermal Systems" by an industrial subcontractor. Plains Electric Generation and Transmission Cooperative, Inc., was expected to initiate a separately funded study of the feasibility of constructing and operating a 4- to 10-MW(e) pilot electrical-generating plant at Fenton Hill if the Phase II heat-extraction system proves capable of supplying its energy requirement. The Fenton Hill Project was committed to assisting in this study where it could be helpful, particularly in supplying up-to-date information on Phase I loop operation, Phase II system design and construction progress, and environmental monitoring of the Fenton Hill area. Liaison was also to be maintained with other organizations interested in HDR development, and Program progress was to be reported frequently at meetings and symposia and in published articles, papers, reports, and news bulletins.

3. DETERMINATION OF RESOURCE POTENTIAL

3.1. Resource Assessment

The purpose of this part of the program is to coordinate the collection and compilation of geological and geophysical data necessary to identify and estimate the magnitude of the HDR resource in the U.S. and to distribute these data to those interested in developing that resource.

To evaluate the resource, we must first determine the resource base, i.e., the total heat content within regions having thermal gradients of $>30^{\circ}\text{C}/\text{km}$ to a depth of 10 km. The 10-km depth was chosen to be consistent with the geothermal resource estimates of the USGS.^{1,2} Most of the effort in FY80 was aimed at determining the resource base.

Within the thermal anomalies, we must determine depths to rock types that can serve as HDR reservoirs. This aspect of the work is incomplete for FY80, but should be ready at the end of FY81. When HDR reservoir rock units have been identified, it will be necessary to work with the reservoir analysis group to determine the accessible resource base.

After establishing the accessible resource base, it will be necessary within that base to construct an engineering model of extractability, to evaluate distribution of potential users, demography, and political and environmental problems in order to estimate the economic resource. The final resource estimates will be available in FY84.

Since the creation of the national HDR program, we have divided the resource evaluation effort into two parts: (1) evaluation of high-grade regions characterized by high temperatures at shallow depths, to be developed for the generation of electricity and (2) broad regions with elevated thermal gradients, to be developed for direct uses.

For the resource evaluation, individual Laboratory staff members are responsible for both types of HDR resource within regions (e.g., Pacific Northwest, Far West, Rocky Mountain States). Within those regions, team members collect existing data, coordinate data collection with other government-sponsored resource evaluations, and schedule new work to fill in areas where data are sparse or missing. In 5 yr this work will be completed, and we shall have a comprehensive evaluation of the HDR resource base and resource.

3.1.1. Eastern Region. Most hot dry rock geothermal resource assessment activities in the eastern United States are in the Atlantic and Gulf Coastal

Plains, the Appalachian Highlands, and the Interior Plateaus. The Coastal Plains are underlain by young, semiconsolidated sediments that dip gently toward the sea. The term Appalachian Highlands, as used here, arbitrarily includes New England, the Appalachian Piedmont, the folded Appalachian Mountains, and the Adirondack Mountains. The Allegheny, Appalachia, and Cumberland Plateaus comprise the Interior Plateaus. There is little visible evidence of geothermal energy in these regions; volcanic activity stopped 200 Myr ago and only a few warm springs exist, most of which are near Saratoga Springs, New York, and in the east-central Appalachian Mountains. Consequently, assessment of geothermal energy in the eastern states has relied upon geophysical measurements, primarily temperature, gravity, magnetic, and electric methods. Measurement of temperature gradients and calculation of heat flow has been the primary method of finding areas of above average geothermal potential.

Atlantic and Gulf Coastal Plains. The geology of the coastal plain consists of unconsolidated to semiconsolidated sediments that dip seaward (less than 2 m/km to locally more than 20 m/km). The sediments on the Atlantic Coast range from predominantly silt and clay in New Jersey to limestone with some sands and silt in Florida. The age, total thickness, and percentage of limestone generally increases southward (Table 3-I). The sediments lie on a gently seaward-sloping basement surface of crystalline metamorphic and igneous rocks. Little is known about these basement rocks because they have been reached by only a few widely spaced drill holes. These limited drill holes and other geophysical data indicate that the coastal plain basement is

TABLE 3-I
COASTAL PLAINS SEDIMENTS

	<u>New Jersey</u>	<u>Georgia</u>	<u>Mississippi</u>
Age (Myr)	0-80	0-100	0-130
Shoreline thickness (m)	500	900	>5000
% Limestone	5-10	10-30	20-40
% Sand	10-20	10-20	5-15

similar to the crystalline rocks of the adjacent Piedmont province. In the Piedmont, 300-Myr granitic plutons containing heat-producing radioactive minerals have intruded into the older metamorphic rock. These plutons locally cause above-average thermal gradients and also cause characteristic subcircular residual negative Bouguer gravity anomalies. Above-average geothermal gradients, found with similar gravity "lows" in the coastal plain, are believed to be the result of similar granitic plutons buried under the sediments.

Geothermal gradients have been measured in shallow (300-m) holes drilled near gravity "lows" (Fig. 3-1)^{3,4} and in available oil and gas wells.* Gradients as high as 37° to 45°C/km have been found. Thermal conductivities measured on samples from these wells have permitted calculations of heat flow. Values reported by the Virginia Polytechnic Institute and State University (VPI&SU) group range from maxima of 79 mW/m² at Stumpy Point, North Carolina; 77 at Wallops Island, Virginia; and 75 at Withams, Virginia, to average values near 40 mW/m². At the present time, the best prospects for hot dry rock resources in the coastal plain seem to be the buried granitic plutons. Because of locally high gradients and heat flow, the "Cris-Wal" area (between Wallops Island, Virginia, and Crisfield, Maryland) has been selected for detailed study. The gradient at Wallops Island is 35°C/km with a projected temperature of 90° at a depth of 2.2 km.

Appalachian Highlands. This region includes all the older, deformed, and repeatedly uplifted rocks of the eastern United States. As used

Fig. 3-1.
Abnormally high geothermal gradients in the eastern United States.³ Contours are in °C/km.

*D. L. Smith, 1979, "Initial Heat Flow Survey of Portions of the Gulf Coastal Plain," (unpublished data).

here it excludes the Interior Plateaus that have been uplifted with little deformation. The region includes all of New England, the Appalachian Piedmont, the Blue Ridge, the Ridge and Valley province, and the Adirondack Mountains. The rocks include Paleozoic and Precambrian metasediments and igneous intrusive rocks, with smaller remnants of Triassic sedimentary rocks, and volcanic rocks preserved in downfaulted troughs.

Attention has been focused on the Conway granite of the White Mountain batholith, New Hampshire, since the early 1960's when it was assessed as a possible source of thorium. It has the highest known concentrations of radioactive elements of any U.S. batholith. Gradients measured in this granite range from 27 to 29.9°C/km in 300-m drill holes. Heat flux after correcting for topographic and geologic effects ranges from 82 to 92 mW/m², the highest values found to date in the eastern U.S. A detailed gravity survey by Wetterauer and Bothner⁵ has shown the plutons near North Conway to be approximately 5 km thick, with a projected temperature of 170°C at 6-km depth. Measurements of gradients in available wells and demonstration drilling of one or two additional gradient holes are being planned by the Laboratory for late 1980. Measurement of gradients in available wells throughout southern New Hampshire, Vermont, and Massachusetts is in progress.

In the central Appalachians most of the work has been done by VPI&SU. Shallow drilling and surface sampling of six granitic plutons in the Piedmont have shown a linear relationship between heat flow, q , and heat generation, A , of $q = 0.69 + 6.9 \times 10^5 A$, with A ranging from 0.25 to 1.1×10^{-12} cal/cm³ s [2.5 to 11 heat generation units (HGU)]. A study of the warm springs in the folded Appalachians has shown that they are the result of deep circulation of meteoric water controlled by major fault zones transverse to the folds. A gabbro drilled near Baltimore, Maryland, was found to have relatively high conductivity, so the gradient and temperatures at depth were lower than had been anticipated. A survey of bottom-hole temperatures of oil and gas wells in the folded Appalachians has been started in West Virginia. Gradients found thus far range from 18 to 25°C/km.

Interior Plateaus. The Interior Plateaus extend westward from the folded Appalachian Ridge and Valley section and southward to Alabama from the northern boundary of New York. They are underlain by a sequence of nearly horizontal Paleozoic (250 to 550 Myr), well-indurated shales, sandstones, and some limestones 2 to more than 5 km thick. Under this blanket of sedimentary

rock is a folded, metamorphosed basement of crystalline rocks that has been reached by only a few widely scattered drill holes. Little is known about this basement; it is assumed to be generally similar to that of the Piedmont.

Most of the geothermal exploration in this region has consisted of compiling bottom-hole temperatures from existing wells and measuring gradients in new wells to determine areas of above normal gradients. Heat flow has been calculated for several widely spaced wells for which the conductivity of cores or cuttings has been determined. Average and maximum gradients and heat flux are given in Table 3-II.

Gradients slightly above average are found along the crest of the Cincinnati arch in Ohio. Existing magnetic, seismic, and gravity surveys have been examined for correlations with other geothermal data, with little success, except that gravity lows in New York are found associated with above-normal geothermal gradients.

3.1.2. Geothermal Assessment of the Midcontinent Region. A significant start was made in FY80 toward assembling of geologic, geochemical, and geophysical information about the midcontinent region of the United States. The midcontinent reporting area includes the states of North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Arkansas, Missouri, Iowa, Minnesota, Wisconsin, Illinois, Michigan, Indiana, Kentucky, Tennessee, and those portions of Texas, Louisiana, Mississippi, and Alabama that are not included in the "geopressed" zone (Fig. 3-2). In the first 6 months of a projected 4-yr program, 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, has begun compiling various geophysical, geochemical, and geologic data and bibliographies for the general area from the Rocky Mountains to the eastern boundary of the area mentioned above. In addition to general coverage of the area, they have also started more detailed work on several test sites within the area. These areas include western Nebraska, the Mississippi embayment--primarily the Arkansas portion, eastern Michigan, and a "hole of opportunity" in Illinois. All of these areas have geophysical or geochemical anomalies that indicate the possibility of higher heat flow than normal in the region.

The Kansas Geological Survey has assembled oil well data and aeromagnetic data from the whole state and, with assistance from the Los Alamos National Laboratory geothermal effort, has deepened two drill holes in order

TABLE 3-II

SOME TYPICAL THERMAL GRADIENT AND HEAT-FLOW MEASUREMENTS
IN THE EASTERN UNITED STATES

	Thermal Gradient (°C/km)		Heat Flow (mW/m ²)	
	Average	Maximum	Average	Maximum
New York	23.06	41.2	59.3	81.0
Pennsylvania	20.04	38.9	57.9	61.2
Ohio	20.66	37.5	56.7	56.7
West Virginia	N.A.	N.A.	53.8	58.7

Fig. 3-2.

Location of mid-continent HDR reporting area, subcontracts, and test sites.

to obtain measurements and samples from within basement rocks. Petrologic and age data as well as other geophysical and geochemical data are included in the contract report,* a forthcoming report on thermal conductivity and heat flow, and eventually a geothermal gradient map of Kansas.

3.1.3. HDR Resource Evaluation of the Rocky Mountain States: Colorado, Wyoming, and Montana. Parts of six geomorphic provinces, representing a variety of structural styles and geology, comprise the Rocky Mountain states of Colorado, Wyoming, and Montana (Fig. 3-3): the mountainous Northern Rockies (NR), Middle Rockies (MR), and Southern Rockies (SR), and the non-mountainous Wyoming Basin (WB), Colorado Plateau (CP), and Great Plains (GP).

High seismicity characterizes the "Intermountain Seismic Belt"⁶ of the Southern Rockies and western Wyoming and Montana; the Great Plains are largely aseismic, whereas much of the rest of the region has moderate seismicity.⁷ Regional Bouguer-gravity lows and Airy-Heiskanen negative isostasy characterize the Wyoming Basin and Southern Rockies, with minor lows in the Great Plains and Northern Rockies.^{7,8} Electrical, gravitational, and seismic evidence indicates that the crust thickens from west to east over the tri-state region.⁹ A narrow north-northeast-trending magnetic high in Colorado coincides with a center line of seismic attenuation;¹⁰ both are possible geothermal indicators. The northeast-trending Eastern Snake River Plain aeromagnetic anomaly¹¹ is the locus of much young volcanism, including Yellowstone, and may reflect Precambrian structure.

Major zones of weakness in the crust (Precambrian relics) and major plate motions and/or extensional rifting have considerably affected the thermal regime in the tri-state region.¹² The Rockies are in the "Cordilleran Thermal Anomaly Zone,"¹³ the overall high heat flow being related to subduction, back-arc volcanism, and rifting over the last 150 Myr. Highest regional heat flow is related to the youngest volcanism and tectonism: Yellowstone and the San Juan Mountains (thick volcanic sequences, calderas), and the Rio Grande Rift (tectonic extension) (Figs. 3-4, 3-5).

Major fault zones (especially of Quaternary age) and basement structures and lineaments, perhaps related to plate motion, tend to localize geothermal

* D. W. Steeples and M. E. Bickford, "An Effort to Recover Precambrian Rock Material by Deepening Two Boreholes in Kansas," Univ. of Kansas, August 29, 1980, (unpublished data).

Fig. 3-3.

Geomorphic provinces and areas of geothermal interest. Abbreviations (alphabetized): B = Beartooth Mts., B-E = Boulder Batholith/Elkhorn Mts. Volcanics complex (Marysville-Helena-Butte area), BH = Bighorn area, BL = Black Hills, BR = Bitterroot Range, B-T = Bridger-Tetons, BV = Beaverhead-West Yellowstone, CC = Craig (Colorado) area, CCB = Canyon City Basin, CM = Crazy Mts. Basin/Upper Yellowstone River basin, CMB = Colorado Mineral Belt, DB = Denver Basin, F = Front Range, GH = Gas Hills area, GR = Green River Basin geopressurized area, J = Jackson area, JL = Judith Mts./Little Rockies, LA = Laramie Mts., LO = Lolo Valley, LH = Leucite Hills, M = Medicine Bow Range, OB = Overthrust Belt, PRB = Powder River Basin, RGR = Rio Grande Rift, RS = Rock Spgs., SJV = San Juan Volcanics, SLV = San Luis Valley, SC = Salt Creek oilfield, T = Thermopolis/Bridger Mts./Owl Creek Uplift, Th = 39-mile volcanic field, U = Uinta Basin geopressurized area, W = Williston Basin, WR = White River Uplift, Y-A = Yellowstone/Absaroka area.

Note: Not all areas shown are discussed in text. Geomorphic provinces: abbreviations in text. Boundaries after Mallory et al. 1972.⁷

Fig. 3-4.

Heat flow and active hydrothermal areas.^{6,7,16}

Fig. 3-5.

Geothermal gradients based on selected temperature measurements in drill holes.

areas. Significant crustal features include several with northeast trends (four transform-fault zones,¹⁴ the Colorado Lineament/Mineral Belt, the Jemez Lineament, and the Eastern Snake River Plain); the northwest-trending Olympia-Wichita Lineament;¹⁵ and the Rio Grande Rift. Intersections of such linear tectonic features, which serve as heat conduits, are particularly conducive to high heat flow (Figs. 3-4, 3-5). The thermal regime is also influenced by crustal thinning related to rifting and extension, and possibly by heat generated during plate motion.

A variety of potential geothermal reservoir rocks reflect a complex thermal regime: Mesozoic batholiths, Tertiary intrusives, Precambrian basement, upper Cenozoic volcanics, and deep sedimentary basins.

Northern Rocky Mountains. Heat flow in the Northern Rockies is rather homogenous and moderate at 1.8 to 1.9 HFU (mantle-heat flow, about 1.4 HFU).¹⁶ Late Cenozoic age volcanism is volumetrically limited, but there are numerous Tertiary granitic plutons. Although there are no extensive, abnormally hot hydrothermal areas in the province, several hydrothermal systems are associated with the Intermountain Seismic Belt in Montana. Thermal springs are located generally along faults and associated with Laramide age intrusive rocks.

Characteristically isolated, shallow, and small, the hydrothermal convection systems have reservoir temperatures commonly 85° to 160°C (some values >200°C).¹⁷ Most geothermal activity centers on the Boulder Batholith/Elkhorn Mountains Volcanics complex in the Helena-Butte area, which includes Marysville and Boulder Hot Springs known geothermal resource areas (KGRAs).² This late Cretaceous/early Tertiary igneous system is characterized by high heat flow and thermal gradients (Fig. 3-5). Without surface manifestations, the Marysville thermal anomaly (≤ 20 HFU; $\leq 240^\circ\text{C}/\text{km}$) is apparently related to deep hydrothermal convection.¹⁸ In the Marysville area, the highest heat flow correlates with negative gravity (though lower to the south) but has high resistivity, low seismicity and lack of microearthquakes;¹⁸ these conflicting or unusual geophysical results are caused by convection rather than conduction. The Boulder Batholith is a positive HDR target.

Middle Rockies. The Middle Rockies include the abnormally hot, extensive and active geothermal system of the Yellowstone caldera complex. Although Yellowstone Park is withdrawn from exploration, in Montana are two KGRAs bordering the park in Montana: Corwin Springs and Yellowstone.²

Outside the park, heat flow is low to normal (1.2 to 1.7 HFU) in the northeast to moderate or high in the central and southwest portions of the province;^{2,6} gradients $\geq 30^\circ\text{C}/\text{km}$ are characteristic.¹⁹ Although low-temperature geothermal systems are common, few (except Yellowstone) are $\geq 90^\circ\text{C}$. The Yellowstone-Absaroka-Jackson area has extensive young volcanism and is probably underlain by shallow cooling silicic magma and/or Precambrian crystalline rocks. In Yellowstone Park heat flow varies from 2.5 HFU to 50 HFU, averaging 6-10 HFU. With the highest thermal energy of any in the U.S., this system is thought to be only 3.5% hydrothermal (mostly hot water-, though locally vapor-dominated) with surface and subsurface temperatures of 73° to 421°C (includes measured and calculated values).^{2,6} Geophysical and heat-flow data indicate that it is sharply bounded to the east and northeast, but in the tectonically (seismically) active north, west, and south are Huckleberry Hot Springs (150°C reservoir)² and the two bordering KGRAs.

Wyoming Basin. With fairly continuous low-to-normal heat flow (1.3 to 1.6 HFU) and gradients mostly $\leq 30^\circ\text{C}/\text{km}$ over much of the province, there are low-temperature systems throughout the Wyoming Basin, but few are $\geq 90^\circ\text{C}$. There is above-normal heat flow (1.5 to 1.7 HFU) and correspondingly above average gradients ($\geq 30^\circ\text{C}/\text{km}$) in the west and southwest, perhaps partly

explicable by the geopressured area in the northern Green River Basin. Hot spring activity is limited to the north-central part, around the anomalous Gas Hills (1.2 to 3.4 HFU, averaging 1.9),^{20,21} where there are Tertiary volcanics and Precambrian exposures. The Leucite Hills, also a Tertiary volcanic field but lacking surface thermal phenomena, may be a low-temperature prospect.^{20,21} The province is characterized by low gravity and low-to-no seismicity.^{7,8}

Southern Rockies. The Southern Rockies have considerable geothermal potential, with late Cenozoic volcanism and calderas, extensional rifting and normal faulting, deep sediment-filled grabens, deeply circulating thermal waters, and unusually high heat flow. Reiter's "Southern Rocky Mountains Complex thermal anomaly,"²² centered on the Rio Grande rift (1.6 to ≥ 2.5 HFU; reduced, up to 2 HFU), is complicated to the west by the high thermal flux in the San Juan volcanic field (2.1 to ≥ 2.5 HFU) and to the east by a 2- to 2.3-HFU zone.²²⁻²⁴ There are four KGRAs in the northern Rio Grande rift: Mineral, Valley View, Poncha Hot Springs, and Alamosa County.^{1,2} According to Decker,²⁰ there is a sharp transition, defined by geophysical and heat-flow data, across the Nash Fork shear zone (which essentially parallels the Colorado/Wyoming border); for example, Wyoming's Laramie and Medicine Bow Ranges display only 1.1 to 1.5 HFU, whereas in Colorado's Park and Front Ranges, heat flow is 2 to ≥ 2.5 HFU. Most of Colorado's 200 thermal springs are associated with middle to late Cenozoic volcanism and young tectonism in the Rio Grande rift, the San Juan Mountains, and/or the Colorado Mineral Belt.^{1,24,25} Geophysical characteristics also confirm broad geothermal areas: high seismicity, low seismic velocity, low gravity, a shallow conductive layer, etc. The southern part of the province has high gradients everywhere, locally $>65^{\circ}\text{C}/\text{km}$.^{2,19} Two factors of particular interest to HDR are the extensive exposed or near-surface Precambrian basement (especially Front and Laramie Ranges), and the low-permeability sediments² blanketing a supposed shallow cooling magma body in the Rio Grande rift.

Colorado Plateau. The Colorado Plateau province is characterized by above normal heat flow (>1.5 HFU) in Colorado, related to active normal faulting and late Tertiary/Quaternary volcanism. Locally, heat flow is notably high (2.2 to >2.5 HFU along the eastern margin), and gradients as high as $>50^{\circ}\text{C}/\text{km}$ have been reported.²⁶ In the northeastern Uinta Basin, there is a possible geopressured area with heat flow >1.5 HFU. However, a lack of

basement exposure and thick sedimentary cover make this province a low-priority target.

Great Plains. Generally, low-to-average, moderate-to-high heat-flow values (1.8 to >2.5 HFU) and/or high thermal gradients (>45°C/km) are reported in some areas. The Madison and Dakota formations are large-volume thermal aquifers underlying much of the Great Plains. The province may have HDR geothermal potential beneath deep sedimentary basins. The basement is generally in the 4700- to 5000-m-depth range in the Williston and Powder River Basins but may be shallower (<2200 m) in central Montana and eastern Colorado (Denver Basin).

Conclusion. The best HDR geothermal prospects (see Fig. 3-3) are in the Rio Grande rift, Colorado Mineral Belt, and the San Juan volcanic field; the Yellowstone-Absaroka-Jackson area; and the Marysville-Helena-Butte area (the Boulder Batholith/Elkhorn Mountains Volcanics complex). More geophysical and heat-flow work is needed throughout most of this tri-state region to better define (or discover) HDR geothermal targets.

3.1.4. Southwestern United States. Parts of five physiographic provinces are encompassed by the states of Arizona, New Mexico, and the Trans-Pecos region of Texas: the Colorado Plateau, Basin and Range, southern Rocky Mountains, Rio Grande rift, and the Great Plains (Fig. 3-6). This physiographic diversity is a reflection of the complex and varied geology within the region. Differences are most apparent between the relatively undisturbed Colorado Plateau and Great Plains and the intensely faulted and disturbed Rio Grande rift and Basin and Range provinces.

Considerable direct and indirect evidence is available indicating enhanced crustal temperatures within the region. For a region of this size, there is a relatively large number of heat-flow measurements available in the literature. Somewhat arbitrarily we have contoured those areas with heat flow in excess of 83.8 mW/m^2 (2 HFU). In Arizona there are six such areas, five of which occur within the more recently, structurally active Basin and Range province; one lies on the Colorado Plateau near Sanders, Arizona. These areas are shown in Fig. 3-7. Three areas of >2.5 HFU, central Maricopa County west of Phoenix, eastern Pima County south of Tucson, and west central Yuma County, are particularly attractive because of the consistency of the data, size of the anomalous region, and/or the proximity of a large population center.

Fig. 3-6.
Geomorphic provinces of the southwestern United States.

In New Mexico, heat-flow values above 83.8 mW/m^2 form a more continuous pattern than in Arizona. As shown by Edwards et al.,²⁷ these high values are concentrated in two bands or regions. The largest of these is essentially coincident with the Rio Grande rift in the southern two-thirds of the state and broadening out in the north to encompass the late-Cenozoic volcanic fields in north-central and northeastern New Mexico. This broadening is thought to be related to the Jemez Volcanic lineament crossing the rift at the Jemez Mountains and continuing on toward the northeast. The second region of high

Fig. 3-7.

Contoured heat-flow data in heat-flow units (10^{-6} cal/cm²s). Shaded areas indicate volcanic fields of less than 5 Myr.

heat flow is in west-central New Mexico, approximately coincident with the Jemez lineament.^{28,29}

For a number of reasons, the band along the Rio Grande rift probably has the highest potential for HDR. First, this band represents the largest area in the state with heat flow greater than 83.8 mW/m^2 . Second, some of the highest heat-flow values are concentrated near the west side of the rift, particularly near young volcanic centers or the intersections of cauldron boundaries with the rift.³⁰ Heat-flow values in excess of 251 mW/m^2 (6.0 HFU) are reported at four sites along the rift: the Jemez Mountains, Socorro Peak, San Diego Mountain, and Mirage. Third, sediments in the deep basins along the rift may serve as insulating blankets for the heat sources. Fourth, the major population centers of the state lie within the rift, providing users for the resource.

The smaller area in west-central New Mexico also appears to have HDR potential. Heat-flow values as high as 126 mW/m^2 near Zuni Pueblo, at the approximate center of the area, have been reported by Reiter et al.³¹ Late Cenozoic basaltic volcanism was common throughout the area, beginning at about 3.8 Myr B.P., with major activity at about 1.5 Myr B.P.^{28,32} This activity continued up until approximately 700 A.D. when the McCartys flow was erupted.³³ Precambrian basement rocks, which may have low permeability because of extensive Laramide mineralization, crop out in the center of the Zuni Mountains and are only shallowly buried by Paleozoic sediments around the flanks of the mountains. Because of the coincidence of regionally high heat flow, young volcanism, potentially suitable reservoir rocks, and major users in the towns of Grants and Gallup and the uranium mills and mines, Laughlin and West²⁸ proposed this area as an HDR site.

In addition to these large regions of high heat flow, numerous igneous centers younger than 5 Myr have the potential of being HDR heat sources (Fig. 3-6). All available radiometric ages less than 5 Myr were compiled for the region to provide insight into the distribution of these young igneous rocks.

In Arizona there are six areas with significant volumes of young volcanic rocks. Three of these, Mohave County, San Francisco Peaks, and the Springerville volcanic field, lie on the boundary of the Colorado Plateau and the Basin and Range provinces. Two of these are wholly basaltic and only the San Francisco Peaks volcanic field has intermediate to silicic volcanic rocks. Three other basaltic fields, the Sentinel Plain - Arlington, San Carlos - Peridot, and the San Bernardino, occur within the Basin and Range province in central and southern Arizona. Both the Springerville and the San Bernardino fields extend into New Mexico.

Igneous rocks less than 5 Myr are concentrated in 10 major areas in New Mexico; 2 of these were listed above. The remainder of the fields lie within the Rio Grande rift or along the Jemez lineament on the Colorado Plateau or Great Plains. Within the rift, beginning in the south, these are the Potrillo basalt field, the Jornada del Muerto flow, Carrizozo and Broken Back Crater flows, the flows near Albuquerque, the Jemez Mountains, and the Taos Plateau flows. Along the Jemez lineament, the Springerville volcanic field extends into New Mexico, merging with the Zuni Centers, Bandera lava field, and Mt. Taylor. The Jemez Mountains lie on the intersection of the lineament and the rift while to the northeast, the Mora County and Raton-Clayton fields also lie

on the lineament. Activity within all the New Mexico fields was predominantly basaltic except for Mt. Taylor and the Jemez Mountains where large volumes of silicic rocks were erupted. Small volumes of silicic rocks were also erupted in the Taos field.

No volcanic rocks less than 5 Myr have been reported for the Trans-Pecos region of Texas.

In Arizona, New Mexico, and the region of Trans-Pecos, Texas, work is continuing on better defining the timing and duration of volcanism, and the extent of the regional scaled areas of high heat flow. Depths to basement rocks and the nature of the basement are also being examined. To allow prediction of the orientation of manmade fractures, the present and past stress fields are under investigation.

3.1.5. HDR Geothermal Prospects in California, Nevada, and Utah. California, Nevada, and Utah offer many promising high-grade areas for HDR exploration. The purpose of this report is to present briefly the major characteristics of five of the HDR prospects in the region: The Geysers-Clear Lake, Long Valley Caldera, and Salton Trough in California; the Battle Mountain Heat Flow High in Nevada; and Roosevelt Hot Springs in Utah. In California, The Geysers-Clear Lake and Salton Trough geothermal fields are associated with transform fault zones, whereas Long Valley Caldera and Coso Hot Springs are located on the boundary between the Sierra Nevada and Basin and Range tectonic provinces.

The Geysers-Clear Lake region, located in the California Coast Ranges, contains the largest commercially exploited geothermal regime in the world with approximately 800 MW(e) installed and 2000 MW(e) expected in the future. The Geysers is a vapor-dominated system whereas systems to the east beneath the Clear Lake Volcanics are water-dominated. Potential reservoir rocks consist of impermeable meta-sediments and greenstones of the Franciscan assemblage and, less likely, the Great Valley sequence. The geology of these rocks is extremely complicated due to early Tertiary thrusting and late Tertiary strike-slip faulting. North and east of The Geysers lies the Clear Lake volcanic field, which has been active from about 2 to 0.01 Myr B.P.³⁴ Gravity, teleseismic, electrical resistivity, and magnetic studies coupled with an abundance of thermal springs strongly indicate that a shallow silicic magma chamber still exists below the Clear Lake Volcanics.³⁵

Drilling at The Geysers shows the temperature is 240°C to a depth of nearly 4 km, whereas beneath the Clear Lake volcanic field the basement rocks

are 200°C at 2 km throughout a region of 100 km².³⁵ Such high temperatures at shallow depths in rock units with low permeabilities make The Geysers-Clear Lake area particularly attractive for HDR. However, because the impermeable basement is not crystalline rock, this system is unique among the potential reservoir HDR sites presented from California, Nevada, and Utah. Further discussion of this region and the prospects for HDR will follow.

The Salton Trough in southern California is located over the East Pacific Rise at the southern end of the San Andreas transform fault zone and is a deep rift valley filled with fluvial and lacustrine sediments of the Colorado River delta. The tectonics of the Trough are dominated by en echelon transform faults with active right-lateral strike-slip movement. Extensional faulting and a thinned crust allows injection of basaltic magmas into overlying basin-fill sediments. Four rhyolite and one dacite domes have also erupted. Two major geothermal fields have been identified in this area: Salton Sea in the north and Cerro Prieto geothermal field in Mexico, which currently produces 150 MW(e) with an additional 170 MW(e) planned by 1985. High-temperature brines (295 to 365°C) associated primarily with pull-apart basins between strike-step fault zones have been encountered between 1.5- and 3-km depth.³⁶

Surface volcanism consists of only five small silicic eruptions that occurred in the north-central Trough (0.06 Myr B.P.) and near the Cerro Prieto field (maybe as young as 0.01 Myr B.P.)³⁶ The hydrothermal systems are apparently not associated with the silicic volcanism. Depth to basement in the Trough is not known but is at least 6 km in the north and greater than 3 km in the south. The effective permeability of the basement rocks is unknown, although down-faulted slices of Mesozoic rocks along the margins of the Trough are thought to be relatively impermeable. Active metamorphism of Salton Trough sediments reduces their permeability so that the hotter regions store less water.³⁷ Thus, HDR reservoirs rocks may exist at depth.

Long Valley Caldera in east-central California lies on the border between the Sierra Nevadas of California and the Basin and Range tectonic province of Nevada-California. The Long Valley Caldera and volcanic field is similar in some respects to the Valles Caldera system in New Mexico and HDR development of the area west of Long Valley Caldera would probably be analogous to the project in progress at Fenton Hill. Long Valley Caldera consists primarily of rhyolitic ash-flow tuffs and domes ranging in age from 2 to about

450 Myr B.P.³⁸ North, south, and west of Long Valley Caldera granitic rocks of the Sierra Nevada batholith crop out. Seismic and gravity data suggest a silicic magma chamber that may still be active below the western part of the caldera. Measured heat flow just west of the caldera is 3.75 HFU, almost four times the expected value for the Sierra Nevadas.³⁹ These data indicate a significant heat source below the western caldera, providing a temperature of about 200°C at 3.5 km in crystalline Mesozoic basement.

The Battle Mountain High of Nevada lies within the Basin and Range tectonic and heat-flow province of the U.S., which is characterized by crustal extension and thinning and a high average heat flow of 2.2 HFU. The Battle Mountain heat-flow high trends northeast across northern Nevada. It was an area of major silicic volcanism between 6 and 17 Myr ago and averages 2.5 to 3.5 HFU.⁶ Seismic data indicate a 30-km-thick crust that thickens by 8 to 10 km to the north and south from the Battle Mountain Trend.^{40,41} Sixteen hot springs with calculated geothermometry temperatures of 140 to 215°C lie within this region.⁴² Extensive geological, geophysical, and hydrological studies in Grass Valley, the Southern Black Rock Desert, and Beowawe Geyser area in the Battle Mountain High indicate that major range-bounding faults act as conduits for hot water that is heated to temperatures of 150 to 200°C at depths of only 2 to 6 km.⁴³⁻⁴⁵ Hot dry rock development in northern Nevada may be successful if located (1) within a low-permeability reservoir rock such as local Cretaceous granitic intrusions or within basin-fill sediments sealed by hydrothermal mineralization, and (2) within low-permeability rocks beneath sediment-filled basins adjacent to range-bounding fault systems where high conductive gradients have been measured.

The Roosevelt Hot Springs, Utah, lies near the eastern edge of the Basin and Range province in the Mineral Mountains, a range of Tertiary granitic plutons and meta-sedimentary rocks capped by a 0.8- to 0.5-Myr rhyolitic volcanic field. Gravity and seismic surveys provide tenuous evidence for a zone of partial melt beneath the Mineral Mountains. Recent hydrothermal activity has formed silica sinter, silica-cemented alluvium, and sulphur deposits and is controlled by both high- and low-angle faults. Silica and Na-Ca-K geothermometry calculations indicate reservoir temperatures of 286 and 241°C, respectively, which agree well with measured temperatures of 260°C at depths of 2 km.⁴⁶ Potential HDR sites lie west of the conventional hot-water

reservoir in hydrothermally sealed sediments and underlying down-faulted granitic rocks beneath Milford Valley.

3.1.6. Pacific Northwest Region. The northwest U.S. has great geothermal potential for low-temperature hydrothermal suitable for space heating and direct use as well as for HDR for areas with no natural hot springs or aquifers. The recent drought years, as well as growing population in Seattle and Portland, have called attention to the fact that hydroelectric power is not limitless and new energy sources must be developed. Hydrothermal sources have been used for space heating and processing for years in both Klamath Falls, Oregon, and Boise, Idaho, and the use of these resources is now being expanded.

For most of the northwest, HDR development will not involve drilling into granitic rocks, but either fracturing or making use of natural fracture systems in basalt or metamorphosed sedimentary rocks (e.g., marine and volcanoclastic sediments) that do not contain enough water to be developed as hydrothermal systems.

The geologic setting in the northwest is one of Precambrian continental crust in much of Idaho and northern Washington and oceanic crust of basalt and marine sediments, including an early Mesozoic volcanic arc, throughout the rest of Washington, Oregon, and northern California. Much of the region has been intruded by Mesozoic (mostly Cretaceous) granitic plutons, the largest of which is the Idaho Batholith, and smaller plutons of Tertiary age. Tertiary and Quaternary volcanic activity has been extensive, from the Cascades to the flood basalts of the Columbia Plateau and Snake River Plain, covering most of the older rocks and obscuring older geology and structure.

Heat flow is generally as would be predicted from the tectonic setting. West of the Cascades, heat flow is low, averaging 35 mW/m^2 (0.85 HFU). Heat flow is difficult to measure in the Cascades; within volcanic rock units it is difficult to drill deep enough to get below ground-water effects. Measured heat flow, which is probably too low, averages 50 to 75 mW/m^2 (1.2 to 1.8 HFU). East of the Cascades, heat flow is highest: southeastern Oregon averages 90 mW/m^2 (2.1 HFU), the margins of the western Snake River Plain average 100 mW/m^2 (2.4 HFU), and all the rest of the area averages above 71 mW/m^2 (1.7 HFU) (Fig. 3-8).

Seismic refraction studies show the crust is generally thinner in Washington, Oregon, and northern California than under cratonic regions: approximately 20 km on the coast deepening to 30 km under the Basin and Range

Fig. 3-8.
Revised heat-flow map of the western United States.^{13,53}

province of Nevada. Neither the Cascades nor Coast Ranges appear to have a significant crustal root.⁴⁷ The crust appears to thin to 20 to 25 km under the Columbia Plateau, but thicken under the western Snake River Plain to 40 to 45 km.

The most promising areas for HDR development are the margins of the Snake River Plain, Idaho (where granitic plutons underlie sedimentary and volcanic cover), the Brothers Fault Zone, Oregon [which has comparable gradients (50 to 60°C/km) and heat flow, but no defined reservoir rock can be found], and possibly some of the Mesozoic or Tertiary granitic plutons in Washington.

The difficulties of developing HDR in much of the northwest have to do with drilling and/or fracturing volcanic or metasedimentary rocks. HDR technology has not yet been tried in stratified (layered) rocks, and this technology needs to be developed before any complete assessment of HDR potential for the northwest can be made.

3.1.7. Geothermal Gradient Map of the Conterminous United States. A geothermal gradient map has been prepared to help determine the HDR geothermal resource of the U.S. (Fig. 3-9). The Laboratory has supported projects across the country to collect and evaluate gradient data for HDR exploration. These temperature gradient surveys (especially where existing drill holes are used) are a rapid, cost-effective initial means of identifying and delineating HDR prospects. This map is a first attempt to gather and synthesize all new gradient data as well as data from published and unpublished sources. (The gradients referred to here are determined at discrete intervals down the borehole and are not extrapolations from one bottom-hole temperature.) Approximately 900 points (from 87 references) are plotted and contoured on the first edition

Fig. 3-9.

Thermal gradient map of the conterminous U.S. indicating regions of high conductive thermal gradient where HDR geothermal techniques may be applied.

of this map. The figure shown here is a simplification of the original map, which is printed in color at a scale of 1:5 000 000.¹⁹ Each year an updated version incorporating new measurements will be published. These data, including heat-flow and conductivity measurements, where available, are on file at the Los Alamos National Laboratory and available upon request.

All gradients are calculated from measurements taken at discrete intervals down the borehole to eliminate temperature-depth profiles that show strong hydrologic interferences. In this manner, a picture of the regional conductive gradient emerges. However, it is impossible to eliminate completely the effects of ground water, circulating hydrothermal fluids, and varying conductivities of rocks. This compilation represents the best attempt to "weed out" unrepresentative data while the broad contour interval of 15°C/km encompasses regional variations. As an exploration tool, this map can be useful in (1) identifying regions within the U.S. where geothermal information is lacking, (2) noting regional trends and anomalous areas of elevated heat flux, and (3) making comparisons with other geological and geophysical information.

3.1.8. Preliminary Estimate of Resource Base. Evaluation of the High-Grade HDR Geothermal Resource Base. The present HDR experiment at Fenton Hill is being performed in part of an igneous system, with heat being conducted from a large, young, silicic magma body located beneath the Valles Caldera. Igneous systems are relatively small, local anomalies on the order of a few kilometers to tens of kilometers diameter, but represent the highest grade geothermal resource available to us. For this reason, igneous systems are considered separately from the overall regional assessment of the HDR geothermal resource of the U.S. Most of the heat in them is in the form of HDR. The hydrothermal portion of igneous systems is generally less than 10%. Estimates by Brook et al.⁴⁸ indicate that the hydrothermal portions range from 1.4 to 3.4%.

Admittedly, not all of the energy remaining in these systems exists as HDR, but preliminary work indicates that most of it is in that form. An estimate of the total thermal energy in the 62 young volcanic fields (igneous systems), to a depth of 10 km, of the conterminous U.S. is about 101 000 quads.⁴⁹ Omitting Yellowstone Park, the estimated resource base is about 66 000 quads. Even if only 50% of this energy is in the form of HDR (a very conservative estimate), there is a high-grade resource base of 33 000 quads in the young igneous systems of the lower 48 states.

Regional HDR Resource Base Evaluation: So that we may convince people of the utility of HDR for direct-use purposes, we must identify and understand regions with elevated thermal gradients within the U.S. ($>30^{\circ}\text{C}/\text{km}$). The advantage of this resource is its broad base; within these anomalies, users may be located (rather than moving the user to a high-grade resource) (Table 3-III).

One of the most important parts of the resource evaluation effort is heat-flow measurement. With limited funds for that purpose, we will be filling in large portions of the U.S. where heat-flow data are sparse or absent. Covering heat flow within the U.S. is a large job and may be accomplished over the next decade by cooperation among the federal geothermal programs. We are now cooperating with DOE and USGS geothermal programs in this endeavor. All data from all programs will eventually be stored in a central data facility at the USGS (Geotherm).

During FY80, the HDR program has already fielded a comprehensive heat-flow measurement program, now mainly through university contractors:

J. E. Costain, Virginia Polytechnic and State University

E. Decker, University of Wyoming

Y. Eckstein, Kent State University

W. Hinze, Purdue University

D. Hodge, State University of New York, Buffalo

R. Roy, University of Texas, El Paso

G. Simmons, Massachusetts Institute of Technology

D. Smith, Florida State University

D. Steeples, Kansas University

In addition to this work, the Los Alamos National Laboratory has made a number of thermal-gradient and heat-flow measurements in Arizona and New Mexico.

Starting in FY81, we will have a heat-flow-measurement expert on the Los Alamos-HDR staff who will take over some of the work now being covered by contractors to the HDR program.

Using heat-flow measurements as calibration points, we are identifying the extent of regional anomalies through the use of regional tectonic information and various geophysical measurements (aeromagnetic, gravity, electrical methods).

By showing a direct correlation between shallow conductors and heat flow, the HDR program has successfully used magnetotelluric (MT) surveying to

TABLE 3-III

HDR REGIONAL RESOURCE EVALUATION
(Summary 1980)

Region	Range of Thermal Gradients (°C/km)	Potential Reservoir Rock Units	Data Compilations in Progress	Most Useful Exploration Techniques	Main Thermal Sources
Eastern U.S.	6-46	Precambrian granitic, metamorphic terrane	Gravity, aeromag., tectonic, heat flow, electrical, water chemistry, geology	Heat flow, gravity	Heat generation in K, U, Th-rich granitic plutons
Midcontinent U.S.	8-55	Precambrian granitic, metamorphic terrane	Gravity, aeromag., tectonic, water chemistry, heat flow, MT, seismic, geology	Heat flow, gravity, MT	Heat generation in K, U, Th-rich granitic plutons
Rocky Mountain Region	16->100	Precambrian granitic and metamorphic ter- rane, cemented sedi- ments, volcanic rocks (very complex)	Geology (volcanology), heat flow, gravity, water chem- istry, MT, seismic, aeromag., tectonic	Volcanology, heat flow, tectonic, MT, gravity aeromag.	Heat generation in K, U, Th-rich granitic plutons, crustal thinning, magma
Southwestern U.S.	14-84	Precambrian and younger, granitic and metamorphic terrane, metamorphosed volcanic rocks	Gravity, aeromag., tectonic, volcanology, water chemistry, MT, seismic	Volcanology, heat flow, MT, gravity	Crustal thinning, magma
Far Western U.S.	6->100	Granitic and meta- morphitic terrane (variety of ages), tightly cemented sedi- ments, greenstone	Tectonic, volcanology, heat flow, MT, gravity, aeromag., water chemistry	Volcanology, heat flow, water chemistry	Magma, crustal thinning
Northwestern U.S.	8->100	Granitic and meta- morphitic terrane (variety of ages), cemented volcani- clastic rocks, thick basalt flows (?)	Tectonic, volcanology, heat flow, gravity, aeromag., water chemistry	Heat flow, volcanology	Crustal thinning, magma

TABLE 3-IV
REGIONAL HDR RESOURCE BASE TO 10 km (>15°C)

Area	Gradients °C/km	Total Area (km ²)	Heat Content (10 ¹⁸ cal)		
			0 - 3 km	3 - 10 km	0 - 10 km
Eastern U.S.	30	146 070	11 495	119 631	131 024
Eastern U.S.	45	5 832	682	7 161	7 844
Western U.S.	30	1 036 080	81 539	848 549	929 363
Western U.S.	45	256 977	30 066	315 567	345 634
Western U.S.	60	50 139	8 373	82 127	90 500
Totals			132 155	1 373 035	1 504 365

identify the extent of regional thermal anomalies. This work has been a basic tool for exploration aspects of the program.

An estimate of the HDR geothermal resource base is determined using the 1980 thermal gradient map of the U.S. (Fig. 3-9). Total heat contents were determined for regions with gradients of 30, 45, and 60°C/km. The heat content was calculated to a depth of 10 km and for temperatures of >15°C (Table 3-IV). The total HDR regional resource base estimate in the conterminous U.S. is $1\,504\,365 \times 10^{18}$ cal or 5.9×10^6 quads.

The estimated regional HDR resource base of about $1\,504\,365 \times 10^{18}$ cal ($\sim 6 \times 10^6$ quads) for the conterminous U.S. is considerably smaller than the estimate of 32×10^6 quads for conductive regimes by Diment et al.⁵⁰ That estimate is based on the entire U.S., whereas this estimate is for regions with gradients of >30°C/km.

3.2. Progress Toward Site 2 Selection

A second HDR site must be selected by 1982. With this in mind, a wide variety of prospective candidates is being studied and evaluated. There are two site categories: (1) sites with high thermal gradients (magma-hydrothermal systems), to be used for the generation of electricity, and (2) sites with moderate thermal gradients (>25°C/km but <40°C/km) for direct-use purposes. A variety of these prospective sites was described in the 1979 Annual Report;⁵¹ those studied specifically during 1980 are described here.

Some of the best information on these prospective sites has come from wells drilled for hydrothermal development that had high temperatures, yet

failed to produce adequate steam or hot water. We are grateful to companies that have provided information on these "hot but dry" wells.

Information on all candidate HDR sites is kept in a series of loose-leaf notebooks at the HDR program office and at the DOE offices. This "handbook" will be published after the selection of Site 2.

3.2.1. Mountain Home, Western Snake River Plain, Idaho. Introduction. One of the most promising areas for hot dry rock development in the northwest is along the margins of the western Snake River Plain (SRP). The SRP is an arcuate depression in southern Idaho filled with Tertiary- and Quaternary-age volcanic rocks, which are younger in the east. The margins of the western SRP are fault bounded, with at least 2743-m (9000-ft) vertical displacement along the northern margin⁵² and somewhat less displacement on faults of the southern margin. The Idaho Batholith lies just north of the SRP, but it is not known how far it extends beneath the plain.

Heat flow is greatest along the margins of the plain, rather than within it.⁵³ This may be partly the result of either cold water within aquifers in the plain or deep-circulating hot water along the boundary faults. Brott et al.⁵³ attributed the higher heat flow along the margins of the plain to refraction of heat, from a thermal event 10 to 15 Myr ago, into the more thermally conductive granite on the margins of the plain.

Target Prospect. The area chosen for detailed study is a 400-km² site on the northern margin of the western SRP near Mountain Home, Idaho (Fig. 3-10). Harding-Lawson Associates of Novato, California (HLA) were awarded the contract for the detailed study. This part of the northern margin was selected because it did not appear to be as badly faulted as other sections of the margin. There were two deep wells, with gradients of 61 and 64°C/km, and it had been reported that the Bostic 1A well, in the southern part of the prospect, had bottomed in granite of the Idaho Batholith at 2941 m (9648 ft) with a bottom-hole temperature of 195°C. In the course of the study, it was discovered that the hole actually bottomed in altered latite, probably part of the Tertiary Idavada volcanic sequence.

To help evaluate the HDR potential of the prospect, geologic, geophysical, hydrologic, and water-chemistry studies were performed by HLA. The purpose of their studies was to determine the structure of the area, especially the location of faults and depth to basement, the permeability of the

potential reservoir rock, the Idaho Batholith, and the thermal regime, which necessitated an understanding of the hydrology and water chemistry.

Geology and Structure. Most of the prospect lies within the Mountain Home Plateau on the edge of the Snake River Plain. The Mt. Bennett Hills form the northern and northeastern margin of the prospect. They are separated from the western SRP by northwest trending faults that cut across the northeast edge of the prospect (Fig. 3-11). The geology southwest of the major fault consists of Tertiary and Quaternary interbedded basalts and nonmarine sediments. In the Mt. Bennett Hills, older Tertiary Idavada (silicic) volcanics are exposed. North of the Mt. Bennett Hills the Idaho Batholith underlies the Idavada Volcanics.^{54,55} The predominant structure of the area is the set of northwest trending faults that form the northern boundary of the SRP. There is more than 3000 m total displacement, down to the southwest, along this fault zone,⁵⁶ which occurred in late Tertiary and early Quaternary time. There has been no apparent offset since middle Quaternary time.⁵² Faults are exposed in the Mt. Bennett Hills, and others have been located by lineament analysis where they are covered by sediment in the plain.

Geophysical Surveys. A 500-station gravity survey disclosed a broad gravity low in the northwest corner of the prospect, but failed to locate any faults that were not exposed at the surface. Telluric profiling along three north-south lines indicates a resistivity low in the northwest part of the prospect, corresponding with the gravity low. The combination suggests either deeper basin fill or extensive faulting, making that part of the prospect unsuitable for HDR. The rest of the area exhibits a uniform resistivity at depth. Microseismic activity, recorded for 48 days, averaged less than one

Fig. 3-10.
Location map showing survey lines (B—B) and major faults (—).

Fig. 3-11.
Schematic geologic cross section and Bouguer gravity along line B.

event per week within 25 km of the seismograph, demonstrating the suitability of the area from a seismic standpoint.

Hydrology and Water Chemistry. Small and perched aquifers occur in every geologic formation in the area, in both intercalated sediments and fractured volcanics. Hot springs emanate along two northwest-trending fault zones, one along the base of the Mt. Bennett Hills, one in the plain. Silica concentrations suggest equilibrium temperatures not much higher than 60 to 80°C. Assuming the Bostic gradient is representative, this suggests water circulation to 750- to 1000-m depth.

Conclusions. Based on gravity data and the Bostic 1A well cuttings, depth to granite in the southwestern portion of the prospect is greater than 3 km. The location of and displacement on faults still needs to be determined to determine depth to Mesozoic reservoir rocks. Los Alamos National Laboratory will conduct additional studies in FY81 to finish evaluation of the prospect.

3.2.2. Roosevelt Hot Springs, Utah. Roosevelt Hot Springs are part of a high-temperature ($>200^{\circ}\text{C}$) hydrothermal system in southwestern Utah that is being extensively developed for electrical power generation. Because of its high temperature and the existence of five hot dry wells, available data were compiled to evaluate the HDR geothermal resource.^{57,46}

Roosevelt Hot Springs lies west of the Mineral Mountains in Milford Valley. This north-trending range, which is composed primarily of Precambrian through Mesozoic-age rocks intruded by Tertiary granitic plutons, lies near the boundary between the Basin and Range and Colorado Plateau tectonic provinces. Regional heat flow exceeds 2.5 HFU (105 mW/m^2). The crest of the Mineral Mountains is covered by rhyolitic domes, flows, and minor pyroclastic deposits 0.5 to 0.8 Myr. Limited geophysical evidence, primarily teleseismic P-wave delay data, suggests a shallow silicic magma reservoir residing beneath the range.

The active hydrothermal system circulates in breccia zones in both low- and high-angle faults (Fig. 3-12). Because this system lies west of the young volcanoes, it is not certain whether the geothermal system is caused by a shallow magma body or due to deep circulation of fluids along range-bounding faults. Bottom-hole temperatures reach 260°C at depths of 2000 m, and a 20-MW(e) demonstration power plant utilizing the hot water resource is planned.

Fig. 3-12.
East-west cross section through Roosevelt Hot Springs geothermal field. The most attractive HDR prospect is west of the Opal Mound fault.

Hydrothermal alteration of both Precambrian gneissic and Tertiary granitic rocks is extensive and well documented.

Several hot dry wells have been drilled on the periphery of the hydrothermal field, particularly west of the Opal Mound fault in Milford Valley (Fig. 3-12). Three of these wells possess thermal gradients of 55 to 60°C/km and bottom in Tertiary granite and Precambrian gneiss. Granite is preferred over gneiss as an HDR reservoir rock because the latter has a well-developed foliation. East⁵⁸ conservatively estimates that at least 160 km² of area is underlain by nearly impermeable rock within √2- to 3-km depth. If so, the exploitable HDR resource is as much as seven times the size of the conventional hot-water resource, and might be exploited with technology under development at Fenton Hill, New Mexico. The next phase of HDR development at Roosevelt would be to gain access to one or two of these hot dry wells to study permeability, porosity, and fracture characteristics of the reservoir rock.

3.2.3. The Geysers-Clear Lake Region, California. The Geysers-Clear Lake region lies about 150 km north of San Francisco, California, in the California Coast Ranges, and is now the largest power-producing geothermal province. It includes a vapor-dominated zone at The Geysers and a hot-water-dominated zone to the northeast. Reservoir rocks of both zones consist of fractured graywackes and other marine rocks of the Franciscan assemblage and Great Valley sequence that have been metamorphosed to zeolite and higher facies. Early Tertiary subduction followed by late Tertiary strike-slip faulting associated with the San Andreas transform zone have produced an incredibly complicated basement geology.⁵⁹

The heat for the geothermal systems originates from a shallow silicic magma reservoir that has erupted the Clear Lake volcanic field (2.0 to 0.01 Myr). This reservoir has been delineated by gravity, seismic P-wave delay, electrical resistivity, and aeromagnetic data. Over 75 km³ of volcanics, mostly dacite, have been erupted.^{34,35} Heat flow exceeds 4 HFU over a large region.

Although intensive development of the vapor-dominated zone continues, exploration for hot-water resources to the east beneath the Clear Lake volcanic field has been relatively unsuccessful due to low permeability of potential reservoir rocks. Of 10 or so deep wells drilled, only one has encountered a significant water entry. Apparently, hydrothermal reactions

within the underlying graywackes seal the rocks faster than the active tectonic environment can fracture them. Most of these wells (Fig. 3-13) reach temperatures of 200°C at depths of 2000 m. Thus, roughly 150 km² beneath the Clear Lake region appears very attractive for HDR research on the basis of temperature (Table 3-V).

Unfortunately, technology for creating an HDR reservoir in fractured metagraywacke does not exist, and it is not known what problems will be encountered. The Laboratory intends to study the Clear Lake region in more detail in FY81. In addition to compiling a heat-flow map of the geothermal region, these investigations will be aimed at selected subsurface, geophysical, and geochemical properties of metagraywacke as a reservoir rock and an analysis of the prevailing stress regime. A successful HDR geothermal system in rock other than granite would expand the applicability of HDR immensely.

3.2.4. Wallops Island, Virginia. In late 1979 an area between Crisfield, Maryland, and Wallops Island, Virginia, (Fig. 3-14) was chosen for detailed evaluation as a potential HDR demonstration site. It was chosen largely on the basis of reconnaissance measurements reported by the group working at VPI&SU.⁴ Thermal gradients of 34 to 46°C/km and heat flow of 67 to 77 mW/m² were measured in the area, and basement-surface temperatures were estimated to be between 71 and 90°C. The area is on the east flank of a large gravity low centered under Chesapeake Bay and a small gravity low at Wallops Island. These lows were

Fig. 3-13.
Map of The Geysers-Clear Lake region. The producing zone at The Geysers is outlined; pattern indicates the main Clear Lake volcanic field. The Collayomi fault zone separates the vapor-dominated and hot-water-dominated geothermal provinces. Points are locations of 10 deep wells that have encountered temperatures of roughly 200°C. The area of HDR potential underlies the Clear Lake volcanics.

TABLE 3-V

WELLS IN THE CLEAR LAKE FIELD, CALIFORNIA

Map No.	Name	Operator	Depth (ft)	Bottom-hole Temperature	Bottom-hole Rock Type	Comments
1	S & B #1	Aminoil USA	11 150	Very hot ^b	Franciscan- Graywacke?	Dry-logs available
2	B & R Unit #1	Aminoil USA	11 150	Very hot ^b	Franciscan- Graywacke?	Dry-suspended
3	Bouscal #1	Republic	9 000	Very hot ^b	Franciscan- Greenstones	Dry-suspended
4	Sullivan #1	E. Towns?	6 400	Hot ^b	Serpentine	Dry-abandoned
5	Neasham #1	Occidental- Republic	9 800	>260°C ^a	Franciscan- Argillite	Water entry at 8500 ft (120 000-lb flashed steam) margin
6	Kettenhoffen #1	Thermogenics	6 200	200°C	Franciscan- Graywacke- argillite	Dry-abandoned
7	Magma-Watson #1	Magma-Dow Chem.	5 700	200°C	Serpentine	Dry-abandoned
8	Thurston #1	Union	10 200	Very hot ^b	Franciscan- Greenstone	Water entry (very marginal)
9	Borax Lake #1	Phillips	10 000	Hot ^b	Franciscan	Dry
10	BJ #1	Aminoil USA Thermal Power & Gulf	10 230	Hot ^b	Franciscan	Dry-No H ₂ O entries Logs available

^aVerbal information from Kip Neasham, Lakeport, California (land owner).^bPrivileged communication.

Fig. 3-14.
Site location and data base.

thought to be caused by granitic intrusions having above-average radiogenic heat production.

D'Appolonia Consulting Engineers were awarded a contract to carry out the Laboratory's exploration program at the site. The program included drilling and logging four gradient holes to 300 m, acquisition of 1300 line-miles of new aeromagnetic survey data, a controlled-source time-domain electromagnetic (TDEM) survey, and 25 line-miles of Vibroseis reflection-seismic surveying. A high correlation was found between thermal gradient, gamma-log signatures, and stratigraphic units. Variations in stratigraphy across the prospect area cause a greater change in gradient than does variation in heat flow. This required reinterpretation of the VPI&SU data. The aeromagnetic and the electrical surveys showed an increase in basement dip in the eastern third of the site, and several local anomalies that may be caused by graben-like structures in the basement. The electrical structure is five-layered, with the layer above basement being least resistive, probably due to high-salinity aquifers. The seismic survey provided depth control for

interpretation of the electrical and magnetic surveys. Gradients range from 25°C/km for the Yorktown formation to 50°C/km in the Calvert formation.

3.2.5. West-Central New York. The earliest indication of above-average thermal gradients in west-central New York was the map published by the American Associates of Petroleum Geologists (1976). This led to work by Dennis Hodge, State University of New York at Buffalo, and his associates to seek additional data about these anomalies and any new ones that could be found. This work has been in progress for two yr.

The geology of western New York consists of a thick sequence of nearly horizontal Paleozoic sedimentary units lying upon a complex basement of metamorphic rock about which very little is known. The sedimentary units dip generally southward so that Ordovician-age formations exposed at the north edge of the state are covered by progressively younger rocks to the south. Devonian-age formations cover the southern half of the area. The rocks are mainly shale with increasing amounts of sandstone in the lower half of the section. Because of the southeasterly dip, the depth to basement increases from less than 1 km near Lake Ontario to more than 4 km at the state line south of Binghamton.

Most of the geothermal exploration has been based on compilation of bottom-hole temperatures from existing oil and gas wells. These have been supplemented by detailed temperature logs in twelve new wells. A computer model of gradient distribution has been developed for the entire western third of New York. This model shows well-defined geothermal-gradient anomalies southeast of Buffalo (East Aurora), southeast of Rochester (near Auburn), and east of Elmira. The East Aurora and Elmira anomalies coincide with previously reported gravity lows, and are thought to be the result of low-density radioactive granitic intrusions in the basement rocks. The gravity low near Elmira is one of the strongest in the eastern U.S. The probable cause of the Auburn anomaly is still unknown. Although the gradients in Tioga County, east of Elmira, appeared to be slightly higher than at Auburn, and the temperatures at the basement surface would be much higher because of the great thickness of overlying sedimentary rock, the Auburn site was given priority for additional work because of the relatively shallow (1500 m), hence more accessible, depth to basement. Additional measurements and modeling completed in the past few months has shown two anomalies where the earlier model showed only one. The lower, broader anomaly, of 38°C/km, is west of Geneva, in Ontario County. The

smaller but stronger anomaly, of $41^{\circ}\text{C}/\text{km}$, is centered 8 km south of Auburn. Heat flow also has been determined for this area showing $82 \text{ mW}/\text{m}^2$ near Auburn and $52 \text{ mW}/\text{m}^2$ near Elmira. Thus it appears that Auburn is the best accessible prospect for a hot dry rock site in New York. The Tioga County area near Elmira offers higher temperatures but at considerably higher cost.

3.2.6. Exploration for Hot Dry Rock Geothermal Areas Using Magnetotellurics in Arizona, New Mexico, and Colorado. As a part of the national HDR Program, the Los Alamos National Laboratory is conducting a regional magnetotelluric survey in Arizona, New Mexico, and Colorado. Over 200 MT sites are spaced along several long profiles that have been located where geologic and geophysical studies indicate HDR potential (Fig. 3-15). The objective of this survey is to map the depth to pervasive, electrically conductive zones within the crust and upper mantle over a large region, crossing several tectonic boundaries. A map of this type may help to locate potential HDR geothermal

Fig. 3-15.
Locations of MT sounding profiles.

areas (where the conductive zone is shallow); it may also indicate correlations between the conductive zone and regional structure and tectonics.

So far, the Laboratory has completed data collection on all profiles except the Colorado line, four stations in the Aquarius area, and a portion of the Flagstaff-Tucson line from Flagstaff to Phoenix. Data collected by the University of New Mexico and Brown University are also being studied, as well as nonproprietary data collected by Geotronics, Inc.

Several prospects within the region are of particular interest. These are the Rio Grande rift, the Castle Dome and Aquarius areas, and the Zuni area along the Jemez lineament. The Rio Grande rift is a Cenozoic feature consisting of north-south trending elongated basins in a right en echelon pattern. The structure of the rift has been influenced by a series of transverse, northeast-southwest trending shear zones, one of which is the Jemez lineament. The Jemez lineament appears as an alignment of Cenozoic volcanics and intersects the Rio Grande rift at the Jemez Mountains. The Castle Dome area, exhibiting a high geothermal gradient and an anomalous gravity low, has been suggested as a possible Tertiary caldera.⁶⁰ The Aquarius area is associated with high heat flow, shallow depth to Curie isotherm, and a gravity low, and may be associated with a shallow depth to the electrically conductive zone.⁶¹

Heat-flow values of 3.0 HFU have been measured in the Zuni area.²⁸ Because of this, a detailed MT/audio-MT (AMT) survey was done here.⁶² The survey consisted of a grid of 26 MT sites overlying a finer grid of 121 AMT sites. Two-dimensional analysis of these data has been completed. Interpretation of the results shows an electrical strike direction approximately parallel to the Jemez lineament and anomalously high electrical conductivity. These observations are substantiated by results of preliminary interpretation of three east-west regional profiles traversing the Jemez lineament in that region. Integration of these studies with geological, teleseismic, and heat-flow observations suggests that the Jemez lineament is a major zone of weakness extending deep into the lithosphere and acting as a conduit for the ascent of magma.

4. FENTON HILL TECHNOLOGY DEVELOPMENT PROJECT (SITE I)

Experiments to investigate the possibility that geothermal energy might be extracted from HDR at depth were initiated at the present Fenton Hill site early in 1974 with the drilling of the experimental well GT-2 to a depth of 2.929 km (9609 ft) and to a bottom-hole temperature of 197°C (386°F). Following a series of fracturing experiments in GT-2, a second well, EE-1, was drilled nearby to a depth of 3064 m (10 053 ft). These two wellbores, penetrating into the crystalline basement rock, have served as a laboratory during the succeeding years for the testing of ideas and for the development of the technology of HDR energy extraction.

The history of operations at Fenton Hill and the development of the site there have been covered in the HDR Project Annual Reports for the fiscal years 1976 through 1979. Fenton Hill continues to be the focus of HDR experimentation and demonstration. This report continues the story through FY80.

The Fenton Hill technology development effort comprises two major parts: (1) research (Phase I) system experiments, and (2) engineering (Phase II) system development. Progress made in these two separate parts of the program are reported in this section. Appendix B lists the field experiments conducted during FY80.

The Phase I experiments have utilized the wellbores EE-1/GT-2B and the fracture system connecting them in a series of energy extraction and other tests to demonstrate that large heat-transfer areas can be produced in HDR at depth. The knowledge developed in this research phase of the program is then being used to plan the reservoir that is being constructed at Fenton Hill in the second part of the program--the engineering (Phase II) system.

The construction of the new engineering phase system began in FY79 with the beginning of drilling of one new deep well, EE-2, and has continued in FY80 with the successful completion of EE-2 on May 12, 1980. Drilling of the second new well, EE-3, began in FY80; it is scheduled for completion in FY81.

In addition to the Phase I/Phase II developments, several other important activities are covered in this section. These include the welcome participation of the government of West Germany in support and prosecution of the Fenton Hill work under the terms of an International Energy Agency agreement; the manifold activities carried out under the category "Reservoir Engineering and Analysis," i.e., support work required by both Phase I and Phase II; a

brief review of related research and development underway outside the Los Alamos National Laboratory, domestic and overseas; equipment and material development; a review of the environmental surveillance program for the Fenton Hill operations (a program that is now in its sixth year); and finally a brief review of Phase III studies.

It is to be noted that FY80 was a year of significant progress in the Fenton Hill Project. An extended period of testing demonstrated that a fracture connection had successfully been made between the EE-1 and GT-2B wellbores where the vertical borehole separation distance is 320 m. Circulation through this connection (Run Segments 4 and 5) was maintained for a total of 5628 h, and a total of 13×10^6 kWh of thermal energy was extracted from the rock at depth.

A second significant accomplishment has been the completion of well EE-2 to a depth of 4661 m (15 289 ft) and the drilling of EE-3 to partial completion at a depth of 3044 m (9987 ft). Both wells were drilled along the planned trajectories with the inclination of the production section being 35° to the vertical. The bottom-hole temperature of EE-2 was measured to be 317°C .

EE-2 and EE-3 will constitute the injection and production wells of the new engineering (Phase II) system. The vertical wellbore separation distance in the producing zone will be 360 m. Based on the results achieved with EE-1/GT-2B fracture connections, some considerable degree of confidence can be felt for the success of a fracturing operation in the new system.

4.1. West German Government Participation

On September 19, 1979, under the aegis of the International Energy Agency (IEA), an Implementing Agreement was signed in Paris enabling direct West German (FRG) participation in the Fenton Hill project. This agreement [between the Department of Energy and its FRG sister organization, the Kernforschungsanlage-Jülich GmbH (KFA)] is for a period of 4 fiscal years, FY80 through FY83, and can be continued at the option of the parties thereafter.

The major provisions of this agreement are

- creation of a four-member Fenton Hill Project Steering Committee with membership by the parties in proportion to their financial contributions,
- assignment of up to three KFA scientific staff at Los Alamos as full participants in the conduct of the Fenton Hill project, and

- an annual financial contribution by KFA to the cost of the Fenton Hill project equal to 25% of the DOE's annual allocation to the project, with a maximum limit of \$2.5 million.

The first meeting of the Steering Committee was held in Los Alamos at the Laboratory on January 14, 1980. Bennie DiBona (DOE/DGE) was elected chairman and Hans-Jochim Stöcker (KFA) was elected vice-chairman. The Committee reviewed project planning and discussed arrangements for the KFA participation.

The Steering Committee met a second time on July 29, 1980 in Washington, D.C. Technical progress at Fenton Hill since the first meeting was reviewed and project plans for the next year were discussed. Arrival of the KFA scientist assignees at Los Alamos was expected near the end of the fiscal year.

4.2. Research (Phase I) System Experiment

4.2.1. Energy Extraction Run Segment 4. Run Segment 4 was an experiment carried out from October 23, 1979, to November 15, 1979, to make a preliminary assessment of the energy-producing and other characteristics of the new fracture connection. This new fracture system, which constitutes the Phase I research reservoir, intersects EE-1 at 2.93 km (9620 ft) and joins GT-2B at several locations in the vicinity of 2.7 km (8660 ft).

A detailed topical report was issued on this experiment;⁶³ therefore, the results of Run Segment 4 are summarized here only briefly. This experiment was followed by Run Segment 5, a much more extended energy-extraction evaluation of the same system (cf. Sec. 4.2.2.), which is continuing on into FY81.

The geometry of the flow paths in the present EE-1/GT-2B fracture system is as shown schematically in Fig. 4-1. The larger fracture intersecting the EE-1 wellbore at 2930 m (9620 ft) carries all of the flow leaving the injection well, EE-1. (The smaller fracture carried 95% of the flow during the 75-day heat extraction experiment, Run Segment 2.)

A summary of important results of Run Segment 4 follows.

- Energy Extraction. The total energy extracted from the reservoir during the 23-day experiment period was 65-MW days. Figure 4-2 shows the thermal power vs time over the test period. During the last 14 days of the run, the average thermal power was ~ 3 MWt. The power varied widely during the early part of the run due to variations in flow and pressure conditions.

Fig. 4-1.
EE-1/GT-2B research reservoir system.

Fig. 4-2.
Extracted thermal power.

- **Flow Rate.** The flow rate during the latter steady state portion of the test was 6.0 kg/s (95 gpm) at an injection pressure of 9.65 MPa (1400 psi) and production pressure of 1.1 MPa (160 psi).
- **Flow Impedance.** The total impedance to flow through the reservoir at steady state low-back-pressure conditions was $1.4 \text{ GPa}\cdot\text{s}/\text{m}^3$ (13 psi/gpm). Observations made during the early part of the run (when the total impedance was somewhat higher) made it possible to calculate where this impedance was distributed across the total system. The results are given in Table 4-I. It is encouraging to note that the impedance to flow through the fracture itself is relatively low, the majority of the impedance being at the entrance and exit from the fracture. Exit and entrance impedances will be of strong interest in the Phase II system and may be subject to some engineering control.

- Temperature of Geothermal Fluid. Downhole temperature surveys were made at intervals during the experiment. The levels at which fluid entered the GT-2B wellbore could be determined from these experiments. During low-back-pressure operation the fluid temperature in GT-2B at 2591 m (8500 ft) was 156°C. This temperature is lower than the undisturbed rock temperature in the production zone because of the cooling that had been produced during the 75-day heat extraction Run Segment 2. Figure 4-3 is a semiquantitative representation of the temperature field existing in the production zone during Run Segment 4.
- Flow Distribution Studies. Four sodium-fluorescein tracer experiments were conducted during Run Segment 4. Some of the results are shown in Table 4-II. Included in the table for comparison are the corresponding observations made during the earlier Run Segments 2 and 3 while flow was going through the old system. Figure 4-4 shows the fracture-system volumes that can be deduced from the dye-tracer studies.
- Water Loss. The water-loss rate at the end of the 23-day operation was 1.3 ℓ /s (20 gpm). More definitive data for a longer-duration run come from Run Segment 5 (Sec. 4.2.2.).
- Geochemical Behavior of the Reservoir. Samples of the geothermal fluid were collected at regular intervals from the GT-2B production wellhead and at the makeup pump. Samples of dissolved gases were also collected. 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, SO_4^{--} , Cl^- , HCO_3^- , F^- , and total suspended solids (TSS). Gas samples were analyzed for H_2 , N_2 , O_2 , CO_2 , CH_4 , and H_2S . The detailed results of these analyses are given in Ref. 63. It was found that the silica concentration in the geothermal fluid rose to a value of 230 ± 8 ppm during closed-loop operation. This concentration level corresponds to an equilibrium temperature of 190°C according to the quartz geothermometer. This approaches the 197°C indigenous rock temperature at 2.93 km (9620 ft).

- **Seismicity.** Reservoir seismicity was monitored with a surface seismometer array and a geophone package positioned downhole in well EE-2. Details of events detected and analysis of same may be found in Sec. 4.4.2.

TABLE 4-1
FLOW-IMPEDANCE TEST RESULTS OF EE-1/GT-2B SYSTEM

Impedance	Location	Value	
		GPa·s/m ³	(psi/gpm)
Z ₁	EE-1 entrance region	0.09	(1.0)
Z ₂	Across main fracture	0.41	(3.7)
Z ₃	GT-2B exit region	1.1	(9.2)

Fig. 4-3.

Inferred fracture system model with qualitative indication of thermal field at the beginning of Run Segment 4 reservoirs.

Fig. 4-4.

Apparent fracture system volumes for the Run Segments 2, 3, and 4 tests of the old and new EE-1/GT-2B.

TABLE 4-II
SUMMARY OF DYE-TRACER EXPERIMENTS EE-1/GT-2B FRACTURE SYSTEMS

Experiment	EE-1 Injection Pressure bars	GT-2B Production Pressure bars	GT-2B Production Flow Rate ℓ/min	Average Fluid Production Temp. °C	Mean <V> ℓ	Median [V] ℓ	90% Trimmed Mean V ℓ	Mode V ℓ	Variance σ_0^2	Variance σ_u^2 (90%)	Pe ^{*-1} ^a
First Reservoir LBP (75 day) ^b											
1-1 (2/9/78)	88	11	435	150	34405	25563	29254	11400	0.65	0.44	0.591
1-2 (3/1/78)	85	11	787	110	37472	28936	30889	17000	0.62	0.43	0.942
1-3 (3/23/78)	66	11	833	95	54684	45062	46250	22700	0.51	0.42	0.944
1-4 (4/7/78)	59	11	927	90	56232	48400	49203	26500	0.47	0.39	1.120
First Reservoir HBP (28 day) ^c											
1-5 (9/28/78)	93	97	462	111	33094	24730	26615	3800	0.75	0.56	0.358
1-6 (10/13/78)	93	97	560	98	56485	46477	48143	11400	0.45	0.36	0.306
1-7 (10/26/78)	93	17	939	~98	49612	40549	41843	20800	0.49	0.38	0.347
Second Reservoir (23 day)											
2-1 (10/26/79)	172	11	386	153	206781	192268	184455	136300	0.26	0.22	0.195
2-2 (10/29/79)	172	103	488	154	229695	210908	209416	143800	0.17	0.12	0.360
2-3 (11/2/79)	93	11	394	153	262098	216083	242565	115100	0.38	0.34	0.281
2-4 (11/12/79)	93	11	382	153	282630	236036	263378	128700	0.32	0.28	0.310

^aPe^{*-1} = D/UR = inverse dispersional Peclet number for single one-dimensional zone fit.

^bLBP = low back pressure.

^cHBP = high back pressure.

4.2.2. Energy Extraction Run Segment 5. The results of Run Segment 4 (Expt. 215)⁶³ showed that hydraulic fracturing from the recemented EE-1 casing had created a new reservoir system with a much larger heat-transfer surface. This new system produced about 100-gpm flow rate under low-back-pressure conditions. The much larger heat-transfer surface, indicated by the stability of the outlet temperature during Run Segment 4, made it necessary to run the continuous-circulation loop (hereafter "loop") for a considerable length of time to characterize the reservoir. At present during Expt. 217, the loop has been running 200 days and is only now showing a slight temperature draw-down of about 3 to 5°C. Upon completion of Run Segment 5, a complete report will be prepared. Here we summarize the major results to date.

Objectives. There were several major objectives for this loop circulation experiment: (1) to establish bounds of effective heat transfer under low-back-pressure conditions; (2) to measure fracture impedance, long-term water losses, flow-through volume, and degree of mixing; and (3) to determine the operating characteristics of the Barber Nichols binary cycle electrical unit.

Reservoir Operating Characteristics. Figure 4-5 is a history of the inlet (EE-1) and outlet (GT-2) pressures. The anomaly 75 days into the experiment coincides with a 9-day shut-in and will be apparent on all the history plots that follow. This shut-in was included as part of the operation in order to measure reservoir temperatures during the period of partial thermal recovery. The gradual decrease in EE-1 pressure noted in Fig. 4-5 is attributed to mechanical wear of the pumps. The step increase in the GT-2 pressure at 156 days is due to additional back pressure imposed by the surface piping network. Figure 4-6 shows fluid temperatures at EE-1 and GT-2B wellheads. The outlet temperature (GT-2B) has been remarkably stable throughout the experiment. The decline in temperature at GT-2B towards the end is due to both an equipment malfunction and a real decline in reservoir temperature. This will be further addressed in the temperature/spinner surveys section of this report. Inlet and outlet flow rates are shown in Fig. 4-7, and the accumulative circulated flows are presented in Fig. 4-8. The flow rates for both wells have remained reasonably constant throughout the experiment, about 6.4 m^3/s (100 gpm) in EE-1 and 6 m^3/s (90 gpm) in GT-2B. Figure 4-9 shows the history of the water-loss rate. Included are anomalies due to leaks, the shut-in, and the fresh-water flush (which will be discussed subsequently). The steady decline in rate follows a $(\text{time})^{-1/2}$ behavior, characteristic of

Fig. 4-5.
Inlet (EE-1) and outlet (GT-2B)
pressures.

Fig. 4-6.
Inlet (EE-1) and outlet (GT-2B) well-
head temperatures.

Fig. 4-7.
Inlet (EE-1) and outlet (GT-2B) flow
rates.

Fig. 4-8.
Cumulative circulated flows.

Fig. 4-9.
Reservoir water-loss rate.

Fig. 4-10.
Run Segment 5, reservoir flow impedance history.

one-dimensional fluid diffusion into the rock adjoining the reservoir. The water-loss rate at present continues to decrease, and is currently at a 0.6-l/s (9-gpm) level. The impedance history, corrected for buoyancy, is shown in Fig. 4-10. The impedance has also remained reasonably constant at 16.4 bars/l (15 psi/gpm) throughout the experiment.

A number of diagnostic experiments were performed throughout the circulation phase--a bromine-tracer study, a 9-day shut-in for thermal-recovery measurements, a fresh-water-flush geochemistry experiment, periodic temperature/spinner downhole surveys, and seismic monitoring. These are discussed in more detail below.

Br⁸² Tracer Study. Previous radioactive tracer experiments using both I¹³¹ and Br⁸² isotopes have provided unique information concerning both the movement of fluid through the fracture system and the actual volume of the reservoir. A tracer experiment employing a 40-mCi NH₄Br⁸² source was performed 1 month after the start of Run Segment 5. The tracer, injected into the injection well, EE-1, by pressurization from an accumulator, was followed by logging with a gamma-radiation-detector tool in both wells during its passage: (1) through the EE-1 wellbore; (2) into several exit fractures, Fig. 4-11; (3) behind the EE-1 casing at several points; and (4), finally, as it

Fig. 4-11.
Bromine-tracer activity behind EE-1 casing.

Fig. 4-12.
Bromine-tracer activity below GT-2 casing.

exited at different times at three natural fracture zones that afford communication from the main hydraulic fracture zone to the extraction well, GT-2B (Fig. 4-12). These natural fractures are described further in the section on temperature and spinner results. The history of the tracer activity at these various depths provides the basic data for analysis of transit time for flow across the several fracture paths along with estimates of fracture volumes. Preliminary analysis indicates a reservoir volume 8 to 10 times the size of the reservoir before the recementing of EE-1.

In addition to downhole measurements of the Br^{82} tracer, a gamma radiation detector was installed at the surface so that the Br^{82} could be continuously monitored. This allowed comparison of the present data with that of a previous fluorescein dye experiment.⁶⁴⁻⁶⁵ Both results are presented in Fig. 4-13. The increased sensitivity possible with radioactive tracers allowed the resolution of residence-time distributions to approximately ten-reservoir volumes of total flow rather than the three-reservoir volume resolution of the fluorescein dye experiments. Surface monitoring has identified a secondary flow path with a residence time of about eight reservoir volumes, which is tentatively believed to be the source of pore fluid described later, in the discussion of the fresh-water geochemistry experiment. Further study of this and other Br^{82} tracer experiments will clarify the role of this secondary flow path.

Fig. 4-13.

Comparison of residence-time distributions obtained using Na-fluorescein dye and Br^{82} as tracers.

Shut-In Temperature-Recovery Experiment. Six temperature logs were taken in EE-1 during a 9-day shut-in (May 20 to 29, 1980) of Run Segment 5. These logs show the time-dependency of reservoir thermal recovery following heat extraction. Interpretation of these data, still under way, provides a basis for determining reservoir geometry and heat-transfer characteristics, as well. The temperature recovery calculated from the six logs and a seventh run just before shut-in is plotted in Fig. 4-14. However, recovery behavior representative of the reservoir features is just beginning to emerge from that resulting from the radial field due to wellbore cooling. Previous shut-in experiments indicate that a longer recovery period is desirable.

Fresh Water Flush Geochemistry Experiment. The fresh-water-flush experiment measured the response of the reservoir to a step change in inlet-fluid composition. The geochemical response should depend strongly upon several factors, particularly the temperature distribution in the reservoir at a given time, reservoir area and volume, and the change in temperature distribution with time. A two-part fresh-water flush was performed in June, during which concentration measurements of ~20 elements and ionic species in the produced water were obtained hourly. The discussion of two major constituents, silica and chloride, is summarized here. Silica is produced by dissolution of quartz,

and its behavior is essential in understanding the applicability of the quartz geothermometer to these reservoirs.

Approximately 250 000 gal of fresh water were injected into the reservoir starting on June 26. The fluid produced at GT-2B was vented to the GT-2 pond until the entire 250 000 gal had been injected. The system was then returned to closed-loop operation on June 28. The concentrations of silica and chloride in the produced fluid are presented in Fig. 4-15. Two days after the return to closed-loop operation, the second part of the experiment was started. In this part, 50% of the injected flow was fresh water and the other 50% was produced (GT-2) fluid. The rest of the produced fluid was vented to the EE-1 pond. This mixture gave an injected fluid composition intermediate to that circulated during the normal closed-loop operation and the 100% fresh-water flush. The concentrations of silica and chloride again declined; however the decline was slightly less steep than was observed in the first part of the experiment (Fig. 4-15). After the second part was completed, the silica and chloride concentrations in the produced fluid recovered to the values measured before the fresh-water flush.

Preliminary interpretation of the fresh-water-flush experiment indicates that the hot region of the reservoir has declined in extent or temperature as a result of heat extraction. This decline is measured by the rate of change of silica concentration with respect to fluid volume injected. Further analysis of the experiment is deferred until chemical analyses of the fluids are completed.

Temperature/Spinner Downhole Surveys. The thermal-drawdown history of the present fracture system resulting from the Segment 5 operation is best measured in the GT-2B wellbore, just above the bottom of the casing, where the total flow through the system is sampled. This is evident from a series of temperature measurements run during the course of Segment 5 at a depth of 2591 m (8500 ft), which show a very broad temperature maximum at ~60 days after the

Fig. 4-14.
Temperature recovery in EE-1 wellbore during shut-in.

Fig. 4-15.
Silica and chloride concentration history.

start of the operation with a subsequent increasing rate of temperature drop, as shown in Fig. 4-16. Flow-rate (spinner) logs run over the open-hole region of GT-2B have been used to measure the fraction of the total flow issuing from each of three major natural fractures that convey flow from the main hydraulic fracture system to GT-2B (Fig. 4-17). Used in conjunction with the temperature logs, the flow-rate logs can be used to estimate the temperature of the water issuing from each of these natural fractures into GT-2B. Each of these temperature histories, which are also shown in Fig. 4-16, exhibits a different behavior. The bottom natural fracture, below 2703 m (8870 ft), shows a gradual rise to an apparent maximum at 150 days. The temperature of the fluid exiting the fracture zone at 2673 m (8770 ft), which provides approximately one-half of the total flow (Fig. 4-17), has generally decreased during the entire Segment 5 operation. The temperature of the uppermost fracture zone [2600 to 2646 m (8533 to 8680 ft)] has remained relatively high and was probably not significantly changed during the entire operation.

The thermal-drawdown results are summarized in Fig. 4-18. The decrease in the mean temperature measured at 2590 m in GT-2B is now plotted positively as a function of time. The drawdown can be measured from either the initial temperature, day 1, or from the peak temperature of the "total flow" curve (Fig. 4-16), which occurs at about 60 days. The spread of the measured temperatures shown in Fig. 4-18 accounts for the two methods of measurements. The solid curves are predictions based upon the theory described in Ref. 66.

Fig. 4-16.
Temperature variations at several
fracture/wellbore intersections.

Fig. 4-17.
Exit-fracture flow history.

Fig. 4-18.
Summary of thermal-drawdown results.

It can be seen that the match is only fair, primarily because the present draw-down is small, only 2 to 4°C, but a fracture area of 40 000 to 60 000 m² is in accord with the observations so far.

Seismic Monitoring. Results from a single downhole geophone experiment on June 25, 1980, indicate that very little microseismic activity is associated with Expt. 217. During a 3.25-h monitoring period at 2600 m (8550 ft) and an additional 2.5 h at 1500 m (5000 ft), only two events were recorded that appear to represent seismic signals. This is a far lower rate of seismicity than was recorded during the low-back-pressure phase of Expt. 215, which itself was very low and was measured under operating conditions similar to those currently in effect.

Discussion and Conclusions. As mentioned above, the effective heat-transfer area may be obtained by using numerical models to fit the observed temperature drawdown. The drawdown in the 1978 Run Segment 5 (75-day test) indicated a heat-transfer-surface area corresponding to a fracture area of 8000 m² for the first of the two research (Phase I) reservoirs created to date. A similar modeling effort on the new reservoir indicates that the effective fracture area is in the range 40 000 to 60 000 m². The ratio of effective areas of the two reservoirs (in the range five to eight) is in reasonable agreement with the ratio of volumes, eight to ten, measured with Br⁸² tracer experiments in both reservoirs.

The impedance behavior of the two reservoirs is also different. In the first reservoir, the impedance dropped from about 1.8 GPa·s/m³ (16 psi/gpm) to about 0.34 GPa·s/m³ (3 psi/gpm) in the 75-day run period, presumably because of the large thermal drawdown of about 100°C and the subsequent thermal contraction and opening of flow paths. The present system has a nearly constant impedance, about 1.7 GPa·s/m³ (15 psi/gpm), but the thermal drawdown is almost negligible.

With respect to water loss, it is particularly meaningful to compare the results from this experiment up to 75 days with those from the 75-day test in 1978. Although both sets of data contain many anomalies due to transients and operational difficulties, the first 30 days of each may be compared. (This is the period before the significant pressure decrease in the 75-day test.) As shown in Fig. 4-19, both cumulative water-loss curves are similar in shape and magnitude, implying that the water-loss area in the reservoir has remained essentially the same.

The Barber Nichols electrical generating unit went on line during May. The design specification, 60 kW, was produced. Although it was intended for the generator to operate continuously through the experiment, mechanical parts failures prevented more than intermittent operation.

4.2.3. Energy Utilization Experiments.

These experiments are intended to demonstrate utilization of the extracted energy in ways that the water-to-air heat exchangers cannot. Two such experiments are being pursued at Fenton Hill.

(1) Thermal Electric Generating Unit (TEGU). The TEGU is a 60-kW(e)

Fig. 4-19.
Cumulative water loss.

Fig. 4-20.
R-114 60-kW(e) binary-fluid power cycle.

(net) generating package, which uses the hot geothermal fluid as the energy source and supplies power to the Fenton Hill secondary electrical-distribution system in parallel with the utility supplied power.

The TEGU is a binary-fluid skid-mounted package with an organic-fluid Rankine cycle power plant complete with vaporizing, generating, and condensing equipment. The energy source, or geothermal-water side, conducts the hot water first through the tubes of a pool-type boiler and then through a tube within a preheater, and back to the geothermal loop. The geothermal fluid

is pressurized water with TEGU-acceptable design range of 90 to 175°C. The water side has a maximum working pressure of 10.3 MPa (1500 psi) and the water is circulated through it by the main circulating pumps of the Fenton Hill heat-extraction loop.

The Rankine-cycle organic fluid, Refrigerant 114, is boiled in the pool boiler, and is 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. The system schematic diagram is shown in Fig. 4-20, and Fig. 4-21 shows the Rankine-cycle diagram. The unit has been operated on-line at Fenton Hill with some difficulty, primarily due to electronic-control-unit reliability. During operation, it has performed with water-supply temperature of 132°C and ambient air at design condition of 3.8°C and has produced 60-kW net output. This is better than design-cycle efficiency of 5.7%, apparently partially due to still-clean heat-transfer surfaces. Operating time has also been interrupted and limited by energy-extraction loop experiments and by site-power interruptions.

(2) The utilization of Fenton Hill HDR energy to heat the site shop/office building is planned for the Phase II extraction operations. A water-to-water heat exchanger will be utilized with the secondary water flowing

Fig. 4-21.
Temperature-enthalpy diagram at design conditions.

through the building heating system, which currently uses an electrically heated boiler and circulating water. The heat exchanger to be used was obtained from government surplus listings.

4.2.4. Performance Characteristics and Implications. Because of uncertainties in predicting the value of the energy produced and in estimating drilling and completion costs, and because of the general variability of the resource quality (particularly the geothermal gradient), it is difficult to specify requirements for HDR reservoir performance that must be met to guarantee commercial viability. Nonetheless, minimum acceptable levels of performance have been proposed.^{67,68} These tentative requirements are stated as the characteristics of a pair of wellbores (injection well and production well) and a fracture system such that a thermal output of 20 to 50 MW(t) would be maintained over a 10-yr period of continuous operation with a drawdown not to exceed 20% at the end of the 10-yr period. It is estimated that this would require:

Effective heat-transfer area	$0.5 - 2 \times 10^6 \text{ m}^2$
Mass flow rate	35 - 75 kg/s
Average initial reservoir temperature	150 - 250°C
Overall flow impedance	$<0.4 \text{ GPa}\cdot\text{s}/\text{m}^3$.

In addition, the geochemical quality of the circulated fluid must be high enough to avoid serious corrosion or solids-deposition problems in either the surface or the subsurface system. Furthermore, permeation water loss must be manageable in terms of potential induced seismic effects from extended pressurization and in terms of what is practical economically. Although difficult to quantify, total dissolved solids levels of 2000 to 4000 ppm and water-loss rates no greater than 2 to 10% are reasonable goals.

The original objective of the Phase I research-system development was to establish engineering feasibility for HDR reservoirs in low-permeability crystalline rock. The degree to which the Phase I field-engineering results should approach the economic performance levels cited earlier is subject to varying interpretations. Still, even with this uncertainty, the early Phase I reservoir system (prior to the March 1979 workover) demonstrated some of the required characteristics, but fell short in a number of other important areas. Although the water-loss rates, fluid geochemistry, and flow impedances observed, along with the absence of induced seismicity, were acceptable even by commercial standards, the measured effective heat-transfer area of 8000 m^2 was two orders of magnitude smaller than that projected for a commercial system.

At this point, we began to explore methods of using the GT-2B/EE-1 wellbore system to answer several key questions concerning reservoir development:

- (1) Can fractures with larger heat-transfer surface areas be activated by hydraulic fracturing? (For example, individual swept areas of $100\,000\text{ m}^2$ would require only 10 fractures to achieve 10^6 m^2 .)
- (2) How do swept area and overall flow impedance scale with inlet-to-outlet vertical wellbore-separation distance? Or stated differently, how far apart can low-impedance flow connections be created with efficient fluid mixing?
- (3) How do water losses scale with reservoir size?
- (4) Can reservoir size be predicted in advance of actual thermal drawdown?

Making the step from a single 8000-m^2 fracture, with an average inlet-to-outlet vertical wellbore-separation distance of 100 m, to multiple fractures with separation distances of approximately 300 m and a total area of $1 \times 10^6\text{ m}^2$ is obviously an important intermediate goal toward achieving a successful Phase II reservoir. The Segment 4 workover therefore provided an opportunity (because of the EE-1 and GT-2B wellbore geometry) to try to improve the existing connection between the lower section of EE-1 and GT-2B. A reservoir with acceptable flow and heat-transfer characteristics created over this 300-m or greater vertical separation distance would serve as a prototype of the individual fractures planned for the EE-2/EE-3 Phase II system. (Our initial goal there is to create multiple fractures between inclined wellbores separated vertically by 360 m over a 1000-m open-hole span, which effectively defines the total reservoir.)

The massive hydraulic fracturing (MHF) treatment of the open-hole section of EE-1, following recementing of the upper zone, successfully produced an enlarged reservoir as discussed in the earlier sections and has helped to provide answers to the questions raised--thereby reducing the risks associated with Phase II and HDR development in general. Our success in forming a low-impedance reservoir with 300 m of wellbore separation distance and over $50\,000\text{ m}^2$ of useful area essentially represents answers to questions 1 and 2. What remains now is to repeat this operation several times in the EE-2/EE-3 system. The factor-of-two increase in water loss with the enlarged reservoir is much less than would be predicted by a linear extrapolation based on heat-transfer area, but predictions for water-loss rates from a larger multiple-fracture system as planned for Phase II can only be speculative at this time.

The fourth question is far from answered but progress has been made. The use of geochemical indicators and tracers to establish residence-time distributions and volumes for the fracture system, coupled to improvements in our interpretation and resolution of microseismic information, may provide a mechanism for predicting reservoir size before actual thermal exhaustion occurs. Other experimental evidence may provide a direct estimate of reservoir size. The observed thermal drawdown occurring during the Phase I tests suggests that effective swept area is empirically correlated to the square of wellbore separation distance. This measure of size agrees with tracer-determined fracture-volume measurements in comparing the original and enlarged EE-1/GT-2B systems.

Based on actual achievements at Fenton Hill over the last year, one cannot help but be cautiously optimistic about the Phase II demonstration of a commercial-sized system. However, several important issues remain to be resolved even assuming that the success of the GT-2B/EE-1 system can be translated to the new, deeper EE-2/EE-3 reservoir. These include such things as initiation of fractures at specific wellbore locations, adequate reduction of inlet/outlet wellbore impedance for highly inclined holes, and flow control into a system of multiple fractures with different impedances.

4.3. Engineering (Phase II) System Design and Engineering

4.3.1. Reservoir Design. The Phase II reservoir is intended to serve as a demonstration of commercial viability. As indicated in Sec. 4.2.4., it is difficult to specify exact requirements for reservoir performance to assure commercial viability; nevertheless, performance goals were set in Refs. 67 and 68. Basically these goals call for the production of a nominal power 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, or nearing completion, for the Phase II reservoir indicate that the mean reservoir temperature will be 260°C (500°F). Over the 10-yr evaluation period the average drawdown will 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 extracted 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 taken as 50°C. The net change in the mean water temperature is thus 180°C, requiring a flow rate of 46 kg/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.⁶⁹ Using thermal transport properties for Fenton Hill granites measured in situ,⁷⁰ it can be shown that an effective area of approximately $1 \times 10^6 \text{ m}^2$ 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 one single fracture, or several parallel fractures. In the latter case the fractures would have to be far enough apart so that thermal interaction between the fractures, which would diminish performance, could be avoided over the time span of interest, or else more area would be required to offset the diminished performance. A single fracture would require, if circular, a radius of 580 m, which is beyond established fracturing technology in HDR reservoirs. We have instead adopted the conservative philosophy that the Phase II fractures will not be much larger than the fracture that constitutes the second of our Phase I reservoirs, the reservoir we are currently evaluating in Run Segment 5. 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 about $50\,000 \text{ m}^2$, as established by its thermal-drawdown characteristics. However, this fracture was the result of the modest attempt in which only 1500 m^3 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 360 m. 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 for a total of $1 \times 10^6 \text{ m}^2$.

Because the horizontal earth stresses at depth are usually considerably smaller than the vertical, or overburden, stress, the fracture planes will be vertical. In order, then, to accommodate 14 fractures with reasonable horizontal separation distance between fractures, it becomes necessary to deviate the wells from the vertical direction in the hot downhole region, as shown in

directionally drill until a deviation of 35° from vertical is attained. Then each hole will be drilled straight ahead for an additional 1000 m, corresponding to a true vertical penetration of about 800 m, 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 for the two wells, designated as EE-2 and EE-3, follow in the next sections. Final details regarding fracturing operations are still being considered but a brief description is provided here as follows. The fractures will be made with ordinary water although it is possible that an inexpensive additive will be included to reduce friction losses in the injection well as well as to decrease permeation losses from the face of each fracture as it is propagated. Our experiences in these granitic formations indicate that upon the cessation of pumping and fracturing, the fracture faces are "self propped" due to asperity-to-asperity contacts on the fracture surface. Therefore proppants in the fracturing fluid are not required, resulting in considerable savings 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. Experience during the hydraulic fracturing operations, Expts. 195 and 203, which resulted in our current 300-m fracture, showed that pumping rates of up to $0.05 \text{ m}^3/\text{s}$ (750 gpm), pressures of 200 bars (3000 psi), and total injection volumes of 1500 m^2 (400 000 gal) of water were used in creating the fracture. Currently we plan to have a capacity of $0.08 \text{ m}^2/\text{s}$ (1300 gpm), 350 bars (5000 psi), and up to 4000 m^3 (10^6 gal) on hand for each of the Phase II fractures. Each fracture will be initiated between straddle packers in the open wellbore. These packers, manufactured by Lynes and Guiberson, were specially designed for the high temperatures they will experience. Should both of these packers fail, we can isolate selected locations with cement plugs that can later be drilled out following fracturing. Downhole fracturing locations will be selected from geophysical, temperature, televiewer, caliper, and tracer logs, focussing upon zones of potential rock weaknesses. Upon completion of the fractures, metering of the flow rate into each fracture will be accomplished with downhole, wire-line-activated flow control equipment.

4.3.2. Drilling and Completion of Well EE-2. The drilling of EE-2 began on April 3, 1979, and was completed on May 12, 1980, to a drill string depth of 4661 m (15 289 ft). The major portion of the footage in the hole was made

with conventional rotary techniques, using appropriate bottom-hole assemblies, but numerous downhole motor runs were made to guide the hole along the desired azimuth and inclination.

A detailed account of the drilling of EE-2 to a depth of 10 067 ft below the rig floor (i.e., that portion of the drilling operation executed during FY79) was given in the Annual Report for FY79⁵¹ (Sec. 4.2.1.). A continuation of that account is contained in this section.

The drilling of wells EE-2 and EE-3 is being done by Brinkerhoff/Signal. The drilling contract was let by DOE/AL00 and the work is covered by Davis Bacon Act requirements. The firm of Grace, Shursen, and Moore Associates has been retained under contract to the Los Alamos National Laboratory to aid in planning and execution of the drilling and completion. Technical responsibility rests with the Laboratory.

Figure 4-23 is a plot of wellbore penetration for EE-2 vs days and date since the beginning of drilling. It is to be noted that this plot covers work accomplished in FY79 in addition to that accomplished in FY80.

From the depth of 10 067 ft reached on September 30, 1979, drilling continued to 11 576 ft using 12-1/4-in.-diam tri-cone bits and roller reamers.

Fig. 4-23.
EE-2 drilling history (depth along drill string).

At that depth, a transition was made to a hole size of 8-3/4 in. This was accomplished by drilling for 10 ft with an 11-in. bit followed by drilling the next 10 ft with a 9-5/8-in. bit. The remainder of the hole, beyond 3541 m (11 616 ft), was drilled with 8-3/4-in. tri-cone button bits and roller reamers on the drilling assembly to assist in the maintenance of hole size. This portion of the drilling operation was relatively straightforward with one major exception: at a depth of approximately 4250 m (13 940 ft), a loss of circulation of drilling fluid occurred due to damage/collapse of the 13-3/8-in.-diam casing at a depth of approximately 518 m (1700 ft). It turned out to be exceedingly difficult to repair this damaged casing. A series of cementing and milling operations at best produced no improvement and at times appeared to be causing further damage to the casing along more of its length. During this period 6200 sacks of cement were placed in the 1780- to 2400-ft region in attempts to stabilize the hole. Much of the time during this period was spent in milling through cement, fill, and collapsed casing. On March 22, it was decided that the hole was clear enough to attempt to set casing even though circulation had not been restored and all operations would have to be carried out with no returns. A fairly complicated pre-cooling was carried out, 9-5/8-in. casing was run to bottom (411 580 ft) on March 28, and more pre-cooling done through March 30. The casing was cemented-in on March 31 and post-cooling accomplished through April 2. Milling through gunk at the bottom of the hole was not finished until April 26, at which time regular 8-3/4-in. drilling was resumed. The total depth of 4661 m (15 289 ft) was attained on May 12. This was followed by 4 days of wireline tool work, and on May 16 the drill rig was released (to move over to the EE-3 location).

In summary, the well EE-2 was successfully completed in the total drilling time of 409 days. As has been noted in this report and in the FY79 Annual Report, a large amount of time was consumed by unplanned and costly incidents or equipment failures, the remedies for which were difficult and expensive.

It is also perhaps worth emphasis that EE-2 has been the first well drilled into deep hot hard crystalline rock along a carefully controlled trajectory and with the deep production hole section at the high inclination of 35° from the vertical. Control of direction and inclination has been difficult and has severely taxed the capability of the downhole motors and steering tools available to do the job. The attempt will be made to transfer experience gained from EE-2 to the drilling of EE-3.

4.3.3. Drilling Well EE-3. The bottom-hole assembly for hole EE-3 was picked up on May 21 and the hole was spudded on May 22. The rig had been skidded from the EE-2 site 46 m (150 ft) to the west without lowering the mast. The 30-in. conductor pipe and the cellar had been previously emplaced. A new mud pit, to be used in conjunction with the EE-1/2 mud pit, and an extension of the drill site had been prepared prior to skidding the rig.

Drilling was performed with 26-in. bits to a depth of 577 m (1894 ft) without serious lost circulation problems, but at this depth, loss of circulation was complete. Two attempts were made to cement off the lost circulation zone by pumping 500 sacks of thixotropic cement. The hole was drilled through the cemented zone after the first attempt, and circulation was lost again. After the second cementing attempt, the hole was drilled into the cement to 541 m (1775 ft). Considerable sloughing of the hole walls and bridging of the hole was experienced, and it was now necessary to set the 20-in. surface casing in order to continue drilling.

Fill that was in the bottom of the hole prevented the casing from reaching the bottom, and it was set to 481 m (1580 ft). Twenty-four hundred sacks of cement were pumped into the annulus behind the 20-in. casing without filling the annulus. An additional 650 sacks were pumped into the annulus from the surface, which filled it to the top.

Drilling was then started with a 17-1/2-in. bit, and circulation was lost again at 567 m (1860 ft). One attempt was made to cement up the lost circulation 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 as our water supply from 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. This also caused some delays as the usage rate exceeded the practical hauling rate. The granite was encountered at 732 m (2404 ft), and the drilling continued to 783 m (2567 ft).

A 13-3/8-in.-diam casing was run into the hole and cemented in two stages. The first stage consisted of 200 sacks of cement to bond the bottom of the casing to the granitic formation for about 45 m (150 ft). After this cement was set, the casing was tensioned with casing jacks to a load of 341 000 kg (750 000 lbs), a stretch of the casing of 48 cm (19 in.). This was done to prevent the occurrence of excessive compression loads in the casing

when it is heated by hot fluids after the completion of the Phase II system. Next the casing was cemented from 422 m (1384 ft) to the surface through a cementing sleeve that was emplaced in the casing string at that depth.

Rotary drilling continued using a variety of tungsten carbide button bits to a depth of 1964 m (6444 ft). This drilling was plagued by occasional washouts of the drill collars and two short fishing jobs but was the least troublesome of any of the drilling of EE-2 or EE-3 to date. At this depth the hole direction was $10^{\circ}\text{N}58^{\circ}\text{W}$ and had to be turned to a northeasterly direction in order to proceed in the proper relation to hole EE-2.

The next 17 days and 224 m (736 ft) of drilling were spent in turning the hole from $\text{N}58^{\circ}\text{W}$ to $\text{N}83^{\circ}\text{E}$ during which drilling the inclination reached a high of $14\text{-}3/4^{\circ}$ and then dropped to 7° . A directional driller was employed during this operation and Scientific Drilling Company's "Eye," a continuous directional sensing instrument, was employed after it became apparent that inclination and azimuth angles of the hole could not be controlled by the use of single-shot directional equipment.

A variety of downhole "mud motors" was employed for this work: the Baker Service Tool motor, Smith Tool Company's Dynadril, and Christensen's Navidrill. No preferences were established from among these motors during this drilling.

After a discontinuation of drilling to permit the inspection of drill pipe and the rig and replacement of the rig drive shaft, rotary drilling was reinitiated. It was thought that this drilling would raise the inclination angle of the hole and that the azimuth angle would gradually turn to the left. This drilling started at 2300 m (7542 ft) and went to 2390 m (7840 ft) during which the inclination angle increased from 7° to $13\text{-}1/4^{\circ}$ as was desired. However, the azimuth angle changed drastically from $\text{N}83^{\circ}\text{E}$ to $\text{N}46^{\circ}\text{E}$. If this were allowed to continue, the proper positioning of hole EE-3 with EE-2 would be jeopardized. Therefore, it became necessary to again initiate directional drilling, which was in progress at the end of the fiscal year.

4.3.4. Engineering Design Of Surface Systems. The design of the Phase II surface system has been completed during FY80. The loop has been designed to have a heat-rejection capability of 50 MW(t), a flow rate of geothermal fluid of 1000 gpm (max), and a reservoir inlet pressure of 3000 psi (max).

Figure 4-24 shows the general system arrangement; only the major valves are shown in the figure. For discussion, the system is divided into four

Fig. 4-24.
Phase II surface system design.

areas: (1) water storage, (2) heat exchangers, (3) pump building and process control room, and (4) interconnecting piping and wellhead plumbing.

Water Storage. It is planned that a new storage pond of 5 000 000-gal capacity will be constructed in FY81. (Further discussion of water storage and supply for operations can be found in Sec. 4.3.5.) The pond is lined to prevent leakage and has a floating cover to reduce evaporation. The pond will be supplied either from the local water well(s) or trucks, or both. Two transfer pumps are situated adjacent to the pond. One pump is electrically driven and will provide water to the holding tank at 500 gpm. The second pump is gasoline powered and will be used only for emergency pumping.

Heat Exchanger. The heat-exchanger area has been redesigned. The existing heat exchangers can dissipate 25 MW. Space to double the present capacity has been provided. In addition, extensive changes to the valving and piping to facilitate operations have been delineated.

Pump Building and Process Control Room. The present system (Phase I) is capable of ~1400-psi injection pressure. The pumps to do this, four

super-chargers and four circulating pumps, are located in two areas ~200 ft apart. The Phase II system will require ~1000 gpm at 3000 psi. Additional pumps to raise the pressure to this value have been purchased. In the new design, all pumps (14) will be housed in this pump building. The final control element and flow measurement to the injection side will also be located in this building. Also, the process control room will be located here. The pump building will serve both the Phase I and Phase II systems.

Interconnecting Piping and Wellhead Plumbing. The interconnecting piping has been sized to handle the maximum anticipated flow of 1000 gpm at the pressures anticipated. Wherever possible, the piping will be placed underground to minimize interference with site operations. Both wellheads will have lock and valve systems to permit logging under operating conditions. The production well (EE-3) will have a remotely operated valve at the surface to be used to shut in the well if required.

4.3.5. Water System Development, Fenton Hill. The final specifications for the 5 000 000-gal storage pond were approved and submitted for bids. Boyle Engineering Corporation was selected to design the pond and related distribution system; however, because of budget constraints, the construction package was delayed pending additional funding. A small, but badly needed, additional water storage capacity was acquired with the completion of a reserve pit for EE-3.

Several small test holes were drilled into the Fenton Hill volcanics to acquire information to assess the aquifer. One test hole was a duster, but results from the other test holes indicated ample availability of ground water. An exploratory water well (FH-2) was drilled to about 450 ft; the water level stabilized at 371 ft below surface level. A test at a pumping rate of 20 gpm for 2.25 h of pumping indicated a drawdown of 0.8 gpm/ft. The pumping rate was increased to 40 gpm and after 40 min of pumping, the water level dropped to the top of the pump setting with a specific capacity of about 1 gpm/ft.

Because of the poor performance of water well FH-2, a third water well (FH-3) was drilled and cased to 450 ft. Water was encountered at 380 ft, rising and stabilizing at 370 ft below surface level. Initial testing of this well indicated it was relatively unproductive, less than 4 gpm. It was determined that some form of well damage had occurred, and routine methods undertaken to repair the damage were unsuccessful.

A consulting hydrologist was contracted to evaluate water well FH-3 and to provide an outside determination of the production capacity of the aquifer. The consultant agreed that attempts to make FH-3 a productive well might or might not succeed. In view of the cost involved and the low probability of success in repairing FH-3, a decision was made to abandon the well and to conduct aquifer pumping tests using the existing, productive water well, FH-1. The consultant assessed the aquifer as being semiconfined, approximately 60 ft thick with a transmissivity of about 7000 gpd/ft and having an annual recharge rate of about 200 acre ft per square mile.

In May the 15-acre-ft annual allotment of water for experimental and drilling purposes was exhausted. Subsequently only water for domestic use could be pumped from the well and water for "makeup" for the loop operation and for drilling had to be purchased and hauled to the site.

4.4. Reservoir Engineering and Analysis.

Reservoir engineering and analysis is the collection and utilization of all the scientific evidence at our disposal to assemble a model, i.e., a physical and mathematical abstraction of the geometry and performance characteristic of our reservoirs. The goal is to use this information to infer the in situ properties of the reservoir, allowing better understanding of the existing reservoir and improved design of future reservoirs. The tools used in reservoir engineering and analysis consist of theoretical, usually numerical, calculations; laboratory-scaled experiments, for example, fundamental studies of properties determined from core specimens; and finally, in situ measurements utilizing geophysical logs and field results. The disciplines to be integrated to obtain an accurate overall description are physics, chemistry, geology, and geophysics. Of particular interest for HDR reservoirs are fluid and solid (rock) mechanics, heat transfer, geochemistry, seismology, petrology, and lithological studies.

Applications of reservoir engineering and analysis, particularly the in situ aspects, have already been discussed in Secs. 4.2 and 4.3.1, which discuss the results of heat-extraction experiments in the Phase I system and the research reservoir, and design of the Phase II reservoir, respectively. In the present section we focus on the analysis tools currently under development. Section 4.4.1. discusses five theoretical modeling efforts. Following these theoretical treatments are discussions of laboratory, and some in situ, observations concerning: (1) downhole geology inferred from drill cuttings

and core specimens, (2) permeability measurements on core specimens, (3) rock mechanical properties, (4) thermal-stress cracking experiments, and (5) geochemistry studies. The final item of discussion concerns related domestic and foreign programs.

4.4.1. Theoretical Modeling Efforts. Incorporation of Thermal-Stress

Cracking in Models for Heat Extraction from HDR Reservoirs. Circulation of water through the primary fracture removes heat from the adjacent rocks by conduction, and in the early stages of the system this is the principal mechanism for energy extraction. At a fixed flow rate, the initial heat-extraction rate cannot be maintained; soon it decreases, principally because cooling forms a thermal skin between the primary fracture and the nearby hot rock. The skin thickness grows with time, forming a progressively greater insulation to the conduction of heat. The extent of the power decrease depends on various factors, some within the control of the plant engineer and some that depend on the changing state of the rock itself. In this latter category is the potential for enhancement of heat-extraction rate as a result of thermal-stress fractures. Because the cooler rock has contracted, it is expected that a system of lateral fractures will develop, branching from the primary crack and extending into the adjacent rock in such a way as to allow convective exchange of heat. The result can be a significant increase in the power output over the results from conduction alone.

To investigate the effects of thermal-stress cracks on the transport of heat to the primary fracture, the REX (Rock Energy Extraction) computer code has been written and used to study the coupled processes of primary-crack flow and lateral thermal-fracture heat and water transport.⁷¹ The development of this computer code has emphasized several important features.

(1) The calculations should proceed with optimal efficiency, allowing for real-time investigations of 100 yr or more in a few minutes of computer time.

(2) The equations must be numerically stable, even in the limit of strongly buoyancy-dominated circumstances.

(3) The code must be prepared to accept evolving rock-mechanics data as they become available and to provide the detailed information required by the coupled rock-mechanics code that ultimately must be constructed to run in tandem with REX.

(4) The study must recognize the combined deterministic-stochastic nature of the lateral thermal crack system, so that the REX code must accept representations of either type.

In this last regard, we have developed two different descriptions of the heat and water exchange through the network of lateral cracks. The deterministic description is based on calculations by the computer code, GEO-III,⁷² which examines the flow through a single idealized lateral thermal-stress crack, with results that are parameterized for inclusion in REX as a function of locally developing circumstances. The stochastic description⁷¹ is based on GEO-III results for early times, and extends to a random-walk representation through a maze of interconnected cracks at late times.

Whereas Sec. 4.4.3. discusses thermal-stress cracking experiments, the techniques described here are purely theoretical, consisting of three essential parts.

(1) The basic laws of mass, momentum, and energy conservation are formulated in differential equations appropriate to the circumstances. These are supplemented with the specification of initial and boundary conditions, material properties, exchange rates, and the derivation of transport models.

(2) The differential formulations are replaced by finite-difference approximations suitable for solution by high-speed computer. Numerical analysis techniques are developed in such a way as to ensure numerical stability, efficiency, and a sufficient degree of accuracy for calculations extending over long periods of elapsed time, typically up to 100 yr.

(3) Numerous examples are calculated in order to investigate sensitivity to our assumptions and to exhibit the results that can be expected under a variety of circumstances.

The basic formulation assumes the Boussinesq approximation for a fluid with density that varies by a small fraction of its nominal value, ρ_0 , as a result of thermal expansion. Compared to sound speed, the fluid velocity is small enough for the material to be considered otherwise incompressible. Accordingly, the conservation of mass in three space dimensions can be described by a balance of volumetric fluxes. With fluid velocity, $\vec{u}$, we have

$$\nabla \cdot \vec{u} = S_{in} + S_{out} + S_c, \quad (1)$$

in which S_{in} and S_{out} are the volumetric inlet source and outlet sink, and S_c is a volumetric sink into the growing lateral thermal cracks. For the momentum equation, any momentum source or sink at the inlet or outlet is neglected. The Boussinesq form is

$$\frac{\partial \vec{u}}{\partial t} + \nabla \cdot (\vec{u}\vec{u}) = -\nabla \bar{\phi} + (\nabla \cdot \nu \nabla) \vec{u} + \vec{g} \frac{\rho}{\rho_0} , \quad (2)$$

in which $\bar{\phi}$ is the ratio of pressure to nominal density, ν is the kinematic viscosity coefficient, and $\vec{g}$ is the acceleration of gravity. Incorporating the mass equation, we have transformed the usual convective term, $\vec{u} \cdot \nabla \vec{u}$, into the divergence of a dyadic in order to produce a conservative form as a basis for the finite-difference equations. The ratio of actual to nominal density, ρ/ρ_0 , can be described in terms of water temperature, T , a reference temperature T_0 , and volumetric coefficient of expansion, β , by the relation

$$\frac{\rho}{\rho_0} = 1 - \beta(T - T_0) . \quad (3)$$

With T in degrees Celsius and ν in units of cm^2/s , it is sufficiently accurate for our purposes to write

$$\nu = \frac{0.279}{T - 3.8} . \quad (4)$$

A modified pressure, ϕ , is introduced such that

$$\nabla \phi = \bar{\nu} \bar{\phi} - \vec{g}[1 - \beta(\bar{T} - \bar{T}_0)] , \quad (5)$$

in which $\bar{T}$ is the horizontally averaged temperature across the span of the primary fracture, therefore a function only of height and time. Accordingly, the momentum equation becomes

$$\frac{\partial \vec{u}}{\partial t} + \nabla \cdot (\vec{u}\vec{u}) = -\nabla \phi + (\nabla \cdot \nu \nabla) \vec{u} + \beta \vec{g}(\bar{T} - T) . \quad (6)$$

For the water temperature equation, we write

$$\frac{\partial T}{\partial t} + \nabla \cdot (\vec{u}T) = S_{in} T_{in} + S_{out} T_{out} + \text{wall source} \quad . \quad (7)$$

The wall source describes two effects: conduction through the rock and convection through the lateral thermal stress fractures. It is modeled by either the deterministic or stochastic representation, as discussed in Refs. 71 and 72.

To efficiently solve these equations numerically requires that we transform the three-dimensional differential equations into two-dimensional finite-difference equations in the plane of the primary crack. W denotes the gap width, which can vary with position and time. Our technique, however, ignores the time derivatives of W because at each stage of the evolution we hold the rock properties constant and seek the corresponding pseudo-steady state in velocity and temperature configuration. The validity of this approach is demonstrated by the existence of two very different time scales, one being the time required for appreciable changes in the state of the adjacent rock, the other being the very much shorter time required for the water velocity and temperature to adjust to changes in the rock state.

To derive the finite-difference equations for heat and mass transfer in the crack, we integrate the equations over the three-dimensional volume contained in a finite-difference cell of dimensions δx by δy by W . In this process, we assume that the velocity components vary with z in a Poiseuille profile in accordance with laminar flow through smooth-walled fractures. Relatively greater buoyancy near the edges of the crack, together with the possible turbulence and the effects of wall irregularity, would induce departures from this idealization; these are represented by a coefficient with slightly uncertain magnitude. In this transformation, the Eulerian time derivative and convective terms in the momentum equation are retained, in order to ensure that strongly buoyancy-dominated circumstances can be calculated. In addition, the convective terms in both the momentum and temperature equations are treated implicitly to assist in the ensurance of numerical stability over long periods of elapsed time, thereby extending the degree of numerical implicitness customarily employed for incompressible flow in the mass convection and pressure terms.

The overall flow of logic for a computational cycle is shown schematically in Fig. 4-25, and in detail by means of the REX computer listing. In each cycle, the iterative solution for pressures and velocities continues to adequate convergence before proceeding to the iterative solution for temperature, which is also forced to adequate convergence before we test for the achievement of a pseudo-steady state. The criterion for pseudo-steady state is the constancy of temperatures between the previous and current subcycles. When this is adequately achieved, it follows that the terms $\partial u/\partial t$, $\partial v/\partial t$, and $\partial T/\partial t$ in the momentum and temperature equations all vanish and the value of δt used in the subcycling becomes

irrelevant except that its value must be small enough to avoid numerical instability. Likewise $\partial W/\partial t$ would vanish if it had been included, but its presence is not required. Indeed, it might be supposed that we could simply omit also the terms $\partial u/\partial t$, $\partial v/\partial t$, and $\partial T/\partial t$ and iterate to convergence at a pseudo-steady state in one subcycle, but this is not feasible for two reasons. The first is that we need the simultaneous constancy of temperatures and velocities, which, however, are strongly coupled among each other, so that subcycling is the only alternative to an extremely complicated simultaneous solution procedure. The second reason is that the difference formulations for the momentum equations exhibit a seemingly incurable numerical instability in the absence of the velocity-component time derivatives. In any case, subcycling turns out to be a highly efficient procedure for achieving the long-elapsed-time computer runs that are necessary for our investigations.

The number of subcycles per cycle is typically 1 to 20, depending principally on the time interval per cycle. In contrast to the small magnitude of δt used in the subcycling, the actual elapsed time per cycle commences with a magnitude of roughly 20 s and increases in such a way that it approaches 7.5%

Fig. 4-25.
The flow of computer logic for the REX code.

of the elapsed time, for example to an interval of 7.5 yr near the end of a 100-yr calculation.

Figure 4-26 shows the position of inlet and outlet for a typical calculation. The results in Fig. 4-27 are presented in the form of velocity vectors and contours of water temperature in the primary crack at four different times. In this example, the water flows rather directly from the source to the sink during the first year or so of operation. Thereafter, with a drop in primary-crack impedance, the flow becomes buoyancy dominated, with cold water falling towards the bottom of the primary crack before curving along its path back up to the outlet. The corresponding temperature contours gradually pull away from the inlet position, until at the last time (100 yr) the lower three-fourths of the crack are scarcely above the inlet temperature (100°C).

Energy-extraction rate is the principal quantity of interest in these calculations. To assess the effects of thermal-stress fracture on the enhancement of energy extraction, we performed a set of calculations that varied only in the value of σ_0/ω , a parameter that describes the rock properties and the propensity for thermal stress cracking. The results are shown in Fig. 4-28. The case with conduction alone corresponds to $\sigma_0/\omega = 0.0$. Our best current estimate for this parameter is $\sigma_0/\omega = 1.0$, which shows appreciable thermal-fracture enhancement to the energy-extraction rate. With $\sigma_0/\omega = 5.0$, the enhancement can be as much as a factor of two. The details characterizing these and additional calculations are presented in Ref. 71.

Water Flow and Diffusion Through Fracture Reservoirs. From the time of the formation of the first fractures at Fenton Hill, it has been assumed that the early-time pressure and flow history of the fracture system was determined by permeation flow out of a large low-impedance main fracture into the surrounding matrix or joints.⁷²⁻⁷⁷ That is, the early-time flow and pressure data have been interpreted in terms of the diffusion parameter $\alpha A/\sqrt{Kc}$ where A is the area of a large zero impedance

Fig. 4-26.
Inlet and outlet positions for a typical calculation.

Fig. 4-27.

Velocity vectors and contours of water temperature at times 1.08×10^5 s, 3.53×10^7 s, and 3.13×10^9 s (100 yr).

Fig. 4-27 (Cont.)

Fig. 4-28.
Energy-extraction rate as a function of time for various values of σ_0/ω .

fracture and k and c are the formation permeability and compressibility. More recent developments make it necessary to examine other possibilities. Three different drillings of GT-2, 2A, and 2B have failed to encounter any such large low-impedance fracture.* The lowest impedance connection was that of GT-2B and EE-1, and the low impedance was established only after long-term pressurization and circulation (Phase I) and high back-pressure flow (Expt. 186).⁷⁷ Since the connecting fractures are among those being inflated during the measurement of the diffusion parameter, it is entirely possible that the impedance giving rise to this diffusion parameter is in the main fracture. This alternative interpretation of the data is that the early-time flow is determined by the impedance and storativity of the main fractures. The

*Note: This statement is somewhat misleading, since when GT-2 was drilled, there was no fracture to find. There is some evidence that GT-2A did intersect a large fracture. GT-2B would probably also have intersected it, although at the wrong place, if it had been continued. However, the GT-2A connection did not give "low impedance."

parameters contributing to the diffusion parameter $\alpha = A_c \sqrt{k_f c_f}$ are the cross-sectional area of the fracture A_c , the fracture permeability k_f , and the fracture compressibility c_f .

The general picture that would allow this interpretation is as follows. Repeated pressurizations of the wellbore reduce the wellbore-to-fracture impedance by breaking down the rock or opening existing connections into large natural fractures or into artificial fractures that are created in the same process. The subsequent pressure and flow histories are characterized by radial or linear flow into high-impedance fractures. If it can be established that this interpretation is possible, then any intermediate case in which fracture flow and permeation flow both contribute significantly may be possible.

This alternative interpretation must also give fracture parameters that are consistent with the other data such as those obtained from tracer studies, wellbore logs, and temperature logs.

All of the existing data sets have been examined to produce an internally consistent picture of the HDR reservoir through Segment 3 of Phase I. This analysis is described in detail in Refs. 78 and 79. The general procedure and conclusions are discussed briefly here.

The diffusion parameters governing injection ($\alpha = A/\sqrt{Kc}$) and circulation ($I = P/\dot{Q}$) were determined by fitting a model calculation to the data. This empirically determined pressure dependence for the fracture properties was shown to be similar to those obtained by other investigators in laboratory experiments on large fractures.⁸⁰⁻⁸²

A flow dependence of the receptivity α was observed in the data for injection tests spanning several years. This receptivity was interpreted in terms of a permeability having a flow-dependent and a constant (laminar) part. It was shown that this behavior could result from either fracture flow or formation (matrix) flow if the formation flow is dominated by cracks and joints rather than by microporosity.

Of the three flow-through connections, the impedance of the final one between EE-1 and GT-2B was found to be flow-dependent as well as pressure-dependent. Rough-wall and turbulent-flow theories were used to show that the transition to nonlaminar flow occurred at reasonable specific flow rates.

Finally, the parameters obtained from the flow data were also combined with those from dye-tracer,⁸³ thermal-drawdown,⁸⁴ and laboratory permeability⁸⁵⁻⁸⁶ data to obtain approximate fracture dimensions and limits on

permeating area and effective confining permeability. To obtain these estimates it was assumed that the early-time injection data were dominated by linear fracture-flow with pressure- and flow-dependent properties and that the long-term linear water loss is associated with a large permeating area. These results are summarized in Figs. 4-29 and 4-30 and show that an internally consistent picture can be developed in terms of average fracture dimensions.

Graphical Summaries. All of the flow characteristics discussed in the previous sections can come from fractures of roughly the same average dimensions, width W , and height h_f . This is due, at least in part, to the number of parameters that have not yet been determined. In particular, those parameters that determine the distribution of the possible flow regimes throughout the fracture are uncertain. However, the hypothesis outlined in the introduction does not lead to any immediate inconsistencies. Two important points must be kept in mind. (1) The assumption has been made that the flow into what may be a complex fracture system can be characterized by the three average parameters c_f , W , and h_f . That is, W and c_f may be averages over several fractures and h_f may be the combined length of several fractures. (2) None of the complications arising from the possibility of radial flow have been introduced. For instance, if the impedances are concentrated near the wellbores by convergent flow, more free parameters can be introduced and the situation becomes even less certain.

In Fig. 4-29 the relation of W to h_f for an average value of $c_f = 3.0 \times 10^{-2} \text{ MPa}^{-1}$ is estimated for the Fenton Hill fractures. The solid line labeled with the measured value of α_f ranges from the zero flow limit where the laminar theory is appropriate. The dashed lines indicate a possible range of W and h_f as calculated from the impedance values obtained in Expts. 184 and 190. A roughness of 1.0 was used for experiment 184 and fully turbulent conditions for Expt. 190. It should be kept in mind that the impedance measurements have been made with one side (EE-1) of the system pressurized and it would be expected that the resulting values of W would be somewhat larger than those obtained from α_f measurements. The lines labeled with values of V_f are for the fracture volume estimates. The curve $V_0 = 1 \text{ m}^3$ sets limits on the zero impedance volume as determined earlier. The dimension of this volume must fall below this curve but well above the α_f curve. The $V_f = 50 \text{ m}^3$ is the fracture volume from dye tracer studies at the end of the 75-day experiment. The vertical line labeled $\sqrt{A_T}$ is the square root of the heat-exchange area

of the 75-day experiment. The vertical line labeled $BQ = 1$ is the dimension transverse to the flow as obtained from the ratio of the linear-to-quadratic terms in α_f for a rough fracture with a roughness of 0.37.

Approximate limits can also be obtained for those parameters that determine the long-term water losses of the system. By assuming that the long-term linear water loss is a formation flow and by assuming a canonical value of pore compressibility as obtained in the laboratory ($c = 4.0 \times 10^{-15} \text{ MPa}^{-1}$), an upper limit on the permeating area and on the effective value of permeability can be determined. Figure 4-30 is a plot of effective permeability confining the system vs the square root of the permeating area. Each straight line represents a limit set by some measured parameter: the allowable portion of the graph is indicated by the directions of the arrows. The parameters and limits annotated on the figure are as follows.

- τ_A : limits set by one-dimensional nature of the flow
- $\dot{Q}$: limit set by small value of long-term water-loss rate
- $\sqrt{A_T}$: limit set by assuming that the permeating area is larger than the heat-exchange area
- k : limit set by smallest laboratory permeability

Fig. 4-29.

Approximate limits on fracture width (W) and fracture height (H_f) set by short-term injection and flow-through parameters.

Fig. 4-30.

Limits on permeability and fracture area set by long-term flow parameters.

Fig. 4-31.

Schematic of the Reservoir System. The terms q and C are respectively the volumetric flow rate and concentration of species i at the location specified by the subscript: m = makeup, l = loss, 1 = path 1, 2 = path 2, in = injection well, out = production well. V and T are the volumes and temperatures of the individual flow paths.

$A\sqrt{kc}$: limit set by assuming that this parameter is determined only by the small-scale porosity

V_v : limit set by approximate venting volumes.

Geochemistry. Geochemical Modeling of the Reservoir. Continued progress on the geochemical model of the reservoir system has resulted in a general mathematical description for changes in concentration of chemical species resulting from mineral dissolution or pore fluid displacement in parallel flow paths. The basic equations describing the chemical behavior of the reservoir system are derived by writing a mass balance on each species and on the total mass for a control volume as shown in Fig. 4-31.

The mass balance can be written as

$$V_T \frac{dC}{dt} = \dot{q}_{in} C_{in} - \dot{q}_{out} C_{out} - \dot{q}_{loss} C_{loss} + \dot{Q}_i, \quad (8)$$

where V_T is the total system volume, $\bar{C}$ is the mean system concentration of i and $\dot{Q}_i$ is the source term for either dissolution or displacement. It can be shown that for first order dissolution, $\dot{Q}_i$ can be written as

$$\dot{Q}_{i(\text{dissolution})} = \dot{q}_1 \epsilon_1 (C_1^{\text{sat}} - C_{in}) + \dot{q}_2 \epsilon_2 (C_2^{\text{sat}} - C_{in}) \quad (9)$$

if we define

$$\epsilon_1 \equiv (1 - e^{-k_1 a^* \tau_1 f_1}) \text{ and } \epsilon_2 \equiv (1 - e^{-k_2 a^* \tau_2 f_2}) \quad , \quad (10)$$

where k_n is the reaction rate coefficient in path n , a^* is the ratio of interfacial area to fluid volume in the path n , τ_n is the mean residence time, and f_n is the deviation from plug flow in path n .

The equation describing pore fluid displacement has a similar form:

$$\dot{Q}_{i(\text{porefluid})} = \dot{q}_1 \epsilon_1 (C_1^\infty - C_{in}) + \dot{q}_2 \epsilon_2 (C_2^\infty - C_{in}) \quad , \quad (11)$$

where now

$$\epsilon_1 \equiv \exp(-\frac{f_1 t}{\tau_1}) \text{ and } \epsilon_2 \equiv \exp(-\frac{f_2 t}{\tau_2}) \quad .$$

By making the appropriate substitutions and assumptions (e.g., $\bar{C} = C_{\text{loss}} = C_{\text{out}}$), Eq. (8) can be reduced to

$$V_T \frac{d\bar{C}}{dt} = \dot{q}_m (C_m - \bar{C}) + \dot{q}_1 \epsilon_1 [C_1^\infty - C_m] + \dot{q}_2 \epsilon_2 [C_2^\infty - C_m] \quad . \quad (12)$$

Letting $C_1^\infty = C_2^\infty = C^\infty$ and making the substitution

$$\bar{C} = C^\infty - (C^\infty - C) \theta \quad (13)$$

then Eq. (12) becomes,

$$\frac{d\theta}{dt} + \frac{\dot{q}_m}{V_T} (\theta - 1) = -\frac{1}{V_T} [\dot{q}_1 \epsilon_1 + \dot{q}_2 \epsilon_2], \quad (14)$$

which has the solution

$$\theta(t) = 1 + [\theta(0) - 1] e^{\frac{-\dot{q}_m t}{V_T}} - \dot{q}_1 \frac{e^{\frac{-f_1 t}{\tau_1}} - e^{\frac{-\dot{q}_m t}{V_T}}}{\frac{\dot{q}_m}{V} - \frac{1}{\tau_1}} - \dot{q}_2 \frac{e^{\frac{-f_2 t}{\tau_2}} - e^{\frac{-\dot{q}_m t}{V_T}}}{\frac{\dot{q}_m}{V} - \frac{1}{\tau_2}}. \quad (15)$$

A similar analysis for the open-loop condition provides a solution for θ of

$$\begin{aligned} \theta(t) = 1 + [\theta(0) - 1] e^{\frac{-(q_m + q)t}{V_T}} - q_1 \frac{e^{\frac{-f_1 t}{\tau_1}} - e^{\frac{-(q_m + q)t}{V_T}}}{\frac{\dot{q}_m}{V} - \frac{1}{\tau_1}} \\ - q_2 \frac{e^{\frac{-f_2 t}{\tau_2}} - e^{\frac{-(q_m + q)t}{V_T}}}{\frac{\dot{q}_m}{V} - \frac{1}{\tau_2}}. \end{aligned} \quad (16)$$

Comparisons of these solutions with data from Run Segment 4 are shown in Fig. 4-32. Values of the parameters used in the fit and used constructing the dimensionless plots are given in Table 4-III. The close fit of the calculations with the actual data indicates that a model with two parallel paths and incorporating pore fluid displacement is sufficient to describe the geochemical behavior in the reservoir.

Fig. 4-32.

Values of the parameters used in the fit and used constructing the dimensionless plots are given in Table 4-III. The close fit of the calculations with the actual data indicates that a model with two parallel paths and incorporating pore fluid displacement is sufficient to describe the geochemical behavior in the reservoir.

TABLE 4-III

VALUES OF PARAMETERS USED IN THE MODEL TO FIT THE GEOCHEMICAL DATA FROM RUN SEGMENT 4

	Open Loop	Closed Loop
$\dot{q}_{GT-2}$	100 gpm (measured)	100 gpm (measured)
$\dot{q}_m$	~200 gpm (~average)	20 gpm (measured)
V_T	100 000 gal (near the measured value)	100 000 gal (near the measured value)
τ_1	0.35 days (measured)	0.35 days (measured)
τ_2	100 days (estimated)	100 days (estimated)
f_1	0.15 (estimated)	0.15 (estimated)
f_2	0.75 (estimated)	0.075 (estimated)
C_{Cl}^∞	1600 ppm (measured)	1600 ppm (measured)
$C_{m_{Cl}}$	15 ppm (measured)	15 ppm (measured)

Geochemical Geothermometry. In an attempt to resolve questions about the interpretation of quartz geothermometry in the Phase I reservoir, an experiment--designated the Fresh Water Flush (FWF)--was performed during Run Segment 5. The intent of this experiment was to determine the flux of silica into solution due to the dissolution of quartz within the main flow path. This flux is directly proportional to the local kinetic reaction rate constant (k), the active surface area of quartz exposed to the circulating fluid, and the local degree of undersaturation ($C_{\text{local}}^{\text{sat}} - C_{\text{local}}$); and it is inversely proportional to the system volume (V):

$$\frac{\partial C}{\partial t} + U \frac{\partial C}{\partial z} = k A_{\text{qtz}} \frac{(C^{\text{sat}} - C)}{V} \quad (17)$$

The operational sequence for the FWF experiment was as follows. After several months of continuous operation, system parameters such as impedance, water loss, wellhead pressures, flow rates, and concentrations of chemical species had reached steady state values. The chemical state of the system was suddenly perturbed by a step change in inlet fluid composition. This was achieved by venting the produced fluid to a storage pond rather than recirculating this fluid and by inserting fresh makeup water in EE-1. The resulting declines in dissolved species concentrations--particularly the silica and chloride concentrations--were monitored by regular sampling of the produced fluid. After 1000 m³ (≈260 000 gal) of fresh water had been flushed through the system, the loop was returned to recirculating closed-loop operation and the buildup rate for dissolved species was observed. Graphs of the observed silica and chloride behavior are shown in Fig. 4-32.

In order to interpret the results of the FWF, solutions of Eq. (8) were obtained with our best estimates of the values of A_{qtz} , V , k , U , and C^{sat} . Because k and C^{sat} are exponential functions of temperature, and

$$k = \alpha \exp(-E_{\text{act}}/RT) \quad (\text{Arrhenius equation})$$

$$C^{\text{sat}} = 154\,817.15 \exp(-3014.6/T) \quad (\text{Quartz geothermometer}),$$

they can also be regarded as functions of distance along a flow streamline because T is a function of this distance.

Solution of the steady state form of Eq. (17) for small intervals Δt over which T can be taken as constant can be used to predict the silica concentration in the fluid at each point in the reservoir for a given temperature distribution. Unfortunately, the published values for α in the Arrhenius equation vary from 3.981×10^5 m/s (as computed from the data compiled from the literature by Apps⁸⁷) to 0.228 m/s as computed from weight loss studies on slabs of biotite granodiorite performed by Charles.⁸⁸ The first of these values predicts a rate that is at least 3 orders of magnitude too large for the observed dissolution rate at Fenton Hill while the second predicts a rate that is approximately 1-1/2 orders of magnitude too slow. The discrepancy could lie in some combination of the following explanations.

- The rate coefficient predicted by Charles' data is the true value for the rate parameter, and our estimate of surface area of quartz exposed to circulating fluid within the reservoir is an order of magnitude too low.
- The true rate parameter could be closer to that calculated from Apps.⁸⁷ The slower rates shown by the experiments at Fenton Hill and in the laboratory at CNC-11 could then be attributed to the removal of silica from solution by secondary alteration phases such as zeolites. This explanation could be supported in part by experiments such as those by Cournoyer, Kranich, and Sand.⁸⁹

Further experimentation both in the laboratory and in the field is currently being conducted to resolve this problem.

Stress/Strain Modeling. Four tasks pertaining to modeling of reservoir stress were undertaken in FY80. The principal vehicle for the stress analysis is the finite-element method. The first quarter was devoted to running uncoupled transient stress analysis problems of either thermoelastic or poroelastic nature. The second and third quarters were devoted to modification of the codes TSAAS (Thermal Stress Analysis of Axisymmetric Solids) and PORSAS (thermal and Porous Flow Stress Analysis of Axisymmetric Solids) and checkout of initial coupled linear problems. Recently we have analyzed more complicated coupled porous thermoelastic problems involving a 50-m fracture and investigation of the use of ADINA (Automatic Dynamic Incremental Nonlinear Analysis) to calculate stress intensity factors for a single crack using theory from linear-elastic fracture mechanics.

The uncoupled problems investigated in the first quarter consisted of:

- Prediction of transient thermal-stress state for granite blocks treated as problems of plane stress. These calculations support the thermal-stress experiences described in Sec. 4.4.3. These blocks were heated to uniform temperature and instantaneously cooled along one boundary to generate a thermal-stress wave. A series of problems involved varying the boundary conditions and material properties for each run and provided a bounded range for the tensile stresses in the granite blocks.
- Concurrently, initial studies of porous elastic diffusion were run on a 50-m fracture using a range of constant-valued permeabilities from measured experiments.
- Evaluation of the uncoupled two-dimensional flow field over 75 days to simulate diffusional effects during Run Segment 2. The thermal and hydraulic parameters were taken from experimental measurements of granites from Fenton Hill. Initial studies indicated that for nominal values of thermal and hydraulic conductivity, temperature waves would move <2 m in 75 days. In the absence of microcracks ($\kappa \sim 0.2 \mu D$) the porous wave moved ~ 6 m in 75 days. Porous flow in microfractured granite moved ~ 30 m in 75 days ($\kappa \sim 10 \mu D$).

During the middle half of FY80, code conversion of TSAAS (a transient thermoelastic finite element code) to PORSAS was planned, executed, and tested. TSAAS provided a numerical solution to the potential energy for an elastic solid,

$$V_e = \int_V \{\sigma\}^T \{d\epsilon\} dV - \int_V \{u\}^T \{F\} dV - \int_A \{u\}^T \{P\} ds, \quad (18)$$

where V_e is the elastic potential energy, σ is the stress field, ϵ is the strain field, u is the displacement vector, F is the body force vector, and P is the surface traction. The thermal term of TSAAS was solved as a temperature potential V_t ,⁹⁰ of the form

$$V_t = 1/2 \{\psi\}^T \{K\} \{\psi\} - \{\psi\}^T \{Q\} + 1/2 \{\dot{\psi}\}^T [C] \{\dot{\psi}\}, \quad (19)$$

where the temperature field $\psi(r, a, t)$ comprises the nodal-point temperature values at time t ; K and C are the thermal conductivity and heat capacity matrices; and Q is the thermal-load vector. The thermal-load vector is the sum of heat generation and surface-flux intensity. The porous flow field potential V_p had the same form as the temperature field and can be written as⁹¹

$$V_p = 1/2\{\theta\}^T[\lambda]\{\theta\} - \{\theta\}^T\{D\} + 1/2\{\dot{\theta}\}^T[B]\{\dot{\theta}\}, \quad (20)$$

where $\theta(r, z, t)$ is the porous flow field, λ is the hydraulic conductivity, D is the fluid load vector, and B is hydraulic capacity.

The total potential energy is

$$V = V_e + V_t + V_p \quad (21)$$

and Eq. (21) is solved using the finite-element method. TSAAS contained the first two terms in Eq. (21). PORSAS was generated by redefining V_t as V_p and coupling all terms of Eq. (21). Several linear, coupled, constant-property, porous-thermoelastic problems were run. Comparisons of the numerical results with analytic solutions are described by Fisher and Bridwell.⁹¹

In the third and fourth quarters, PORSAS was applied to a variety of coupled porous thermoelastic problems. These included:

- Evaluation of the effects of state variables such as temperature or pore pressure on mechanical properties of Berkeley Blue and Barre granite. Initial calibration studies on aluminum determined the stress fields for testing purposes.
- Evaluation of the coupled effects of porous thermoeleastic diffusion on the opening and closing of a fracture during the 75-day Run Segment 2. The thermal diffusivity and porous diffusion terms were evaluated simultaneously. Thermal conduction, i.e., cooling of the rock adjoining the fracture, results in opening of the fracture; the aperture increases. However, diffusion of pore pressure into the rock results in a reduction of the effective stress compressing the rock. Consequently the rock expands and the fracture closes, in contrast to the thermal effect. Since thermal conductivity K has a small variation relative to the permeability, κ , K was assumed constant, whereas a series of runs varying κ from 0.01 to 10 μD were

studied. At low permeabilities, $\kappa \approx 0.1\mu\text{D}$, the fracture opened 16 mm in 75 days. For $\kappa = 1\mu\text{D}$, fluid was available to fill the pores, and the fracture aperture only opened 8 mm in 75 days. For $\kappa = 10\mu\text{D}$, a value representative of microfracturing of the matrix, the fracture aperture completely closed in 75 days.

In the last quarter of FY80, initial efforts were begun to study the effects of a finite fracture on the local stress field. The initial problem of a single crack under MODE I or tensile loading was considered. ADINA's isoparametric quadrilateral element, which contains a quadratic shape function, was distorted to contain the $1/\sqrt{r}$ term required for stress intensity calculations. Comparison of analytic and numerical calculations indicates (1) that fracture opening is accurate to $<1\%$, and (2) stress intensity factors K_I at the crack tip are accurate to $\approx 2\%$. This work has been reported in Ref. 92.

Dispersion and Fluid Dynamic Mixing in HDR Reservoir. During FY80, both sodium-fluorescein and radioactive $\text{NH}_4\text{Br}^{82}$ tracers were used to determine residence-time distributions, effective fracture volumes, and to characterize dispersive mixing effects in the Phase I EE-1/GT-2B system. Code modifications are under way to incorporate both buoyancy-dominated flows and rock dissolution effects in the two-dimensional fracture-flow dispersion simulator.

Earlier concern about dye adsorption or decomposition effects influencing tracer response data has been alleviated by the excellent agreement obtained in the observed residence-time distribution data using both sodium-fluorescein and Br^{82} tracers in the same fracture system (see Sec. 4.2.4.). Chemical decomposition of fluorescein is not important during the first 48 h of exposure to reservoir conditions. Tracer adsorption on the granite matrix is not a problem with either sodium-fluorescein or Br^{82} .

4.4.2. Reservoir Geometries.

Fracture and Wellbore Mapping Development. Reservoir seismicity was monitored during Run Segment 4, Expt. 215, using a geophone package that was positioned downhole in EE-2 in the reservoir vicinity. The downhole geophone package consisted of nine geophones, three each in the x-, y-, and z-direction axes. The sensitivity of the downhole package extends to magnitudes as low as -4. 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. Previously, seismic measurements had been made during periods of active fracture propagation and extension during Expts. 195 and 203; these

measurements are described below. For this reason geophone measurements were not attempted during early stages (1A and 1) of the experiment; instead these measurements were confined to stage 3 (the high back-pressure stage) and stage 4 (the low back-pressure recirculating heat-extraction stage). The first down-hole measurement occurred on October 30, 1979, and encompassed a period that included the final 4 h of stage 3 and an additional 2 h of shut-in. At the beginning of this measurement approximately 7800 m^3 (2.1 million gal) of water had been injected into the reservoir of which 2800 m^3 (740 000 gal) had been recirculated. Throughout the first 4 h, wellbore pressures at EE-1 and GT-2B were maintained at 17 MPa (2500 psi) and 10 MPa (1450 psi), respectively. During the shut-in period the GT-2B wellbore pressure decreased by 0.1 MPa (14.5 psi) while the EE-1 pressure dropped to 12.8 MPa (1850 psi). The second measurement was made near the completion of stage 4 on November 14. At that time roughly $18\,200 \text{ m}^3$ (4.8 million gal) of water had been injected and $12\,100 \text{ m}^3$ (3.2 million gal) circulated. Wellhead pressures were nearly constant at EE-1 and GT-2B, 9.5 MPa and 1.1 MPa (1400 and 160 psi), respectively.

During both measurements the triaxial geophone package was positioned at 2885 m (9465 ft) estimated true vertical depth in EE-2, a location 180 m (590 ft) N5°E of the injection point in EE-1. A schematic of the geophone package is given in Fig. 4-33. We use the Cartesian convention to identify the geophone apex as related to the geophone package. The axis of the vertical geophones, z , corresponds with the long axis of the geophone package. While in position in EE-2 during both measurements, the z and y axes were inclined at roughly 10° to true vertical and to true horizontal, respectively. Records obtained using the z -oriented geophone show an anomalous harmonic distortion, which to date has precluded determinations of the inclination of microseismic foci in the coordinate system of the geophone package.

Results. The rate of occurrence of identifiable seismic events during the stage 3 measurements is shown in Fig. 4-34 along with rates observed during the earlier massive hydraulic fracture treatments (Expts. 195 and 203), which formed the circulating system in March 1979. In comparison with the earlier measurements the present rate of event occurrence is low and constant and did not perceptibly change on shut-in of the system. At the termination of stage 4, however, seismicity of the nature observed previously,^{51,76} characterized by clear shear-wave arrivals, was virtually nonexistent. Only

very few events (perhaps 10) were identified during the entire 6-h period of the stage 4 measurements.

The general character of microseismic signals detected in stage 3 is shown in Fig. 4-35. The signals processed for interpretation showed compression (P) and shear (S) wave arrivals. For the P-waves the first-cycle amplitude-to-noise ratios were in excess of 10 and the polarization eccentricity was greater than 4. The largest event detected had a local magnitude of -1.5, estimated on the basis of a coda length assignment in the local earthquake magnitude scales by extrapolation to the microseismic range. Based on the delay time between P- and S-wave arrivals and the propagation velocities of the respective phases, rock failure occurred at distances as close as 75 m and as far as 600 m from the geophone package, the latter being 250 m greater than any events previously detected.

Figure 4-36 gives radial distances to microseismic event foci in terms of geographic coordinates centered at the geophone package in EE-2 and the azimuth of geophone first motion on P-wave arrival. Assuming that the rate of microseismic occurrence observed during the latter part of stage 3 of Run Segment 4 applies to the entire high-pressure stage and ignoring any seismicity that may have occurred in stage 4, we estimate that the mapped events represent less than 1% of the events that took place during the entire period encompassing stages 2 and 3. The small number of mapped events results primarily from the combination of the limited downhole monitoring time and the low percentage of detected signals of sufficient quality for analysis. Two additional factors contribute to the lack of resolution in the map. First, the loss of vertical control due to the failure of the vertical geophones means that foci otherwise spatially close will separate in projection. Second, in using EE-2 as a vantage point to view the reservoir, signals from certain directions will be highly attenuated and may not be amenable to analysis. For example, as will be seen, signals from events in the southwest quadrant arriving at EE-2 must pass through the fracture zone created during March 1979. Resolution of activity in the southwest quadrant is thereby reduced.

True locations cannot be given in any projection because of the lack of control on signal inclination due to the vertical geophone failure. Consequently we discuss only the limiting case in which it is assumed that all events occurring on the horizontal plane contain the geophone package. Further, the mapped events are subject to a simple two-fold ambiguity

Fig. 4-33.
Los Alamos National Laboratory geophone
package tool 400B.

Fig. 4-34.
Microseismic occurrence rate vs time in
Expts. 195-203, and Run Segment 4.

Fig. 4-35.
Microseismic signal detected by geophone
sonde in EE-2.

direction, centrosymmetric with the geophone sonde location. This ambiguity, which is present in all locations determined from analysis of the signal detected using only a single station, means two directions 180° apart are equally likely directions to the event source. Our practice is to plot events based on geophone first motion only, ignoring the question of first motion at the microseismic source location. A result of this procedure in the past, as in the present case, has been that the seismicity so mapped locates the activity in the possible position closest to the injection well.

The results of our analysis are given in Fig. 4-36. A vague definition appears of one to perhaps three west-northwest-striking zones of seismicity within a rectangular volume of rocks as large as 400×800 m on a side.

Why was the Run Segment 4 seismicity exited along the west-northwest striking zones rather than the north-northwest zone, which accounted for almost all of the activity in March 1979? The only apparent difference between injection during the Run Segment 4 test and Expts. 195 and 203 of March 1979 is the larger accumulation of unrecovered water during Run Segment 4. In the March 1979 experiments GT-2B was shut-in, and total volumes of 603 and 755 m^3 were injected into EE-1 and thence into the reservoir. In Run Segment 4, GT-2B was throttled to allow recirculation but the test was longer, so at the end of stage 3 seismic monitoring, the cumulative difference between inflow and outflow, representing the net amount injected into the reservoir, was 5000 m^3 (1.3×10^6 gal), 6.6 times the highest volume of the March injections. If it is assumed that the west-northwest striking fracture is continuously connected and lenticular in shape, then the fractured surface area must be over $500\,000 \text{ m}^2$ in surface area. Over 80% of this was created during and subsequent to March 1979. This surface area is 10 times the lower bound estimated

Fig. 4-36.
Direction and radial distance to microseismic foci.

from the heat-extraction data. However, the value cited here represents the total area of rock through which the injected water could be infiltrated. It includes all the manmade as well as natural fractures and joints and all the tortuous paths in the reservoir vicinity into which the water could be squeezed when the production well was shut-in. When the production well is vented for heat extraction, only a fraction of these same flow paths would conduct significant rates of flow, so it is expected that the effective heat-transfer area would be substantially less than the seismic area.

The attempt to detect seismicity during the low back-pressure stage of Run Segment 4, stage 4, was to establish whether or not rock failure accompanies active heat extraction. Little seismicity of the scale and nature that occurred in stage 3 was observed; thus it appears that reservoir heat extraction, to the extent we have thus far witnessed, does not cause microseismicity.

The picture that emerges indicates that the north-northwest striking fracture system created in March was extended in the predominately easterly striking direction during Run Segment 4. The easterly striking fracture permeability is not connected along its strike directly to the production well. Because of the large distances to the microseismic foci, and the relatively short period that the system was pressurized, there is no reason to suppose that the fracture permeability created in Run Segment 4 is hydraulically isolated from the EE-1/GT-2 flow-through system. Because of the close lateral proximity of the EE-1 injection point and the production zone in GT-2B, fluid velocities in the extremities of the northwest striking fracture and throughout the west-northwest fracture system will be negligible. The capability for through-put however, appears to exist, and a well penetrating anywhere in the seismically active zones laterally displaced from the injection point at greater distances might result in a significant enlargement of the available heat-extraction area.

Wellbore Mapping. As discussed in Sec. 4.3.1., Reservoir Design, the Phase II reservoir is being created by drilling two wells, EE-2 and EE-3, at an angle of 35° from the vertical, while at the same time maintaining a vertical separation distance of 360 m. In order to locate EE-3 directly over EE-2 at reservoir depths, it is necessary to have reliable surveys of the wellbores. During the drilling of EE-2, single-shot magnetic surveys were made inside a nonmagnetic section of the drill pipe. Such measurements could be in error for two reasons: the effect of the adjacent, possibly magnetic, drill

string on the survey tool, or the effect of an ancient, differently oriented, magnetic field in magnetic minerals in the rock. Since magnetite fractions as great as 25% by weight were observed in some of the cuttings, the latter was a real possibility. A reliable gyro survey was obtained on August 6, 1980, to a depth of 4633 m (15 200 ft), where the temperature was over 300°C. This survey agreed quite well with the single-shot survey data, as may be seen in Fig. 4-37, and gave confidence in the single-shot data taken during drilling.

4.4.3. Laboratory Studies of Reservoir Properties. Field experiments and tests conducted at the Fenton Hill site have continued to address important questions during FY80. However, some subjects require investigation in the laboratory. These are covered in this section of the report and include laboratory measurements of permeabilities of granite cores recovered from the well EE-2, petrologic chemical studies of cores from EE-2, rock/water chemical reactions, fluid chemistry studies of the Phase I reservoir, experiments conducted in the laboratory designed to elucidate the behavior of granite

Fig. 4-37.
Gyro-survey data obtained in EE-2 on August 6, 1980, and single-shot data taken during EE-2 drilling.

specimens under thermal-stress cracking, and rock mechanics experiments to investigate the anisotropy of certain properties of granite specimens.

4.4.3.1. Permeabilities of Core Samples from EE-2. The permeabilities of six samples from EE-2 have been measured as a function of effective confining pressure P_e (confining pressure minus pore pressure) at room temperature (23°C). P_e ranged from about 2 to 30 MPa. Permeabilities k in the 2- to 5-MPa range are generally in the 10^{-17} to 10^{-18} m^2 range, while those near 30 MPa are in the 10^{-19} to 10^{-20} m^2 range. The samples examined were 11743-3, 12854-6, 13461-2A, 13965-1, 14502-3, and 14964-1, where the first five digits indicate the depth along the wellbore in feet. All of these samples, with the exception of 12854-6, show some foliation. Three cores of 11743-3 cut in orthogonal directions were tested and despite the presense of foliation showed no dependence of permeability on direction. The data for these three cores are shown in Fig. 4-38. Permeability in all three directions is quite adequately described by the relation

$$k = 2.12 \cdot 10^{-12} / (1 + 447.1 P_e)^{1.88} ,$$

Fig. 4-38.

Permeability of EE-2 11743 as a function of effective confining pressure measured in three orthogonal cores.

where k is in m^2 and P_e is in MPa. The permeability of this sample was measured only after P_e had been raised to approximately 30 MPa. This is also true of sample 13956-1, the permeabilities for which can be described by

$$k = 3.78 \cdot 10^{-18} / (1 + 0.327P_e)^{1.40} \quad (22)$$

It was noted that for this specimen the permeability did not increase below about 2 MPa.

In the remainder of the samples, permeability was initially measured with increasing P_e . These samples show an irreversible change in permeability with increasing P_e . After pressurization to a P_e of 25 to 30 MPa, permeabilities measured at low P_e are as much as an order of magnitude lower than observed initially. This behavior is illustrated by the data for one core (13461-2A), which are shown in Fig. 4-39. It seems probable that the irreversible change in k is due to reduction of porosity caused by extraction of the sample from the borehole and subsequent cooling. In view of these

Fig. 4-39.

Permeability of EE-2 13461-2A as a function of effective confining pressure showing reduction of permeability with pressurization of the sample. Higher values of permeability were obtained upon initial pressurization of the sample, lower values upon depressurization.

observations it seems likely that the laboratory permeabilities represent only upper bounds on in situ matrix permeabilities.

For these latter specimens, k as a function of P_e has been fit only to that data obtained after maximum pressurization. These relations are for 12854-6

$$k = 8.31 \cdot 10^{-18} / (1 + 0.222 P_e)^{10.08} + 4.68 \cdot 10^{-20} / (1 + 0.06 0 P_e)^{1.8} , \quad (23)$$

for 13461-2A

$$k = 3.55 \cdot 10^{-16} / (1 + 254.7 P_e)^{0.94} , \quad (24)$$

and for 14502-3

$$k = 6.73 \cdot 10^{-17} / (1 + 251.4 P_e)^{0.90} . \quad (25)$$

Only increasing P_e data was collected for 14961-1. It was very similar to that for 13461-2A and 14502-3.

4.4.3.2. The Application of Fluid Chemistry Studies to a Hot Dry Rock Geothermal System: I, Neutron Activation Studies. Neutron activation analysis methods have been developed for determination of element concentrations in geothermal system waters, bulk rock samples, separated mineral phases, and intergranular salts from an HDR geothermal system. Selected trace and major element concentrations have been determined by neutron activation for: (1) 39 water samples taken during the course of a 75-day experimental run of the Fenton Hill HDR system; (2) a bulk rock core section from 2714 m (8904 ft); (3) each of the seven major mineral phases present in the rock; and (4) a sample of intergranular salts obtained by leaching the disaggregated rock at 25°C.

The elements sodium, cesium, bromine, and europium were added to the circulating fluid almost exclusively by the deep reservoir and continued to increase in the fluid during the 75-day test run. Sudden changes in their concentration may indicate significant events in the circulation system prior to days 23, 46, and 55. The elements potassium, calcium, strontium, barium, iron, and cobalt also continued to increase and were added both by surface sources and the deep reservoir. Many of their concentrations also reflect

changes occurring in the circulating system. The elements zinc, molybdenum, arsenic, antimony, and tungsten appear to have reached a steady state within 75 days.

4.4.3.3. Geochemistry. Studies Made in Small Autoclave Reactors. Studies of the rate of interaction of water with granitic rock at 235°C and 275°C using the small autoclave technique described in the FY79 Annual Report⁵¹ were continued. The solutions were analyzed for Na^+ , K^+ , Ca^{++} , Mg^{++} , Al^{+++} , (Fe^{++} + Fe^{+++}) and sometimes Cu^{++} by atomic absorption spectroscopy; for monomeric silica by the ammonium molybdate method; for total silica by a modification of the ammonium molybdate method and by atomic absorption spectroscopy; and for Cl^- by a select ion electrode. For given conditions, experiments were repeated using the same rock sample but with fresh water. These successive experiments are referred to as the first extraction, the second extraction, etc. The results at 235°C for silica, Na^+ , K^+ , and Al^{+++} are shown in Figs. 4-40 through 4-43. The results for Ca^{++} , Mg^{++} , Cu^{++} , total iron, and Cl^- were erratic around 1 ppm, 0.1 ppm, 0.1ppm, 0.1ppm, and 1 ppm respectively and are not shown. It was concluded that:

(1) The silica results at 235°C are very similar to the results at 275°C reported last year.

(2) The results for Na^+ are generally similar to the results for silica except that the curves break over relatively more sharply. This feature makes fitting the curve with a rate equation difficult and we have not found a simple expression. The results for K^+ are even more difficult to fit with a simple expression.

(3) The results for Al^{+++} show an initial rapid rise followed by what appears to be an exponential decline. Presumably the Al^{+++} , which dissolves quickly, is then precipitated by the silica, which builds up exponentially.

4.4.3.4. Geothermometers. A potential new geothermometer is under investigation⁹³ using core samples from GT-2, EE-1, and EE-2. Pleochroic haloes are formed in biotite around included zircon grains as the result of alpha particle radiation damage. The intensity of these haloes is both time and temperature dependent. Samples from the three deep holes at Fenton Hill have been used to calibrate the temperature at which halo annealing occurs. Annealing first becomes evident at a temperature of 134°C and is complete by 151°C. Naeser and Forbes⁹⁴ report total annealing of fission tracks in apatite in GT-2 samples at a temperature of 135°C. The agreement between the

Fig. 4-40.
235°C monomeric SiO_2 (ppm) vs time of extraction with water.

Fig. 4-41.
235°C (Na^+) ppm vs time of extraction with water.

two annealing processes is very encouraging and the new data provide additional information on the thermal history of the Fenton Hill HDR reservoir.

4.4.3.5. Characterization of Core Samples from EE-2. During the drilling of EE-2, six cores totalling 856.6 cm were recovered; one coring attempt produced no core, apparently because of intense rock alteration within the interval drilled. Cuttings and junk-basket samples have also been collected and are being investigated. Initial results of characterization investigations have been obtained, and a report summarizing these data is in preparation.⁹³ Only the highlights of these investigations will be reported here.

Fig. 4-42.

235°C (K⁺) ppm vs time of extraction with water.

Fig. 4-43.

235°C (Al⁺⁺⁺) ppm vs time of extraction with water.

The six cores, and cuttings and junk-basket samples, reveal a very complex geology within the projected HDR reservoir. As shown in Table 4-IV, only two of the cores are monolithologic; the remaining four contain both a metamorphic and an igneous unit. Sharp intrusive contacts are well displayed in several of the cores. All of the cores contain fractures but only in core number 5 are they open; in the other cores the fractures are sealed with a variety of minerals such as quartz, feldspar, epidote, sphene, magnetite, and sulfides. In contrast to sealed fractures observed in the upper regions of GT-2 and EE-1, calcite has a much lower abundance. The fractures in core number 5, which belong to two sets striking roughly east-west, have slicken-sided surfaces coated with biotite, epidote, and amphibole.

Results of the chemical analysis of nine samples from the six cores are presented in Table 4-V; also shown are the results from the analysis of two samples of cuttings from altered zones. The nine analyzed core samples include four samples of the gneisses, three samples of the biotite granodiorites, and samples of both the leucocratic and mesocratic members of core

TABLE 4-IV
CORING HISTORY OF EE-2

<u>Core Number</u>	<u>Coring Interval (m)</u>	<u>True Vertical Depth (m)</u>	<u>Megascopic Aspect</u>
1	3577.6-3579.5	3501.8-3503.3	Biotite granodiorite gneiss intruded by fine-grained granodiorite.
2	3916.1-3918.5	3779.3-3781.3	Mafic metavolcanic intruded by granitic rock.
3	4100.8-4103.8	3930.8-3933.3	Biotite granodiorite.
4	4253.5-4255.8	4057.8-4059.7	Biotite-rich augen gneiss intruded by fine-grained biotite granodiorite.
5	4419.9-4420.8	4194.3-4195.1	Biotite-rich gneiss. Slickensided fault plane parallels axis of core.
6	4560.4-4561.6	4309.5-4310.5	Biotite granodiorite gneiss intruded by fine-grained granodiorite.

number 2. The four gneisses analyzed apparently do not show as marked a chemical heterogeneity as did the gneisses sampled by GT-2 and EE-1. Three of the samples are essentially chemically identical, while the fourth is distinctly more mafic in composition. This homogeneity may result from the fact that only four samples have been analyzed to date; analysis of additional samples may produce a greater spread.

Granodiorite sample 13463-22 and leucocratic sample 12848-4 are chemically similar to each other and to the average biotite granodiorite sample from GT-2 (Sample 1, Table VI, Ref. 95). These samples are characterized by relatively high contents of TiO_2 and P_2O_5 . The remaining granodiorites, samples 11738-1 and 13962-2, have lower TiO_2 and P_2O_5 contents and in the case of 11738-1, a significantly higher SiO_2 content. It seems likely from the chemical evidence that EE-2 has intersected at least two additional igneous rocks besides the major biotite granodiorite of GT-2 and EE-1.

The remaining sample, the mesocratic member of core number 2, sample 12848-6, is chemically different from any of the GT-2 or EE-1 samples. Only

TABLE 4-V

CHEMICAL ANALYSES OF PRECAMBRIAN ROCKS FROM DRILL HOLE EE-2

Lithology	Core 1 11738-1 Granodiorite	Core 1 11740-1 Biot. Granodior- itic Gneiss	Core 2 12848-4 Leucocratic Member	Core 2 12848-6 Mesocratic Member	Core 3 13463-22 Granodiorite	Core 4 13955-3 Biot. Granodior- itic Gneiss	Core 4 13962-2 Granodiorite	Core 5 14505-3 Biot. Granodior- itic Member	Core 6 14965-4 Biot. Granodior- itic Gneiss
SiO ₂	71.99	66.50	66.16	59.96	65.02	59.43	67.68	67.06	66.59
Al ₂ O ₃	14.75	15.20	14.95	14.80	15.00	16.12	16.60	13.90	14.50
Fe ₂ O ₃	0.64	1.90	2.22	2.90	2.73	2.08	1.01	0.99	2.25
FeO	1.07	2.43	2.73	4.50	2.67	5.15	2.06	3.61	3.01
MgO	0.49	1.44	1.29	2.48	1.39	3.40	0.98	3.16	1.57
CaO	1.66	3.26	2.86	4.44	3.26	6.11	2.82	4.22	3.66
Na ₂ O	3.59	3.74	3.20	3.15	3.15	3.34	3.52	3.13	3.60
K ₂ O	4.32	2.71	4.20	3.31	4.19	1.53	3.48	1.30	2.20
H ₂ O ⁺	0.72	1.33	0.76	1.08	0.92	1.19	0.83	1.45	0.92
H ₂ O ⁻	0.08	0.02	0.00	0.08	0.06	0.24	0.00	0.06	0.02
TiO ₂	0.18	0.74	0.82	1.89	0.93	0.98	0.37	0.59	0.82
P ₂ O ₅	0.05	0.20	0.31	0.82	0.42	0.19	0.10	0.02	0.23
MnO	0.052	0.087	0.074	0.135	0.099	0.134	0.051	0.121	0.092
SrO	<0.018	<0.035	<0.039	0.040	0.041	0.036	0.037	0.025	0.036
Sulfur	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Total	99.61	99.59	99.61	99.58	99.88	99.93	99.54	99.64	99.50

TABLE 4-VI

RESULTS OF X-RAY-DIFFRACTION ANALYSIS OF EE-2 ALTERED GRAINS
(Sample numbers give the depth in feet along EE-2 wellbore)

<u>4360</u>	
Calcite	90%
Ca-Si (hydrate?)	10%
<u>6220</u>	
Calcite	90%
Ca-Si (hydrate?)	10%
<u>8540</u>	
Calcite	40%
Quartz	60%
<u>10470</u>	
Illite-montmorillonite	60%
Quartz	40%
<u>11290</u>	
Calcite	50%
Quartz	45%
Magnetite	5%
<u>12140</u>	
Illite-montmorillonite	60%
Quartz	45%
Magnetite	5%
<u>13180</u>	
Illite-montmorillonite	55%
Quartz	25%
Calcite	20%

the schist and the magnetite folia from GT-2 are more mafic than this meta-volcanic.

Petrographic and x-ray-diffraction analysis of cuttings from EE-2 indicated the presence of discrete altered zones intersecting the wellbore. Semi-quantitative estimates of the mineralogic compositions of these zones are shown in Table 4-VI. Approximate locations of the zones are shown in Table 4-VII. The abundance of these altered zones and the presence of the swelling, cation-exchangeable clays, illite-montmorillonite, suggest that the zones may have a significant effect in the development of the HDR reservoir. Geophysical logging and sampling should be performed in EE-2 to confirm the existence of these zones.

TABLE VII

LOCATION OF MAJOR ALTERED ZONES IN THE LOWER SECTION OF EE-2

Depth in Feet Along Wellbore

10070 to 10180	
10300 to 10330	
10440 to 10560	Extensively altered zone
10990 to 11020	
11060 to 11120	
11220 to 11650	Extensively altered zone
11800 to 11870	
12050 to 12200	
12250 to 12400	
12470 to 12550	
12660 to 12760	Extensively altered zone
13180 to 13310	Extensively altered zone

4.4.3.6. Fluid Chemistry Studies of a Hot Dry Rock Geothermal Reservoir. Chemical monitoring of the circulating aqueous fluid may provide the following kinds of information. (1) Changes in certain element concentrations may signal the opening of new fractures at depth and hence the exposure of new hot surfaces to the working fluid. (2) The fluid chemistry may reflect characteristic rock-water interactions occurring in the otherwise inaccessible rock reservoir. Net removal of material (e.g., silica) may indicate increased permeability to the working fluid or alteration products that will ultimately clog the circulating system. (3) Chemical geothermometers based on fluid composition may indicate temperature at depth. (4) Trace elements of economic value may be leached from the rock reservoirs of HDR geothermal systems by the circulating fluids.

The overall behavior of trace elements during the 75-day test is similar to the major and minor element behavior discussed previously.⁸⁴ Some elements appear to increase with time and others level off.

Plagioclase appears to buffer the Na-K-Ca ratios in solutions. The disproportionately low increase of Ca relative to Na in the working fluid suggests the formation of a Ca-bearing alteration mineral at depth.^{63,84} This is in agreement with laboratory circulating system data.⁸⁸

The major possible sources of elements added to the working fluid in the deep reservoir are: (1) mineral-water interaction during circulation, (2) local saline pore solution or interstitial salts, and (3) the deep hot brine of the Jemez system. Mineral-water interaction is known to be significant in pure-water systems;⁸⁸ however, the observed Na concentrations in the circulation fluid are much too high to be attributed solely to plagioclase dissolution. Examination of the major element ratios in the deep Jemez brine suggests that this is not the source of the observed fluid compositions. The evidence from element ratios and mineral solubility point to a saline pore fluid (buffered by the rock) as the source of many of the dissolved species.

4.4.3.7. Laboratory Experiments on Thermal-Stress Cracking of Granite

Specimens. Experimental efforts have concentrated on studying thermal-stress cracking (TSC) phenomena in thin slabs of granite from Elberton, Georgia (commonly referred to as "Berkeley Blue" granite), which are cooled along one edge. The rock samples, measuring 2.5 cm thick by 30 cm wide by 20 cm high, were slowly oven heated in an insulated box with only the upper 2.5 cm by 30 cm edge directly exposed to the furnace environment as shown in Fig. 4-44.

After having reached temperature equilibrium at the designated test temperature--150, 200, and finally 250°C for successive TSC experiments--the insulated sample was removed from the oven and quenched along the upper surface by flowing cold water at 5 to 10°C through a glass-topped manifold bonded to the exposed surface with silicone rubber.

The experimental results from four sets of TSC experiments exhibit many common features, as shown particularly by a linear crack-locating (dual transducer) acoustic-emission (AE) system.

Fig. 4-44.
Insulated container and sample configuration for thermal-stress cracking experiments.

- The initial 2-min cooling period from 150°C results in the formation of eight or nine thermally induced edge cracks, most of which extend very rapidly into the uncooled portion of the rock.
- Further cooling during the subsequent 20 to 30 min produces only modest extension of several of these initial cracks.
- After about 30 min, the two initial cracks, which come closest to dividing the sample into thirds, i.e., at about 10 and 20 cm from one end, begin a second period of rapid growth that typically lasts for another 20 min.
- The final crack depths for these two primary cracks, for an imposed ΔT of about 140°C, range from 4 to 5 cm.
- Upon reheating the thermally cracked rock in its insulated container, the early time compressive closure of the edge cracks extending downwards from the exposed top surface produces very sharp AE signals, apparently from the crushing of asperities formed along the previous cooling-induced tensile cracks. Crack locations derived from these initial heat-up AE signals give a one-to-one relationship with the previously located thermal-stress cracks, affording an excellent way of verifying the presence of all the induced cracks.
- After quenching the rock sample from successively higher equilibrium temperature levels of 200 and 250°C, the final depths of the two

major thermal-stress cracks range from 7 to 8 cm. The final crack pattern is shown in Fig. 4-45.

In preparation for selecting the rock sample geometry for the next series of thermal-stress cracking experiments, a series of numerical plane-stress computations was performed using the PORSAAS finite-element program. Figure 4-46 shows the variation in the near-surface principal tensile stress (σ_{11}) with cooling time for four different sample widths: 30, 40, 80, and 150 cm. As can be seen, there is a very pronounced falloff in the maximum induced tensile stress for sample widths of 40 cm or less. Therefore, a sample width of 60 cm (2 ft) has been chosen for the next series of experiments. This 60-cm sample width corresponds to a joint spacing within the range observed for our present HDR reservoir at Fenton Hill.

In conjunction with the above experiments, and for the design of a thermal self-loading fixture for the next series of thermal-stress cracking experiments, it was necessary to measure the coefficient of thermal expansion (α) for this granite. Figure 4-47 shows a plot of the mean thermal strain in two directions vs temperature. Above 50°C the thermal strain is essentially linear with a coefficient of $10.2 \times 10^{-6}/^{\circ}\text{C}$, within the range given by Clark of $8 \pm 3 \times 10^{-6}/^{\circ}\text{C}$ for granites and rhyolites.

4.4.3.8. Rock Mechanics. Measurements of elastic moduli under uniaxial conditions of the EE-2 core rock were completed. Studies of slow crack growth and fracture toughness were done on a granite similar to some of the Fenton Hill rocks.

Table 4-VIII summarizes the elastic properties of these rocks. In the samples where fractures were present, strain-gauge data were used. Since the strain gauges were positioned away from the fractures, only the properties of the rock itself are measured. The elastic properties are a strong function of stress. Young's modulus increased by a factor of 2 to 4 as stress increased from 0 to 20 MPa. Poisson's ratio also increased from values typically less than 0.1 to values ranging from 0.1 to over 0.4. The variation from rock to rock at any stress is also large. At zero load, Young's modulus varied by a factor of about 4 among the samples ranging from about 4 GPa for 13 958 ft to about 15 GPa for 12 850 ft. At 20-MPa uniaxial stress, the range is still over a factor of 2. Similar wide variations are seen in Poisson's ratio.

We have observed marked orientation dependence in both tensile modulus and fracture toughness in Berkeley granite. A monotonic relationship exists

Fig. 4-45.
Induced thermal-stress cracks in edge-cooled slab of Elberton granite.

Fig. 4-46.
Maximum tensile stress vs time for four sample widths: 30, 40, 80, and 160 cm.

Fig. 4-47.
Linear thermal expansion of Elberton granite.

TABLE 4-VIII
SUMMARY OF ELASTIC PROPERTIES OF CORES FROM EE-2

Core Sample From Depth (ft)	Zero Stress		20 MPa Stress	
	Young's Modulus	Poisson's Ratio	Young's Modulus	Poisson's Ratio
11 739	10 GPa	0.05	30 GPa	0.20
12 850	12 - 17	0.05	15 - 22	0.12 - 0.17
13 461	11	0 - 0.15	33	0.12 - 0.22
13 958	2 - 5	0 - 0.02	17	0.07 - 0.09
13 962	10	0.1	20	0.45

between the two parameters that hold for the present data as well as for literature data on Westerly and Barre Granites. These observations have important consequences in HDR geothermal energy and other geoengineering applications. The orientation of hydraulic fractures at depth may be influenced as much by anisotropic fracture toughness as by in situ stresses. Although a complete theoretical justification of the relationship between tensile modulus and fracture toughness is currently lacking, it does hold promise as a predictive tool for determining fracture toughness from modulus data alone.

4.4.4. Related Domestic and Foreign Programs. Domestic. Over the past 5 yr, scientists at Oregon State University, under the direction of Gunnar Bodvarsson and the sponsorship of the USDOE, have been actively engaged in conceptual design and analysis studies of forced geoheat recovery systems (FGR). An FGR system would involve fluid flow and heat extraction from natural, discretely fractured reservoirs in low permeability, hot rock. Systems of this type are typically found in, but not limited to, areas of hydrothermal activity. In the early 1960's, the idea of artificial fluid injection and recovery from fractured but unproductive regions of the Icelandic hydrothermal system originated. Since that time the Oregon State investigators have examined resource evaluation, reservoir design and modeling, recovery and end-use, and economics.⁹⁶⁻⁹⁹

A small effort is also continuing at Northwestern University to examine acoustic-wave interaction with fractured rock and thermal stress induced cracking following the work reported last year.⁹⁹

Federal Republic of Germany. In addition to their support of the Los Alamos program through the International Energy Agency agreement (Sec. 4.1.), the Federal Republic of Germany has been conducting an independent set of field experiments at two sites, Falkenberg and Urach.¹⁰⁰ Funding for this work has been provided by the Federal Republic of Germany (PLE Jülich) and the Commission of the European Economic Communities (EEC). The following institutions are participating: Federal Institute of Geosciences and Natural Resources (BGR), Hannover; Geological Survey of Lower Saxony; Geophysical Institute of Universities in Bochum, Mü, Braunschweig, and Clausthal. The scientific coordinators for the project are O. Kappelmeyer and F. Rummel with R. Jung and H. Keppler as principal collaborators.

The major objectives of the field work have been to characterize the formations, to produce prototype reservoirs by fracturing, to examine fluid flow and impedance properties, and to develop reservoir models to explain observed results. In addition to the field work and reservoir modeling, laboratory studies have examined rock fracturing and geochemical behavior. The Falkenberg test site for in situ HDR experiments was installed in an outcropping crystalline rock massif in northeast Bavaria. Three seismic detection holes situated at the corners of a triangle with 100-m side length and an operation hole in the center of this triangle were drilled each 300-m deep. The total hole sections were cored. Casing was limited to the uppermost 30 m.

Natural conditions within the reservoir were determined prior to testing by:

- petrographical and structural analysis of the cores;
- TV inspection of the wellbores to identify the orientations of natural joints;
- well logging (resistivity, SP, gamma radiation, temperature, salinity, caliper, dip meter) and correlation of the logs with natural fissures and altered zones from the core sections;
- measurements of natural stress field by hydraulic fracturing (injection volume up to a few liters);
- in situ determination of rock permeabilities by straddle-packer arrangement; and

- measurement of seismic velocities, tensile strength, and other mechanical rock properties.

In the center hole in three different depth ranges, attempts were made to generate fractures hydraulically. In 158- and 289-m depth, natural fissure systems were activated. Between 251- and 255-m depth, an artificial fracture was initiated at a breakdown pressure of 20.3 MPa downhole. The fracture was extended during three pumping intervals at constant flow rate of 3.2 ℓ/s . The pertinent pressure diagram (Fig. 4-48) is typical for hydraulic fracturing in virgin rock, showing a decreasing fracture extension pressure down to 4.6 MPa downhole. At this stage the fracture volume was estimated to be 3 m^3 . This volume corresponds to a radius of 60 m for a penny-shaped fracture. After shut-in the pressure decreased continuously falling short of the least stress component. There is a linear relationship between fracture volume and fluid pressure and between fracture extension pressure and hydrostatic pressure.

Fig. 4-48.
Falkenberg 790CT17/FRAC-experiment: well-head pressure during opening of artificial fracture.

During the fracture experiments, four three-component seismic stations were positioned in the three observation holes at about the depth level of the injection interval. Seismic events were observed during the opening of the artificial fracture in 251-m depth. Sixteen seismic events could be used for determining hypocenters. Most of them are arranged on an almost vertical plane striking 110°E, corresponding well to the print of the fracture on the impression packer from the injection interval. These results were used to determine the locations of two intersection holes (SB5 and SB6), each 16 m distant to the center hole. SB5 succeeded in intersecting the artificial fracture in 249-m depth. Spinner logs showed a direct hydraulic connection between center hole, fracture, and SB5. Natural joints also provided a flow path to SB6.

Circulation experiments were conducted in the artificial fracture between center hole and intersecting holes. The flow impedance in the fracture is relatively low; it decreases with rising back pressure from 0.8 to 0.04 GPa s/m³. Fluid losses at 3×10^{-3} m³/s are less than 20%. Experiments with tracers lead to a residence time of the circulating water in the fracture of about 2 min at 2.5×10^{-3} m³/s injection rate.

The heat exchange between rocks and circulating water was determined experimentally and the results compared with theoretical models. At a temperature difference of 5°C between original rock temperature and injected water, the thermal power of the artificial fracture system was 50 kW after 25 min; 44 kW after 45 min; 22.6 kW after 4.5 h and 22 kW after 8.5 h. The efficient heat-exchange surface has an extension of 175 m², which is considerably smaller than the estimated fracture extension from an elastic model.

Pressure oscillations were stimulated in the fracture by expanding a pressurized gas volume. A considerable decrease of damping was observed during fracture extension. At a constant fracture radius, damping of the oscillations decreases slightly with increasing fluid pressure. This might be used for monitoring changes in fracture geometry.

The test site near Falkenberg will be used in the future for further in situ investigations on: fracture generation (preferably multifracture systems); interaction between natural joints and artificial fractures; manipulation of fracture dimensions for improvement of hydraulic behavior; fracture location; and heat exchange between circulating water and rocks. All

experimental data serve for models transferring the results to conditions at higher rock temperatures at greater depth.

United Kingdom. During the past 3 yr, the Camborne School of Mines under the technical direction of A. S. Batchelor and C. M. Pearson has been investigating the use of combined explosive and hydraulic fracturing techniques for HDR reservoir stimulation. Initial efforts were supported by the United Kingdom Department of Energy (UKDOE) coordinated by J. D. Garnish of the Energy Technology Support Unit (ETSU). Beginning in mid-1980, combined support from the UKDOE and the Geothermal Branch of the European Economic Communities (EEC), coordinated by P. Ungemach, has made possible a large-scale field effort.

The field site for these studies is located at Rosemanowes, Cornwall, in the southwestern section of England. Early experiments focused on the development of methods to enhance permeability by explosive initiation and hydraulic propagation of fractures in otherwise very low permeability rock ($<10^{-6}$ darcy).¹⁰¹ Initially four holes were drilled with percussive equipment to a depth of 300 m (1000 ft) and with a nominal diam of 0.15 m (6 in.). Geophysical logs and surveys followed; these included hole orientation and direction, caliper, gamma-gamma (density), inter-hole seismic ranging, natural gamma, televiewer, and three-dimensional sonic logs. Based on the geophysical data, straddle packers were set at several locations at a depth of ~ 270 m and a number of constant flow-rate injection tests were conducted to measure in situ intrinsic permeability and fracture receptivity ($A/\sqrt{k}$).

Following this characterization of the formation, two stimulation treatments were conducted. The first employed conventional hydraulic fracturing while the second used a combined explosive-hydraulic approach. In the first test, following initial breakdown, flow connections were observed in two of the other holes that had been bored into the formation. These connections were studied extensively to establish inter-well flow impedances and other flow parameters. In the second test, a low-charge-density column of explosives was used to stimulate an impermeable region in a different hole from the previous test. The charge was designed to initiate radial fractures by inducing stresses at the borehole wall that do not exceed the Hugoniot elastic limit of the confining rock formation. Following a successful detonation, five hydraulic fracture extensions, using approximately 100 m^3 (26 000 gal) of water per treatment, were used to enlarge the system and improve its

connectivity to the other wellbores. A continuous circulation test was also conducted to give inter-hole flow parameters for comparison with those obtained from the hydraulically fractured hole. A repeat of the three-dimensional and televiwer logs showed a highly fractured region in the explosive zone.

The results of this treatment were impressive when compared to the first hydraulic stimulation because of

- lower breakdown and hydraulic extension pressures;
- large increase in specific acceptance (defined as the injection flow rate divided by the overpressure) for fluid in the injection well, up to $0.7 \text{ m}^3/\text{s GPa}$ from $<10^{-8} \text{ m}^3/\text{s GPa}$;
- lower interwell flow impedances, as low as $0.3 \text{ GPa}/(\text{m}^3/\text{s})$ (3 psi/gpm) from $>10^5 \text{ GPa}/(\text{m}^3/\text{s})$;
- larger fracture swept areas; and
- reduced water losses to $<1\%$ of the injected flow after 25 h at 10 MPa (1500 psi).

Although it is somewhat premature to draw firm conclusions from these experiments, it would appear that the use of properly designed explosives may provide a practical technique for locating specific initiation sites for the multiple large fractures required in commercial-sized HDR systems.

Recently it was announced that both the U.K. Government and the EEC will make \$7.2 million available to the Camborne School of Mines to expand their reservoir engineering field experiments to a larger scale than previously possible.¹⁰² This new phase of the engineering project will be directed at creating fractures to link two inclined holes drilled in the local granite to a depth of 2000 m, with a vertical separation of 250 m. It is planned to drill both holes with a bottom-hole inclination of 30° to ensure intersection with the vertical fissure system. The second hole will be drilled with both azimuth and inclination control to permit multi-point and out-of-plane accelerometers/hydrophones to be used to locate microseismic emissions generated during hydraulic fracturing. When each well is completed and the logging and cross-hole measurements are finished, the lower hole will be given an unfocused explosive pretreatment.

Although the holes will be interconnected by the natural fissures already present in the granite, the connections will be enhanced and extended by a combination of hydraulic and explosive techniques. The hydraulic fracturing

operation will be guided by three criteria: (1) an injected volume of 5 to 10 million μ , (2) growth of the system as defined by the listening array, and (3) a significant connection between the two holes. A cyclic injection of up to 10 million μ per cycle, followed by rapid venting to back-flush clays and other joint fillings, will continue until successive build-up curves are sensibly identical. This technique has proved successful in the current program and can develop the maximum swept area for the pump size used.

By making volume and pressure tests, it will be possible to establish whether or not a significant system of interconnecting fractures has been created between the two holes. Once such a system has been created, the water will be pumped through it on a cyclical basis in a series of short- and long-term experiments. The overall intention is to test not only the durability of the system but also to examine whether the temperature of the water at outflow (which will rise from 20 to 80°C as it passes through the granite) remains constant. Reservoir characteristics will be studied during circulation by geochemistry, tracer, thermal, and hydraulic methods.

The final objective of the project is the production of a reservoir zone that can support a flow of 100 kg/s over 2 million m^2 of fracture surface. This would demonstrate that economic exploitation of HDR may be possible. However, it is unlikely that the reservoir can be created with less than three or four holes, which implies a 5- to 7-yr research and development program. This, in turn, means that a successful high-temperature plant could not be operational for at least 10 yr.

This new phase of the project will require percussion drilling and the development of suitable hardware to deal with the temperatures to be found at 2000 m. The reservoir study is expected to provide a definitive guide establishing requirements for a 5000- to 6000-m deep, high-temperature system for generation of electricity.

Coordinated with the passive and active microseismic studies being conducted at the Los Alamos National Laboratory, Crampin and associates¹⁰³ at the Edinburgh office of the Institute for Geological Sciences have been actively engaged in the theoretical aspects of acoustic wave interaction with fractured rock. Their latest work has concentrated on developing synthetic seismograms for modeling fracture systems.

4.5. Materials, Equipment, and Instrument Development

Upgrading of developed prototype equipment and instrumentation requires continued efforts to meet the hostile environment to be encountered in the Phase II Energy-Extraction System. New measurement equipment and analysis technology must also be developed in order to characterize the Phase II boreholes and subsequent hot dry rock reservoir. Research in materials, equipment, and instrument development is coordinated with the needs and developments in the other DOE geothermal programs to produce hardware of greatest transprogrammatic utility and obviate duplication. Instrument development experiments conducted during FY80 are listed in Appendix C.

Much work has already been accomplished in the development of downhole instruments that will survive the hostile geothermal environment encountered in the Fenton Hill Phase I wellbores, i.e., 200°C, 41.34 MPa (6000 psi). Borehole logging in the Phase I wellbores is now a routine operation. The Phase II system will, however, place much more stringent requirements for the instrumentation because of the higher temperature, pressure, and inclination of the EE-2 and EE-3 wellbores [317°C, 68.95 MPa (10 000 psi), 35° inclination].

It must be emphasized that the geophysical measurements pertaining to the hot dry rock concept are unique in many respects. The development of equipment includes not only the downhole sonde that houses the transducer and associated line driving electronics, but it also must key on the entire data retrieval system and associated data analysis technology as integral parts of the measurement. The bottom line is the acquisition of useful data that can be used for meaningful interpretation.

The Instrument Sonde Test Facility (ISTF) has already proved to be a useful tool in evaluating high-temperature equipment for both the downhole instrumentation sondes and drilling components. This facility is expected to accommodate numerous materials and component tests in FY81.

4.5.1. Downhole Drill Motor Development and Use. The planned trajectories of the inclined portions (35° to the vertical) of EE-2 and EE-3 have made it necessary to develop and test downhole motors with which directional corrections could be made in the hot (>200°C) deep portions of these holes (using 8-3/4-in.-diam bits).

Two geothermal turbodrills of 13.7-cm (5-3/8-in.) diam were purchased from Maurer Engineering, Inc. (MEI). (No development support was provided to

MEI.) Certain tests on these turbodrills were carried out at the Drilling Research Laboratory in Salt Lake City with support from the Sandia Laboratory Geothermal Drilling and Completions Program, DOE/DGE. Drilling into granitic test blocks was carried out using procedures developed for testing the 19.7-cm- (7-3/4-in.-) diam turbodrill.¹⁰⁴ The operating parameters and penetration rates obtained are shown in Table 4-IX and Fig. 4-49.

As noted in Table 4-IX, the two turbodrills were provided with slightly different blade designs [designated as high flow rate (HFTD) and low flow rate (LFTD)]. Based upon the laboratory tests, it was found that the key to smooth consistent operation of these turbodrills was to limit flow rate and bit weight to the values shown in Table 4-IX. Bit weights above 20 000 lbs resulted in increasingly unstable operation.

Fig. 4-49.
Operating parameters and penetration rates obtained during tests of Maurer turbodrills.

TABLE 4-IX

LABORATORY TESTS OF 5-3/8-IN.-DIAM MEI TURBODRILLS

Rock: Texas Pink Granite

Bit: Smith Tool Co., Geothermal, 7GA, 8-3/4-in. diam

<u>Operating Parameters</u>	<u>Blading Type</u>	
	<u>HFTD</u>	<u>LFTD</u>
Flow rate, gpm	350	300
Bit weight, lbf	15 000	15 000
Rpm	350	350
Torque, ft-lbf	450	450
Swivel pressure, psi	1000	800
Penetration rate, ft/h	25	25

In addition to the laboratory tests, these two turbodrills were given field trials (May 9-12, 1980) at the bottom of EE-2, at a measured depth of 4.66 km (15 300 ft). The temperature was subsequently determined to be 317°C (605°F). High-temperature seals were included in the bearing sections of both tools. The two tools were tested, without bent subs, in straight hole drilling. The tests were restricted in duration to reduce the risk of junking the EE-2 hole. The results are tabulated in Table 4-X. The most significant outcome was the retention of oil in the bearing packages. The major problem encountered was the difficulty of setting weight on the bits due to extreme hole-friction drag on the drill pipe in the 35° inclined portion of EE-2. It was judged, from these limited trials, that the MEI 13.65-cm- (5-3/8-in.-) diam turbodrills could possibly be used in bottom portions of EE-3 for directional corrections. It appears, however, that the addition of a tachometer, or rpm-indicator, system is required in order to have any chance of success in the 35° inclined wellbores.

TABLE 4-X
RESULTS OF MEI 5-3/8-IN.-DIAM TURBODRILL TRIALS IN EE-2

Item/Parameter	HFTD	LFTD
Flow rate, gpm	325	200 - 240
Wt on bit, lbf	20 000	30 000 ^a
Results		
Rate of progress, ft/h	15 - 60	b
Duration, h	1.25	2.50
Depth drilled, ft	11	10
Spin test on rig floor, gpm	60	46
Bit wear	<1/8 in. under gauge (run again in second trial)	~1/4 in. under gauge, some button wear, cones ok
Total depth at start, ft	15 271	15 282
Seal condition at end of test	Retained oil	Retained oil

^aVery difficult to set bit weight; back-off of up to 95 000 lbf was attempted but hole drag held up bit weight application.

^bVery erratic rate of progress was observed.

4.5.2. Drill Motor Activities in EE-3. Directional Drilling in EE-3 above 10 000 ft. As demonstrated in the EE-2 directional drilling program,^{105,106} standard, service-company-furnished, positive displacement motors (PDM) can be used to depths approaching 10 000 ft; i.e., at temperatures <200°C (400°F). The directional drilling of EE-3 to date has used Dyna-Drills (Sii., Dyna-Drill Div., Irvine, California), Baker Motors (Baker Service Tools, Houston, Texas), and NaviDrills (Christensen Diamond Co., Salt Lake City, Utah). The temperature limits on these motors are a result of deterioration of the elastomer materials used in the stators of these PDMs.

Field Trials of Commercial Turbodrills. Recently, the Dyna-Drill Div. of Smith International has started fabrication and is offering as a

commercial service an all-metal, high-temperature turbodrill. Both straight-hole and directional motors are available. With support from the Sandia National Laboratories, DOE/DGE Geothermal Drilling and Completions R&D program, both types of tools have been tested in EE-3.

A directional Dyna-Drill Turbodrill (DDTD) was tested at about 2.67 km (7895 ft) where the formation temperature is about 170°C (350°F). The turbine specifications and optimum operating point are as follows:

Outside diameter	17.9 cm (7in.)
Number of stages	100
Flow rate	350 gpm
Power rating	54 HP
Torque	360 ft-lbf
Rotational speed	800 rpm
Bit weight	20 Klbf
Length	23.8 ft
Pressure drop across tool	600 psi

The trial run was made with the following assembly and conditions:

Bit	12-1/4 in.
Flow rates	430 - 400 gpm
Bit weights	9 - 40 Klbf
Bent sub	1-1/2°

Because the steering tool was inoperative, the test was limited and the results indicated that an average rate of penetration of 4 m/h (12 ft/h) was achieved in about 1 h drilling. It was concluded that the performance with a 12-1/4-in.-diam bit may be marginal, but that with an 8-3/4-in.-diam bit these turbodrills could be used for directional corrections in the 35° inclined 8-3/4-in.-diam portion of EE-3. Addition of a tachometer system to the DDTD would almost certainly be essential. These trials were supported by the Sandia Geothermal Drilling and Completions program.

4.5.3. Wellside Service Unit. To meet the ever increasing demands for well-bore data in the HDR project, an instrumentation and data acquisition system has been designed and installed in a mobile, deisel-driven logging truck. The truck, now referred to as a wellside service unit, is in service and was recently used to temperature survey well EE-2.

The truck itself is an International Harvester chassis with a Cummings diesel engine and hydraulically controlled draw works. The truck was built by Energy Products of Fort Worth, Texas (see Fig. 4-50).

The cable installed on the truck is a 7-conductor, PFA-insulated, TFE bedded, armored cable built by Vector Cable Company of Sugar Land, Texas.

The instrumentation and data acquisition system, installed in this truck, was designed to control and record data from a variety of downhole survey tools (see Fig. 4-51).

The instrumentation system consists of signal conditioners, amplifiers, control circuitry, and a network of patch panels that allow easy configuration changes for whatever survey tool is to be used.

The signal conditioners consist of 12 channels of shielded input conditioning circuitry with excitation of constant voltage, with or without remote sensing or constant current available at each channel.

The amplifier bank consists of 12 channels of instrumentation amplifiers that can be used for impedance isolation, common-mode noise rejection, active filtering, or analog signal gain.

The control circuitry, in conjunction with the data-acquisition system, provides the ability to control downhole relays or downhole multiplex operations, to provide excitation voltages for downhole relays and motors, and to calibrate amplifiers for full-scale values of downhole sensors.

The signal-patching network allows for the patching of excitation voltages to downhole sensors in any arrangement desired. Output signals can be patched directly into the data-acquisition system or into the amplifiers. Signals can be patched or routed into the analog multiplexer of the data-acquisition system or into an analog tape recorder or both. Relay control circuits can be patched into the downhole survey tool in any desired configuration.

The patch-panel network is the heart of the instrumentation system because it has been designed to allow for the versatility to make the many changes encountered between types of survey tools without having to change actual equipment.

All measured data from the instrumentation system can be stored on an analog tape recorder or on a microprocessor-based data-acquisition system.

The data-acquisition system consists of a microcomputer-controller interfaced to a variety of instruments that can be used to measure a multitude of

Fig. 4-50.
Wellside service unit.

Fig. 4-51.
Instrumentation and data-acquisition system in wellside service unit.

different output signals from various survey tools. The system includes magnetic-tape or disc data storage, graphics display, and plotting capabilities.

The main frame of the system is a programmable computer that contains 187K bites of RAM memory. A computer program can be inserted into the machine to control or record data from whatever survey tool is being used. All instruments for measuring signals, all multiplex channel assignments, all control-relay channel assignments, and all ranges and time bases are controlled from the program in the computer. All measured raw data can be converted to engineering units and displayed on a graphics plot or thermal printer while the survey is in progress. The graphics plot can be dumped to the printer for a hard-copy record. In addition to the measurements from the survey tool, parameters such as time, tool depth, wireline speed, and wireline weight can be entered into the computer for data storage and data reduction.

The measurement system consists of several instruments and peripherals that can be programmed and controlled from the computer for whatever output signal that is to be measured.

All analog signals are patched into a multiplexer that is controlled by the computer. The computer program will route the appropriate channel to the appropriate measuring device.

Many of the survey-tool output signals are analog signals that contain a high magnitude of common-mode noise that is induced on the wireline. For these measurements, a high-resolution, integrating, digital voltmeter is used. For analog signals that require a high sample rate, a digital voltmeter that is capable of 5000 samples per second is used.

An electronic counter is used to record data from survey tools that have pulsed outputs such as gamma detectors and fluid-velocity tools. The counter can measure the frequency of pulses from a fluid-velocity tool that can be easily related to velocity or to flow rate if the wellbore geometry is known. The counter can measure counts per second from a gamma detector at various integration times.

For acoustical measurements such as the output of a geophone or accelerometer, a four-channel analog-to-digital converter is used to capture events over a selected time period. This unit is interfaced to transfer the data at (direct memory access) DMA rates to the computer for plotting and disc storage. The computer services the unit on an interrupt basis and transfers data only when triggered by an acoustical event.

Tool-depth measurements are made from a shaft encoder mounted on the wireline measuring head. The output of the encoder is fed to a counter that displays depth in feet and linespeed in feet per minute (FPM). Both depth and linespeed are interfaced to the computer for data reduction and disc storage.

In summary, this wellside service unit can be configured and programmed for many types of surveys. It can be used for a simple measurement of a single downhole sensor or a very complex measurement, such as encountered with our triaxial geophone package. With the measurement versatility and capability of this system, a great deal of downhole electronics in survey tools can be eliminated. This is certainly an advantage when trying to operate survey tools in the environments encountered in geothermal wells.

4.5.4. High-Temperature Cable Program. A cable test program was initiated to evaluate several prototype high-temperature armored instrumentation cables. The high-temperature cable is, at present, the most critical component in the downhole instrumentation systems to be deployed in the EE-2/EE-3 geothermal boreholes.

Prototype cable samples, each 341 m (1000 ft) in length, were purchased from several manufacturers for engineering evaluation. Two categories of samples were purchased: (1) a coaxial cable component (core) sample consisting of a center conductor, dielectric insulator, shield, and outer jacket without the armor package, and (2) an armored, multiconductor cable sample consisting of a central coaxial cable element surrounded by nine outer conductors and the steel contrahelical armor package.

The samples purchased used either PFA Teflon or TFE Teflon as the dielectric and electrical insulation material.

A contract was awarded to Southwest Research Institute to test the prototype cables under the specified test conditions. Initial electrical measurements were made at room temperature and standard atmospheric pressure for both a material-received quality assurance and as a baseline for measurements subsequently made at high temperature and high pressure. The maximum environmental conditions that each cable sample will be subjected to has been specified: 275°C temperature and 58.6 MPa (8500 psi) fluid pressure (water).

Additional high-temperature/high-pressure tests of each cable sample will be conducted by the Sandia National Laboratories and at Los Alamos for confirmation and comparison of test results.

The cable samples will be tested in the Southwest Research Underwater Engineering Laboratory. The autoclave used for the test program is shown in Fig. 4-52. The tests will be performed using 122-m (400-ft) lengths of each prototype sample. The cable will be coiled around a 61-cm- (24-in.-) diam, 122-cm- (48-in.-) long cylindrical drum immersed in the water-filled chamber. Heating will be supplied by external strip heaters primarily to heat up the thermal mass of the steel pressure vessel walls. Internal cartridge heaters will be used to heat the test medium. The ends of the cable will penetrate through the lid of the pressure vessel for termination at the electrical measurements station. The test pressures and temperatures will be brought up according to the profiles shown in Fig. 4-53.

Fig. 4-52.
Cable test chamber.

Fig. 4-53.
Cable test profile. Δ-electrical data at these points.

Tests on two coaxial cable components were conducted in the Southwest Research Test Laboratory. The first coax tested (Type A) consisted of an RG-58 equivalent coax made up of a nickel-plated copper conductor, TFE tape dielectric, flat-braid shield, and a polyimide-taped jacket. A 114.3-m (375-ft) sample was tested according to the prescribed test profile, but it very quickly deteriorated prior to reaching 125°C and 2.76 MPa (400 psi). The second coax (Type B) was constructed of a nickel-plated copper conductor with a TFE dielectric, braid shield and TFE jacket. An 89-m (291-ft) sample of this cable survived the test up to 275°C and 48.3 MPa (7000 psi). This test was discontinued when a thermocouple blew out of the test chamber at 55.2 MPa (8000 psi). Results of the tests are shown in the plot of insulation resistance (IR) vs test profile (Fig. 4-54) and frequency response vs test profile (Fig. 4-55). Failure of the first coax, Type A, was due primarily to manufacturing procedures and defects. Frequency response for Cable B shows very little degradation due to the test profile.

In order to characterize the EE-2 borehole environment (for programmatic planning in the near-term for hydraulic fracturing experiments in the Phase II system), an interim high-temperature cable was purchased to provide needed wellbore surveys. This cable was made by the Vector Cable Company and is similar to a cable procured by the USGS and used in hot boreholes with reportedly good performance. This cable is configured in the "standard" 7-conductor, 7/16-in.-diam, contrahelical, armored, well-logging package, but uses PFA Teflon (rated at 260°C) for the conductor electrical-insulation material and has a TFE Teflon (rated at 320°C) tape-wrapped outer jacket. The jacket is used both as a strengthening member for the core and as an armor bedding (Fig. 4-56). This cable has been installed on the new wellside service unit. The cable was subjected to a "soak test" in the EE-2 borehole to obtain preliminary information on the electrical performance. The soak test was made by running the cable into the wellbore to a depth of 3048 m (10 000 ft) where the temperature was 202°C. The IR of each conductor to armor was measured over a period of 6 h. Test results are shown in Table 4-XI. Conductor No. 7 (center conductor) showed a noticeable IR degradation during this initial soak test.

Following the soak test, this cable was used for the temperature surveys made in EE-2. The three conductors not used for the temperature measurements were monitored throughout the logging runs. It is significant to note that

Fig. 4-54.
Coax cable insulation resistance vs test profile.

Fig. 4-55.
Coax cable frequency response vs test profile.

Fig. 4-56.
High-temperature 7-conductor instrumentation cable.

the center conductor recovered from the low IR measurement and no degradation has been observed in subsequent borehole surveys. When the cable is retrieved from the wellbore, the IR recovers to its original status and no observable damage or degradation can be determined. The cable appears to perform well for short residence time in the high-temperature environment.

4.5.5. High-Temperature Seals. The Los Alamos National Laboratory has been conducting tests on seals for the past 5 yr. Metallic seals of many configurations, along with elastomeric seals of various compositions and design, have been tested at high temperature and pressure [275-300°C and 51.7 MPa (7500 psi)]. This testing has singled out a few seals that operate in this environment. Some of these seals, however, require complicated two-piece seal design, large radial clamping forces, extremely good surface finishes, special assembly tools, etc.

Table 4-XI
HIGH-TEMPERATURE CABLE
SOAK TEST EE-2

Depth = 3048 m (10 000 ft)
emp = 202°C

	Lead Resistance to Armor						
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>
Control At Ambient	4000	4000	4000	4000	4000	4000	1000
Time At 10 000 Ft							
0 H	450	200	175	150	175	225	90
2 H	150	90	100	75	80	85	48
4 H	100	70	70	65	65	75	22
6 H	90	65	65	65	65	70	4

In attempts to keep seal design simple and to allow interchanging of all Viton-type O-rings currently being used with a high-temperature elastomer, the Laboratory has funded L'Garde, Inc., Newport Beach, California, to adapt new elastomer formulations to yield an O-ring that will meet HDR requirements.

The L'Garde contract defined the following tasks:

Task 1: Determine and define requirements for the elastomeric seals for hot dry rock requirements in the 275°C temperature range.

Task 2: Formulate, fabricate, and deliver seals to the Laboratory.

Task 3: Technology transfer to industry by L'Garde with present fabricators to establish a commercial source to the Los Alamos National Laboratory and other users.

Task 4: Summary and final report.

The Los Alamos National Laboratory technical staff selected the HDR cablehead as an appropriate test bed for the new O-ring. Four critical seals, eight connector boots, and a cable-bend protector were selected for prototype fabrication. Interaction and technology transfer with commercial suppliers were immediately implemented by selection of Kemlon Products, a Houston, Texas,

firm, as the manufacturer for the connector boots. The elastomeric compound, ready for molding, was to be delivered to Kemlon by L'Garde.

The operating environment selected for testing describes a hot dry rock borehole. The external fluid, which would come in contact with the elastomer, was defined as noncorrosive water during the energy-extraction phase and drilling muds used during drilling. The elastomer-to-fluid contact from within the tool is limited to nitrogen, Krytox oil and grease, Dow Chemical RTV, and air at 100% humidity. The GEM 267 EPDM elastomer selected by L'Garde for the cablehead application is expected to be compatible with these fluids and should not be adversely affected by the operating cycles.

Three separate "autoclave" tests have been conducted on L'Garde's O-rings at the Laboratory. The pressure-temperature test cycle simulates a typical downhole borehole logging survey at Fenton Hill (Fig. 4-57). The 24-h cycle includes 5 to 9 h at a temperature between 250 to 300°C and hydraulic pressures between 52.4 and 55.16 MPa (7600 to 8000 psi). However, during testing, temperature excursions up to 340°C for durations of 1 h were imposed on the seals.

Testing was conducted on a L'Garde furnished O-ring 2-219, which is used in the Laboratory's HDR cablehead. The test fixture simulates our cablehead assembly and utilizes some of the actual cablehead hardware. Tests have been conducted in both water and Mobil One oil to simulate the wellbore fluid, with air and Krytox grease as the internal environment fluid.

Test No. 1, conducted at 44.8 MPa (6500 psi) and temperature profile as shown in Fig. 4-58, continued for four cycles and terminated upon L'Garde O-ring failure. Inspection indicated failure by separation of the elastomer along the mold line (see Fig. 4-59). Test No. 2, conducted at 53.1 MPa (7700 psi) with temperature excursion up to 340°C, used Mobil One oil. This test ran four cycles (days) but the temperature cycle was altered to an initial high temperature near 300°C, then a soak at near 230°C. No failure occurred; however the L'Garde seal was permanently deformed. The cross section increased in diameter by 11% while the inside diameter increased by 5%. The hardness decreased by 90 durometer (Shore A) to 60. Test No. 3 lasted 5 days; on the fifth day the temperature remained constant at 280°C for 24 h.

The Los Alamos National Laboratory cablehead was assembled with the L'Garde-provided seals, boots, and cable-bend protectors. The first test at the Fenton Hill site in borehole EE-2 (bottom-hole temperature = 317°C)

Fig. 4-57.
Typical pressure-temperature test seal.

Fig. 4-58.
L'Garde O-ring Bal-seal test.

Fig. 4-59.
Bal-seal failure.

resulted in failure of the connector boots in the cablehead. Analysis revealed that the elastomer was electrically conductive and therefore cannot be used for the connector boots. The connector boots were replaced with Viton boots and the test rerun. Five separate downhole logging surveys have since been run in EE-2 using the GEM 267 O-rings. No cablehead failures have occurred. However, as in the lab test, the seal was permanently deformed and had to be changed out after each survey.

4.5.6. Accelerometer Acoustic Detector. An accelerometer is an electro-mechanical transducer that gives at the output terminals a voltage proportional to the acceleration to which it is subjected. A mass acts on the active element, which consists of two piezoelectric discs separated by a contact plate. Several different types of high-temperature accelerometers were purchased for engineering evaluation. The Endevco piezoelectric accelerometer, Model 7704-100, was selected because of its greater frequency capabilities, electrical isolation from its base, and its smaller size--required for mounting in the limited space provided in the downhole sonde.

Preamplifiers are used together with the accelerometers primarily for two reasons. They are utilized to convert the high output impedance of the accelerometer to a lower, more convenient value and to directly amplify a relatively weak signal from the accelerometers. The charge preamplifiers are used to match sensitive impedance changes due to changes in cable capacitance resulting from varying armored cable lengths. A Bruel & Kjaer Model 2634 charge amplifier exhibited high-frequency response, high-gain capabilities, and an accessibility to troubleshoot and repair the charge-preamplifier circuit. The charge preamplifier is a compact two-stage charge amplifier that conditions the output signal from the piezoelectric transducers for transmission to the measuring/analysis instrumentation at the surface.

The accelerometer package will replace the triaxial geophone acoustic detector array now used in the Phase I system for such downhole uses as fracture mapping and the detection of both high- and low-frequency seismic and acoustic signals. The accelerometers will have the advantage of operating in the highly inclined boreholes in the Phase II system, since the accelerometers are insensitive to axis orientation or tilt.

A multiplexing system is an integral part of the downhole electronics. The multiplex is controlled from the surface allowing readout of the dewar internal temperature, the X and Y inclination, and the vertical, upper horizontal

and lower horizontal charge preamplifier battery voltages at the discretion of the operator.

The downhole electronics have been tested and packaged in the downhole sonde configuration (Fig. 4-60).

A comparison between the geophones currently used in the acoustic detector package and the accelerometers is shown in Table 4-XII.

4.5.7. High-Temperature Borehole Survey Tool. The high-temperature borehole-survey tool was designed in February 1980 to be used primarily as a backup directional-steering tool for use during the directional-drilling operations in EE-3. The tool will also function as a borehole-survey instrument during the drilling phase or as a survey tool in the open hole in the completed wellbore.

The survey-tool electronics package (purchased from Humphrey, Inc.) uses a fluxgate magnetometer as an orientation device to measure azimuth (slant-angle bearing). The fluxgate magnetometer is also used to position a resolver that drives a servo amplifier motor to measure roll or tool rotation about its axis. An inclinometer servo drive system is used to measure borehole inclination or slant angle.

The electronics and instrument package are assembled in the downhole sonde, which consists of a pressure vessel, a dewar to protect the electronics, and a replaceable nose cone. The pressure vessel is made of nonmagnetic, Type 316 stainless steel. High-temperature Bal-seals and O-rings provide the pressure seals at pressures up to 68.95 MPa (10 000 psi) and temperatures up to 300°C. The dewar houses the survey instruments and electronics. The dewar, with its associated heat sink, is designed to keep the internal temperature below 80°C for at least 6 h when the external temperature is 275°C. A short nose cone assembly with 22.8-cm- (9-in.-) diam centralizers is attached to the sonde when the tool is used to survey the open hole. A long nose cone is made up with a muleshoe attachment for seating into the drilling assembly for directional drilling operations. The long nose cone uses 8.25-cm- (3-1/4-in.-) diam centralizers to position the electronic package in the center of a 9.14-m- (30-ft-) long Monel drill collar (Fig. 4-61).

A special tool-calibration stand has independent adjustments for azimuth, slant angle, and tool-face angle (Fig. 4-62). The least-count adjustment for all angles is 0.5°. Calibration data were obtained at 10°

Fig. 4-60.
Downhole sonde.

TABLE 4-XII

COMPARISON OF GEOPHONE ACOUSTIC DETECTOR AND ACCELEROMETERS

	<u>Geophone</u>	<u>Accelerometer</u>
1. Construction	Moving Coil	Piezoelectric
2. Measurement	Velocity	Acceleration
3. Sensitivity		
Low Freq (10 Hz-100 Hz)	High	Fair
High Freq (100 Hz-5 KHz)	Fair	High
4. Temperature, maximum	250°C	280°C
5. Maximum Inclination to Axis	20°	No Limit
6. Durability	Medium	High
7. Freq Output (24,000-Ft Logging Cable)	3 kHz	5.3 kHz

Fig. 4-61.
High-temperature borehole survey tool.

slant-angle increments from -45° to $+45^{\circ}$ and azimuth and tool-face angle increments of 45° for a total of 640 data points.

Examination of the data indicated that the azimuth angle is a nonlinear function of both the azimuth reading and the slant-angle reading and the tool-face angle is a nonlinear function of both the tool-face reading and the slant-angle reading. A least-square analysis was used to fit the calibration data. Eighteen-term polynomials were required for the azimuth and tool-face angles to hold the standard error to less than $\pm 1^{\circ}$. A two-term polynomial for the slant-angle calculation gave a standard error of approximately $\pm 0.2^{\circ}$.

4.5.8. Borehole Measurements in EE-2. Borehole TV Diagnostic. The drilling program in EE-2 was plagued by a very critical problem beginning in late December 1979 when the 13-5/8-in. casing collapsed. Possible loss of the borehole [drilled to a depth of about 4267 m (14 000 ft) at that time]) would be a severe setback in the Phase II Hot Dry Rock Program. The extent of the

Fig. 4-62.
Survey-tool calibration stand.

damaged casing was not known until a successful downhole TV survey was made by the Fenton Hill logging crews. The TV camera equipment used to make the surveys consisted of a modified undersea camera and signal processor manufactured by Electrohome, Inc. The downhole camera and lighting head were interfaced to the signal processor using a 3/16-in.-diam, single-conductor armored monoline. Processed video signals were transmitted to a CRT for real-time viewing and stored on video-tape cassettes for later analysis. The downhole system was equipped with two lighting heads, one for viewing underwater and the other for dry-hole photography. Since the casing to be inspected in this case was cemented into the Precambrian granite at a depth of 700 m (2300 ft), temperature was not considered to be a limiting problem. The first successful TV survey was made on December 31, 1979, when the broken and bridged casing was clearly viewed in the interval from 537 m (1763 ft) to 543 m (1783 ft).

During the next 6 weeks, many TV surveys were made in the borehole to find other damaged areas and to inspect repairs. Much difficulty was experienced when attempts were made to view the damaged areas that were below the water level. The poor visibility under water was due to the suspended materials (muds, lubricant, etc.) in the fluid. A flocculent was used with little success to try to clear up the water to increase visibility. The diagnostics obtained from the TV surveys, however, proved that a downhole TV system would be a powerful tool, especially if it could be temperature-hardened and developed for use under water in the wellbore.

EE-2 Temperature Surveys. Following the completion of the EE-2 borehole, the temperature survey became the priority assignment. The anticipated bottom-hole temperature would exceed 270°C. The successful performance of the temperature survey would depend upon the integrity of the sensor, cablehead, and armored cable in the severe geothermal environment. The first temperature survey in EE-2 would also be a field shakedown of the new wellside service unit; microprocessor-based, data-acquisition system; and high-temperature 7-conductor instrumentation cable. The effect of drag on the downhole sonde in the highly inclined wellbore was of some concern.

The temperature sonde used to log EE-2 was 3 m (10 ft) in length, 10-cm (4-in.) diam, and weighed 125 kg (275 lbs). It used a Conex thin-walled, stainless-steel-jacketed thermistor (1-Mohm nominal resistance) calibrated to 240°C. The sensor was excited with 50- μ amp constant current to eliminate conductor-resistance variations due to temperature. The processor was

programmed to measure the voltage across the thermistor, linearize these data with a least-squares fit (obtained from the calibration), and plot temperature in degrees centigrade versus depth. The depth was entered into the computer from a digital counter interfaced to a slant encoder on the wireline measuring head.

The armored, 7-conductor instrument cable was fabricated by Vector Cable Company and used PFA teflon as the electrical-insulation material, extruded over each conductor. The core was wrapped with several layers of TFE teflon tape to provide better mechanical strength to the core and also act as the bedding material for the armor package. This cable was specified to operate continuously at 275°C. The insulation resistance was carefully monitored throughout the entire survey.

A BLH Model U3G2-B load cell was mounted to the upper sheave in the EE-2 workover tower to record wireline weight from a depth of 3048 m (10 000 ft) to the bottom during the survey and subsequent sonde recovery. Drag on the wireline and sonde due to the inclination of the wellbore was recorded.

The first temperature log was made on July 30, 1980, to a depth of 4572 m (15 000 ft). The maximum temperature recorded was 309.78°C. Maximum wireline weight recorded during retrieval of the sonde was 2290 kg (5050 lbs) from 4572 m (15 000 ft) to 4557 m (14 950 ft). The recorded temperature was surprisingly high and prompted a recalibration of the thermistor. The post calibration revealed that a shift had indeed taken place, but in the direction of lower temperature readings.

A second temperature log of the EE-2 wellbore was made on August 12 with a second thermistor calibrated to 240°C and cycled several times to ensure stability. This survey was run to the bottom of the wellbore at a wireline depth of 4616 m (15 145 ft). The bottom-hole temperature was measured to be 316.8°C. The temperature log was repeated coming out of the hole to check the repeatability of the thermistor. Comparison of the data from the two logs showed excellent agreement. The performance of the entire logging system was certainly satisfactory and most encouraging.

A plot of the EE-2 temperature log is shown in Fig. 4-63. The temperature perturbation at about 580 m (1900 ft) is due to cooling (during drilling) of a lost-circulation zone just above the Precambrian granite.

The insulation resistance measurements, recorded during the temperature survey, on the PFA Teflon conductors are shown in Table 4-XIII. The 2-Mohms

TABLE 4-XIII

HIGH-TEMPERATURE CABLE IR MEASUREMENTS
TEMPERATURE LOG EE-2
8/12/80

Time	Depth (ft)	Temp (°C)	Lead Resistance To Armor, M Ω		
			5	6	7
12:24	3 000	94	1000	1000	20.0
14:23	14 000	290	5	5	--
14:40	15 000	314	3	3	2.0
14:50	15 145	317	2	2	1.5
16:43	9 900	200	20	20	20.0

IR measurement at 317°C is an order of magnitude better than the average IR measurement for Tefzel insulation at 200°C. (Tefzel is the insulation material commonly used by the oil- and gas-well-logging service companies in their high-temperature armored cables.)

4.6. Environmental Surveillance

4.6.1. FY80 Hot Dry Rock Seismic

Monitoring. The Fenton Hill HDR seismic monitoring effort passed several milestones during FY80. The number and coverage of the seismic monitoring stations reached an adequate level. Microseismic events at the HDR site provided an important test for the monitoring program. A great amount of seismological research pertaining to the induced seismicity associated with HDR techniques was accomplished.

Fig. 4-63.
EE-2 temperature log (July 30, 1980).

Seismic Stations. Table 4-XIV lists the Los Alamos National Laboratory seismic stations used for HDR seismic monitoring during FY80. Four new seismic stations were added that greatly improved our detection and location capability.

Seismicity.

- Seismicity within 20 km of the HDR site. Fifty-three microearthquakes ranging in local magnitude (M_L) from -1.7 to +1.3 were detected and located (Fig. 4-64) within 20 km of the HDR site during FY80. Most of the activity was centered about 10-km west of the site at a depth of 4 to 7 km. These events are not related to the HDR program and pose no threat. They do show, however, that we are capable of detecting and locating microearthquakes as small as $M_L = -1.0$ at distances as large as 15 km from the HDR site.
- Seismicity at the HDR geothermal site. During FY80, 25 microseismic events ranging in local magnitude from -3.0 to +0.5 were detected within 2 km of the HDR site. Nineteen of these events were recorded on a sufficient number of stations to provide a hypocenter location. Six events with local magnitude ranging from -2.5 to -1.5 were recorded during the high-pressure phases of HDR Expts. 198 and 215. These events locate south and east of GT-2 (Group I of Fig. 4-65) and are within 300 m of GT-2 at depths ranging from 2 to 3 km (in the HDR fracture area). These events are caused by stress release during the high-pressure experiments.

Thirteen events ranging in local magnitude from -1.5 to +0.5 were recorded during the heat-extraction phase of Expt. 217. These events locate about 200 m north of EE-2 (Group II of Fig. 4-65) at a depth of about 1 km. The events are not related to Expt. 217 activities, but rather to the drilling of EE-2. They began about 11 days after EE-2 began losing large amounts (as much as 450 000 gal/day) of drilling fluids at the granitic-sedimentary unconformity (at a depth of about 0.75 km) due to a casing failure during the drilling operation. They subsided about 60 days after the casing was repaired, but before that about 9 000 000 gal of fluid were pumped into the unconformity. It is believed this fluid triggered the release of tectonic stress that had accumulated at the unconformity or related faults. The cumulative seismic energy release of these events was about that

TABLE 4-XIV
FENTON HILL MONITOR STATIONS

<u>Code Name</u>	<u>Geographic Location</u>	<u>Distance From TA-57 (km)</u>	<u>Installation</u>	<u>Magnification^c (at 10 Hz)</u>	<u>Tele-metry</u>
CLP	Clara Peak	42.7	Surface ^a	240 k	R
EUM	Eureka Mesa	21.3	Surface	216 k	R,T
TMRS ^b	Thompson Ridge	3.4	Subsurface ^a	530 k	R,M
LCV	La Cueva	0.3	Surface	456 k	T
BRC	Barley Canyon	3.6	Subsurface	512 k	R,T
LFC	Lake Fork Canyon	0.9	Subsurface	288 k	T
LFMS ^b	Lake Fork Mesa	4.3	Subsurface ^a	576 k	R,T
REDP	Redondo Peak	10.0	Surface ^a	360 k	R,T
SHMS ^b	School House Mesa	3.3	Subsurface ^a	288 k	R,M
JOAQ	Joaquin Lookout	19.4	Surface ^a	723 k	R,M
SPE	St. Peter's Dome	30.7	Surface ^a	688 k	R
WELC ^b	Test Well C	10.9	Subsurface ^a	512 k	R,T

Close-In Stations

Q-1	0.9	Surface	152 k	M
Q-2	0.8	Surface	152 k	M
Q-3	0.8	Surface	152 k	M
Q-4	0.8	Surface	152 k	M
Q-5	0.7	Surface	152 k	M

^aSolar powered.

^bInstalled in FY80.

^cDuring predominately low-noise-background periods.

R = Radio link

T = Telephone line

M = Microwave system

Fig. 4-64.
Microseismic events within 2 km of
the Los Alamos National Laboratory
HDR site, October 1970-June 1980.

Fig. 4-65.
Microseismic events at the Los Alamos
national Laboratory geothermal site.

of an $M_L = 0.75$ earthquake (which would be detectable to epicentral distances of about 100 km).

Conclusions. The surface seismic monitoring conducted as part of the Laboratory's HDR program provided the following significant observations and results.

- We can detect and locate (within ± 2 km laterally and ± 5 km vertically) seismic events as small as $M_L = -1.0$ at epicentral distances of 15 km or more from the HDR site. (This area includes the Baca geothermal location.)
- We can detect and locate (within ± 400 m laterally and ± 600 m vertically) seismic events as small as $M_L = -1.5$ occurring within 2 km of the HDR site.

- Using surface sensors, we can detect and locate the larger micro-seismic events related to fracture formation occurring at depths of at least 3 km.
- The only unexpected seismic activity observed to date in the HDR program is related to drilling problems and not to heat extraction or fracture production.
- No detectable ($M_L > -3.0$) seismic events have been observed that can be related to the heat-extraction phase of Experiment 217 (supported by 6 months of data).
- A calibration explosion at depth in one of the existing geothermal wells would reduce our location uncertainty considerably (possibly to within ± 100 m laterally and ± 200 m vertically).

4.6.2. Hydrologic Monitoring. Water quality from 13 surface water stations and 17 ground-water stations located in the Jemez Mountains adjacent to the HDR site (Fenton Hill) has been monitored to determine if there has been any effect of geothermal development on the environment (Fig. 4-66). This is part of a continuing program that began in 1973.¹⁰⁷⁻¹¹³ There are four groups of surface water based on common chemical properties of predominant ions and TDS (total dissolved solids). The surface water types are (1) sodium and chloride, (2) calcium and bicarbonate, (3) calcium and sulfate, and (4) sodium and bicarbonate. Ground water (wells and springs) is similarly classified into three groups. The principal types of waters are (1) sodium and bicarbonate, (2) sodium and chloride, and (3) calcium and bicarbonate. In comparison with chemical data before 1979, no significant changes in the chemical quality of water has occurred.

The production of water from the supply well (FH-1) at the site in 1979 was about 18.4×10^6 ℓ , an increase of 1.9×10^6 ℓ above the 1978 production. The total production from the well since November 1976 has been 46×10^6 ℓ . Water levels have declined about 1.5 m since production began. Chemical analyses of water from the well indicates that the water meets criteria for domestic or municipal use, as set forth by the USEPA and the State of New Mexico standards or criteria.¹¹⁰

Water in ponds at the HDR site is used in drilling operations and experiments in the circulation loop. The pond water is discharged into an adjacent dry canyon when more storage is required. The rate of discharge is regulated to allow the discharge to infiltrate into the thin alluvium within

300 m of the pond. The total release in 1979 was about 3750×10^3 l. The water in the ponds is highly mineralized (Fig. 4-67). Analyses of the discharge indicated a general increase in most constituents during 1979. The most notable was sulfates, which increased from about 80 mg/l in March to 730 mg% in December 1979. Monitoring of surface and spring discharge below the pond failed to detect any effect of the pond release on the quality of water down gradient from the release area.

4.6.3. Microclimatologic Monitoring. A new tower was put on line in 1980 with meteorological observations at two elevations above ground. There were some instrument failures during the breaking-in phase and backup electronics components were obtained in order to facilitate maintenance and reduce down time. A lightning strike in May 1980 caused extensive damage to the data collection system.

Figure 4-68 shows the average annual percentage of winds from eight compass directions at Fenton Hill. The results of the monitoring activity for 1980 are summarized in Table 4-XV. Appendix D is a monthly tabulation of monitoring activities for FY80. More extensive tabulations are maintained in

Fig. 4-66.
Water quality monitoring locations in the vicinity of the HDR site.

Fig. 4-67.
Chemical constituents in water in ponds at Fenton Hill, 1974-1979.

TABLE 4-XV

MICROCLIMATOLOGIC MONITORING FOR FY80

Month	Wind Speed (m/s)			Temperature (°C)			Relative Humidity (%)			Precipi- tation (mm)	Pressure (kPa)
	avg	max	min	avg	max	min	avg	max	min		avg
Nov 79	3.4	10.9	0.8	-3.7	8.9	-13.2	15.8	28	4	8	71.50
Dec 79	3.3	9.1	0.0	1.9	11.8	-4.7	39.5	43	18	16	71.55
Jan 80	3.5	11.0	1.0	-1.8	10.9	-10.1	29.7	42	16	18	
Feb 80	3.9	13.3	0.0	-0.5	14.5	-14.4	26.2	49	8	29	
Mar 80	4.8	12.5	1.0	-1.2	8.3	-10.7	24.9	40	13	69	73.38
Apr 80	3.3	9.7	1.1	4.6	17.7	-7.3	21.5	46	9	46	73.92
May 80	2.2	5.7	0.5	7.1	17.6	-4.8	48.2	79	31	3	72.99
Jun 80	No data										
Jul 80	No data										
Aug 80	2.5	8.6	0.4	11.5	21.1	4.8				27	74.45
Sep 80	2.3	7.3	0.0	10.0	14.9	0.0				46	74.49

an automated data base for environmental and climatic analysis and regular detailed reports are circulated to interested parties.

The Fenton Hill meteorological site represents a valuable baseline data site for broader scale environmental analysis of the Valles Caldera area. When the present data set is supplemented by other locations, the network will provide space-time meteorological variations that will serve a variety of geothermal development needs.

4.6.4. Biotic Monitoring. Biotic monitoring of the Fenton Hill HDR site has been conducted since 1976. Past objectives were to monitor and establish baseline information about the flora and fauna in the surrounding environs. Preliminary baseline data are now available for avian inventory, climatological monitoring, vegetation surveys, elk population and usage estimations, and small-mammal trapping programs. Results of these studies appear elsewhere.^{51,76,77,114}

Recent studies have focused on the canyon below storage pond GTP-3. There are three ponds at the HDR site that are used as storage for water from experimental use in the circulation loop and drilling operations. GTP-1 received mainly effluent from drilling operations while GTP-2 and GTP-3 have been used mostly as storage for circulation experiments.¹¹³ Effluents from these activities are occasionally released to the environment from GTP-3 via the canyon south of this pond. Chemical analysis of these effluents has detected some trace elements at elevated concentrations. Elements of specific interest include arsenic, boron, cadmium, and lithium.

Table 4-XVI shows concentrations for the four elements of interest in effluent from GTP-3 and from samples taken at 13 surface water sampling stations and 13 ground-water sampling stations.¹¹³ High concentrations in surface and ground waters were due to thermal and mineral springs along the Jemez Fault. The values for the GTP-3 effluent, while higher, more closely reflect

Fig. 4-68.
Fenton Hill wind rose. Average annual percentage of winds from eight compass directions.

those values for ground waters. This would be expected because GTP-3 waters are derived from ground waters.

Studies are now being conducted to determine what effect releases from GTP-3 have upon soils, vegetation, and small mammals within the canyon area below this pond. In 1979 four releases amounted to 3750×10^3 l of effluent discharged down this channel.¹¹⁴ Using reported minimum concentrations in pond waters, this would amount to a potential release of ~0.075 kg arsenic, ~1.88 kg boron, ~0.004 kg cadmium, and ~7.13 kg lithium to the environment below the pond. Pond releases reportedly infiltrate into the alluvium within about 300 m from the pond.¹¹³ Preliminary results from soil cores taken at regular intervals below the pond show elevated levels of cadmium and lithium. Vegetation analyses are also being conducted for these elements from samples obtained along this channel and results are to be made available in the near future.

During the years 1976, 1977, and 1978, three small rodent-trapping grids were used in the canyon below GTP-3. Results from these programs were useful for establishing some baseline information; however, they were not sensitive enough to give sufficient information about the home ranges, species population, and densities of these rodents. In the summer of this year, two permanent 100-m x 100-m grids were established down gradient from GTP-3.

TABLE 4-XVI

TRACE ELEMENT CONCENTRATIONS IN
HDR EFFLUENTS AND NATURAL WATERS

mg/l	Range and $\bar{x}$		
	Surface Waters	Ground Waters	GTP-3 ^a
As	<0.001-0.105 (0.018)	<0.001-0.174 (0.016)	0.02-0.49 (0.11)
B	<0.05-1.2 (0.18)	<0.05-12.4 (1.45)	<0.5-15 (<3.0)
Cd	<0.001-0.004 (0.001)	<0.001	<0.001-0.014 (<0.002)
Li	0.01-1.0 (0.19)	<0.01-13.4 (1.37)	1.9-19 (5.6)

^aFifteen analyses from four releases and one overflow.

With the establishment of these larger grids and more frequent trapping sessions, more detailed information can be obtained about the small mammals in the discharge area.

4.7. Phase III Studies.

Because the Phase II reservoir has been intentionally designed to be of approximately commercial size, it seems only reasonable that it be used, when completed. Further, the only practical use would be for electricity generation--in the absence of any direct users in the Fenton Hill area.

Plains Electric Generating and Transmission Cooperative, Inc., was awarded a contract by DOE for conducting a 5- to 10-MW(e) electricity generation feasibility analysis for Fenton Hill. The proposal that resulted in the contract envisioned three sequential parts: (1) a 1-yr feasibility study; (2) a 1- to 2-yr engineering design and specification effort; and (3) construction.

The feasibility study (Part I) tasks have been detailed and time-sequenced to assure completeness of all aspects. The task sequences are of five categorical types--reservoir characteristics, plant engineering, environmental, economic, and institutional. The reservoir characterization includes configuration, size, temperature, projected temperature drawdown, and lifetime under several operational designs. Plant engineering includes several turbine designs (direct flash, binary cycle, etc.); cooling towers (wet and dry); switchyard; buildings; and alternative transmission corridors. Following reservoir, turbine, and cooling tower characterization, the water requirements will be determined. A majority of the required environmental analyses have been completed; however, those for generation and transmission lines remain. An economic analysis using closely approximated costs, reservoir life, taxes, interest, amortization, etc., from the several categories will be conducted pursuant to Plains' design. The institutional category includes lease acquisition, permit requirements by agency, potential issues and interest-group concerns, and the decision-making process including public hearings and possible intervention. This particular activity is the longest in terms of time and the most complex in terms of success-sensitivity, as experience has taught.

Following a favorable feasibility study, a proposal for a second contract for detailed engineering design and specifications (Part II) will be made. The detailed costs will then be reentered into the economic model used in Part I, and based on this result and other conditions found still

favorable, the many applications for leases, permits, and construction (Part III) will be made.

5. COMMERCIAL FEASIBILITY ASSESSMENT

5.1. Economic Studies

Bechtel National, Inc., and its subcontractors completed the first phase of their "Industrial Assessment of the Economic Feasibility of HDR Geothermal Systems." Individual tasks were divided among the subcontractors according to their particular expertise, with the following major divisions:

Bechtel (San Francisco, California)

- overall project management, energy-conversion-systems design and capital equipment costing, economic analysis and forecasting

GeothermEx (Berkeley, California)

- HDR resource evaluation and reservoir physical property specification

Republic Geothermal (Santa Fe Springs, California)

- drilling and fracturing (hardware specification, downhole reservoir design, and costs)

INTERCOMP (Houston, Texas)

- reservoir performance simulation and modeling

The major objective of this study is to provide an independent assessment of HDR economic feasibility from the private sector. The purpose is to determine what combination(s) of reservoir and economic factors is required for commercial viability in the year 2000. These include reservoir engineering and performance issues, particularly geometric design, lifetime, fluid temperatures, and production capacity (kg/s per pair of wells); resource characteristics (geothermal gradient and formation type and geographic distribution); drilling and plant capital costs; levels of plant and reservoir management; and institutional and regulatory matters (for example, tax treatment). An economic-systems study of this type, using a parametric sensitivity analysis approach, not only provides valuable information on ultimate commercial feasibility, but also can help focus HDR research and development work.

As a part of the economic assessment effort in progress at the Laboratory, we have been examining a potential cogeneration application for HDR at Crown Zellerbach's pulp and paper mill at Camas, Washington. This energy intensive, high-load-factor operation is ideally suited for HDR base-load capacity with steam and electricity requirements in excess of 200 MW(t) and 70 MW(e). During the fiscal year, two engineering design options were considered to provide the quantities of steam, heated air, and electricity

used by the Camas Mill. The first option would provide all the low-pressure (45 psig) steam for process heating, all the heated air required, plus that quantity of electricity that can be produced from the geothermally heated water after the steam and air-heating requirements are met. A second option includes the steam and heated air supplied in option one, plus electric generating capacity to provide the total electric power needs of the Camas Mill [70 MW(e)]. The steam, heated air, and electricity produced by the HDR system for either option is in excess of that provided internally by recovery and waste-paper boilers currently in use at the plant.

The economic sensitivity of possible HDR resource types in the Camas area was explored by considering mill-to-HDR-wellsite distances from 0 to 40 km and gradients of 25, 37.5, and 50°C/km. Individual reservoir performance was specified, with ten 300-m radius fractures selected per well pair with a mass flow rate of 75 kg/s. Parasitic power losses for geothermal-fluid transmission to the plant, downhole pumping, and cooling-fan motors were also included.¹¹⁵ Pumping-power requirements for fluid transmission beyond a well-to-mill distance of 20 km were found to exceed the electrical output of the option one case.

For the cases examined, drilling and reservoir-development costs dominated the economics, requiring 75 to 90% of the total investment. Calculations were based on 1980 estimates of 2.2¢/kWh for purchased electricity and a fossil-fuel equivalent cost of \$5.85/10⁶ Btu delivered, with annual escalation rates of 6.5% for electricity, 15% for fossil fuel, and 7% for equipment and drilling assumed. Because of heat-exchanger design considerations, the optimum temperature for geothermally heated water delivered to the mill was 244°C (472°F). Given these reservoir and economic assumptions, commercially acceptable after-tax rates of return of greater than 17% result for gradients above 37°C/km even at mill-to-well distances of 40 km. Readers interested in the details of these calculations should refer to Ref. 115.

5.2. Legal Studies

An earlier study, "Hot Dry Rock Geothermal Energy Resource Ownership and the Law"¹¹⁶ revealed a definitional problem in several state statutes that acts to preclude the production of hot dry rock heat, since only the heat contained in naturally occurring water (hydrothermal) is addressed. Without inclusion in enabling legislation, the legality of ownership and the ability

to produce HDR heat can only be decided judicially. The ownership problem is, therefore, a major constraint in some states.

Because the present HDR technology is based on the use of water as the heat-transfer medium of choice, and, because the water must originate in another geologic formation, if on-site, or from elsewhere, a question arises concerning the problem of diverting water for this heat-transfer use. Particular concern exists since both Indian and Federal water-rights laws are being changed, as is the trend in States' opinions of beneficial use. It seems obvious that an inability to appropriate nearby but not indigenous water might preclude the use of water as the heat-transfer fluid from this resource in many instances. Therefore, the control of water seemingly becomes the control of the resource. The extent to which water law controls HDR heat extraction requires clarification, and if it is found constraining, this should be made widely known to both industry and government. The investigation of this problem is continuing.

5.3. Other Institutional Studies and Activities

An important step toward commercializing the HDR technology being developed at Los Alamos National Laboratory is the widespread dissemination, particularly to industry, of information concerning its major constraining problems. This requires that we (1) present the problems (or comparative lack thereof) in an understandable way; (2) suggest remedial strategies; and (3) facilitate implementation of the most advantageous mitigation strategy. The "Industrial Assessment of the Economic Potential and Commercial Feasibility of Hot Dry Rock Geothermal Systems" described above was expected to be an important part of this commercialization strategy. Unfortunately, it was necessary to terminate the study near the end of the fiscal year because of budget constraints.

Phase II reservoir-development plans and operations required that the Memorandum of Understanding (MOU) between the Department of Energy and the U.S. Forest Service be amended to include a small site expansion to accommodate the drilling rig and a storage pond. The drilling of EE-2 to its total planned depth and temperature provided the confidence that the Phase II reservoir would be successfully completed. This knowledge, together with a markedly increased amount of environmental monitoring data, indicated a need for updating the Environmental Analysis included in the MOU. This was initiated and will be completed early next year.

The existing water appropriation at Fenton Hill is insufficient for the Phase II reservoir operation, and an increased appropriation will be required. A consulting hydrologist, acceptable to the New Mexico State Engineer's Office, completed an investigation of a shallow on-site fresh-water aquifer to support an application for the increase.

6. PROGRAM MANAGEMENT

During this fiscal year, some changes occurred in the program organization, as shown in Fig. 6-1. James K. Gaddy was assigned to manage the "Special Projects and Liaison" function; Hugh D. Murphy became task manager of both "Program Analytical and Experimental Support" and "Fenton Hill Reservoir Engineering"; and Gary Langhorst assumed responsibility for the "Fenton Hill Environmental Surveillance" task.

Program management effort this year again spanned a broad spectrum of activities. Included were regular meetings with our advisory bodies, two meetings of the Fenton Hill Project's International Steering Committee, and a formal review of the HDR Program by DOE's Energy Research Advisory Board (ERAB) through its Geothermal Panel. These meetings are discussed in Sec. 6.1. Preparations were made for the third annual Hot Dry Rock Information Conference to be held in Santa Fe, New Mexico, on October 29-30, 1980.

Fig. 6-1.
Hot Dry Rock Geothermal Energy Development Program Organization.

The HDR Program Plan was finalized and published.¹¹⁷ Other publications are listed in App. E. Planning activities are discussed further in Sec. 6.3.

6.1. Advisory Body Interactions

Program personnel met with its two major advisory bodies--The National HDR Program Development Council (PDC) and the Fenton Hill Project International Steering Committee--on several occasions during the year.

Steering Committee members were B. G. DiBona (DOE), chairman; H.-J. Stöcker (KFA), vice-chairman, and A. J. Jelacic (DOE), secretary. Their first regular meeting of the year was held at Los Alamos on January 17, 1980, with Dr. R. Neumann representing Dr. Stöcker. This meeting was devoted primarily to review of the status of the Fenton Hill project and discussing details of the KFA participation. The second regular meeting was held in Washington, D.C. on July 19 and 20, 1980, with Dr. R. Holigaus and Dr. R. Neumann representing Dr. Stöcker. This meeting focussed its attention on the planning for the Phase I and Phase II work at Fenton Hill.

PDC meetings included a regular meeting of its Executive Committee and two scheduled meetings of its technical committees. These are discussed in the following section.

6.1.1. HDR Program Development Council. The Executive Committee of the HDR Program Development Council (PDC) met at the Los Alamos National Laboratory on April 16, 1980. Present were C. M. Swinney, Chairman; G. Bodvarsson; W. Dolan; B. Greider; C. B. Raleigh; L. J. P. Muffler, alternate to Dr. Raleigh; and ex-officio members and Program Office Staff from the Laboratory and AL00. Phase I loop operations, Phase II plans and drilling, HDR resource evaluation, and Site 2 selection activities, instrument and equipment development, and the financial position and funding projections of the HDR Program were reviewed. The fifth draft of the HDR Program plan was discussed and recommendations were made concerning its next revision. It was agreed that, in addition to the two technical committees mentioned below, a PDC Equipment Technology Committee should be formed to review the Laboratory's instrumentation and equipment development activities and advise the Program Office concerning them. Comments, conclusions, and recommendations from this meeting were subsequently reported to DOE/DGE by letter from the Committee Chairman to the DGE Director.

The PDC Reservoir Engineering Committee met at the Los Alamos National Laboratory on November 27, 1979. Present were G. Bodvarsson, Chairman;

W. Brigham; D. Kassoy; J. Martin; K. Gray; and Laboratory staff members from the Program Office and the Fenton Hill Project. The meeting was of the workshop type, and discussions were concerned particularly with reservoir-rock properties, the geostress environment, present reservoir-testing and modeling techniques, applications of HDR techniques to hydrothermal well stimulation, the possible advantages of generating steam in manmade fracture systems, and the factors that affect HDR system economics. K. Aki of the Massachusetts Institute of Technology (MIT) was subsequently added to this committee.

The PDC Site Selection Committee met at Los Alamos on January 28-29, 1980. Present were R. Christiansen, Chairman; G. Crosby; Y. Isachsen; H. Olson; T. Glenn, alternate to M. Wright; and members of the Program Office and Laboratory Project Staff. Sixteen areas considered promising for HDR development were discussed individually, then divided into the following groups: (1) areas of demonstrated high temperature at shallow depth; (2) specific target areas of relatively high geothermal potential; (3) large regions of high geothermal potential; (4) areas in the western U.S. having above-background temperature gradients; and (5) areas in the eastern U.S. considered to have potential as direct-use sites. Of the areas considered, The Geysers-Clear Lake region of California--which has demonstrated high temperature at shallow depth--was assigned first priority as the next area to be investigated in detail as a possible location for HDR Experimental Site 2.

6.1.2. ERAB Review. The Energy Research Advisory Board (ERAB) is a group of prominent persons from industry and academia chartered to review various DOE energy research and development efforts for the Secretary of Energy. On April 3, 1980, the Hot Dry Rock Study Group, a subcommittee of the ERAB, met in Denver, Colorado, to review the status and objectives of the HDR program.

The ERAB members in attendance were Dayton Clewell, Vice President (retired), Mobil Oil and Carl Savit, Senior Vice President, Technology, Western Geophysical Company. The other HDR Study Group members in attendance were: William Dolan, Manager, Geothermal Branch, AMAX Exploration, Inc.; Carel Otte, Geothermal Division, Union Oil Company of California; and Professor George Keller, Colorado School of Mines.

DOE representatives included: Robert Weinraub, Executive Assistant to the ERAB; Bennie DiBona, Director, Division of Geothermal Energy; Ronald

Thoms, Division of Geothermal Energy; and W. Porter Grace, Albuquerque Operations Office.

Los Alamos National Laboratory representatives included: Lawrence Germain, Deputy Associate Director for Alternate Energy Sources; Gregory Nunz, HDR Program Manager; Jefferson Tester, Professor, MIT, (previously Group Leader, G-5 Resource Engineering); and Grant Heiken, HDR Assistant Program Manager-Resource Evaluation.

After formal presentations by each of the Laboratory representatives on the status and objectives in technical and programmatic terms, discussion and evaluation centered on these points: (1) level of success of recent HDR experiments; (2) necessity of thermal-stress cracking to the HDR concept; (3) economic feasibility of the HDR concept; (4) reasonableness of the program goals and objectives; (5) pace of the program; (6) balance of program elements; and (7) integration of the HDR program with other related geothermal programs.

General agreement was accorded on the positive nature of items (1) through (6), and that item (7) was being improved. Specific consensus was recorded regarding the desirability of Site 2 being at a location of a shallow, high-temperature resource. Details of this synopsis are in William Dolan's Summary to the HDR Study Group, which is included as Appendix F.

6.2. Program Planning

The Program is now subdivided into four major elements: "Technology Development," which includes the Fenton Hill and (future) Site 2 demonstration projects; "Resource Evaluation," which includes characterization of specific candidate sites in addition to evaluation of the national HDR resource; "Institutional Issues Analyses," embracing all the appropriate legal, regulatory, environmental, and public perception studies; and "Commercial Feasibility Assessment," in which economic and market analyses are conducted and the results from the other three elements are ultimately synthesized.

The present schedule for the program, as given in the HDR Program Plan, is presented as Fig. 6-2. The schedule is based upon a critical-path-method (CPM) analysis of requisite Program act coupled with budgetary forecasts. The methodology is discussed further in the next two sections.

An Annual Operating Plan (AOP) for FY81's effort was drafted and submitted. This document will be revised as the year unfolds and major expenditures are better defined.

Fig. 6-2.
Hot Dry Rock Program milestone schedule.

6.2.1. CPM Analysis Time-phasing of the Program's required activities is planned and scheduled through a conventional PERT-type critical path analysis. Once the basic data are assembled, the procedure is automated via a commercial software package called "ASA" (automated CPM analysis). Detailed schedule data, together with the usual event-priority "bubble chart" and an overview time-line diagram, are printed out. This information is updated quarterly, and on an ad hoc basis if a program perturbation occurs that has significant schedule implications.

6.2.2. Automated Cost and Effort Projection To date, the fiscal and manpower analysis accompanying the CPM analysis has had to be done manually. This results in several drawbacks:

- Iterations in future budget and manpower projections are extremely tedious.
- These projections are necessarily deterministic (or "nominal only"), whereas the schedule projections are, to a certain degree, uncertain and treated stochastically. The stochastic approach is obviously more realistic, but the mind-boggling complexity of the calculations obviates such treatment manually.

- Cost and obligation are not projected separately.
- Inflation is difficult to deal with (irrespective of uncertainty in the rates).

It was therefore decided to develop a software package, to interface with the ASA package, which would

- temporally distribute the expected values and variances of manpower, and of constant-dollar costs and obligations, over the program activities;
- perform all requisite computations to obtain expected totals and deviations for a desired period (i.e., one future fiscal year, several fiscal years, or program-to-completion);
- calculate costs and obligations in either constant, or current-year [using input escalation rate(s)] dollars; and
- provide optional graphic output of a set of bivariate probability ellipses, at specified confidence levels, for program-to-completion: cost vs time, manpower vs time, and cost vs manpower.

At the end of FY80, the interfacial programming is completed and debugged. All of the required algorithms are developed and programmed with debugging in process. Suitable input/output formats are being developed. The graphics package is operative. A sample set of cost-time ellipses, for confidence levels ranging from 50 to 99%, is shown in Fig. 6-3. Cost and time data presented are checkout examples only. It is expected that the complete package will be operational by mid-FY81.

Fig. 6-3.

Example of bivariate probability ellipse output of automated cost/effect projection software for program management.

ACKNOWLEDGMENTS

We thank the following for their contributions to this report. P. Grace, Assoc. Program Manager, DOE/ALO; G. Heiken, R. Spence, J. Gaddy, and P. Franke, HDR Program Office; F. Goff, J. Maxwell, A. Eddy, W. Laughlin, J. Aldrich, D. Gambill, A. Kron, B. Arney, and J. East, Resource Characterization; J. Tester (former G-5 Group Leader, now a professor at MIT), H. Murphy, H. Fisher, C. Grigsby, G. Zyvoloski, R. Potter, E. Cocks, R. Aamodt, and D. Brown, Reservoir Engineering; C. LaDelfe, M. Ander, C. Hudson, C. Pearson, J. Albright, T. Dey, P. Halleck, and F. Homuth, Geophysics; B. Dennis, R. Lawton, and S. Koczan, Geoscience Instrumentation; R. Hendron, J. Hill, J. Rowley, and R. Williams, Field Operations and Engineering; S. Barr, Atmospheric Sciences; J. Neudecker, WX-8; C. Holley and L. Blatz, CNC-2; R. Vidale, I. Binder, and A. Gancarz, CNC-11; R. Demuth and R. Harlow, T-3; and G. Langhorst, LS-6.

We also thank Barbara Ramsay, word processor, for her assistance in the preparation of this report and John Tubb, Anthony Garcia, Connie Wilson, and Janet Repa for their illustrating support.

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APPENDIX A

UNITS AND CONVERSION FACTORS

Units

1. Pressure - Pa (psi) [P]
2. Volume - m^3 (ft^3 or gallons or bbl) [V,Q]
3. Mass - kg (lb) [m]
4. Volumetric flow rate - m^3/s (gpm, bbl/min) [$\dot{q}$]
5. Mass flow rate - kg/s (lb/s) [$\dot{m}$]

6. Time - s, h [t]
7. Permeability - darcy [also with (m²)] [k]
8. Energy, Joules (Btu) [E]
9. Power, watts (Btu/h or horsepower) [P or Ê]
10. Viscosity, Pa-s (centipoise) [μ]
11. Density, kg/m³ (lb/ft³) [ρ]
12. Thermal conductivity, W/mK (Btu /ft h °F) [λ]
13. Temperature, °C [T]
14. Diffusivity, m²/s (ft²/h) [$\alpha, \alpha_H, \alpha_T, \alpha_M, D$]
15. Length, m, km (ft, mi) [L]
16. Area, m², km² (ft², mi²) [A]
17. Force, newton, kg m/s² (lb_f) [F]
18. Heat capacity, J/kgK (Btu/lb 16°F) [C_p]
19. Compressibility, $\frac{1}{V} \left(\frac{\partial V}{\partial P} \right)_T$, Pa⁻¹, bar⁻¹, (psi⁻¹) [β]
20. Thermal expansion coefficient, $\frac{1}{V} \left(\frac{\partial V}{\partial T} \right)_P$ K⁻¹(°C⁻¹) [β_t]
21. Flow impedance, MPa·s/m³ (psi/gpm) [Z]

APPENDIX B

FIELD EXPERIMENTS CONDUCTED DURING FY80

Exp. No.	Date	Description	Results
215	10/30/79	Geophone sonde set in EE-2 to monitor high-pressure flow in EE-1/GT-2B fracture system.	Recorded many micro-seismic signals during flow test.
215	11/2/79	Repeated temperature and spinner logs in GT-2B.	Record downhole temperature and flow in GT-2B.

APPENDIX B (Cont.)

Exp. No.	Date	Description	Results
215	11/14/79	Repeated geophone experiment in EE-2 to monitor microseismic signals in EE-1/GT-2B.	Again many microseismic signals were recorded.
215	11/15/79	Terminated flow test and shut-in both GT-2B and EE-1 wellheads. Shut-in pressure monitored for several days.	See write-up of results.
217	2/27/80	Background temperature	Background temperature logs in GT-2 and EE-1. Logs were obtained.
217	2/27/80	Flow through surface piping to check all surface equipment and data acquisition system.	System test prior to starting up Experiment 217 (Phase I/Segment V).
217	3/30/80	Start-up of Experiment 217.	Start-up required several flow steps to determine impedance dependent flow and pressure.
217A	3/13/80	Temperature survey GT-2.	Station probe at 8500 ft to monitor initial temperature profile for 48 hours.
217	4/1/80	Spinner/Temperature Survey in GT-2.	Spinner and temperature logs were obtained.
217	4/8/80	Temperature Log in GT-2.	Temperature profile was obtained.
217	4/14/80	Loop Shut-in.	Buoyancy data were obtained.
217	4/17/80	Temperature Log in EE-1.	Temperature profile was obtained.
217	4/28/80	Loop Shut-in.	Buoyancy data were obtained.
217	4/29/80	Spinner/Temperature Survey in GT-2.	Spinner and temperature logs were obtained.

APPENDIX B (Cont.)

Exp. No.	Date	Description	Results
217	5/5/80	Temperature Survey and Monitor in GT-2.	Temperature log was obtained. Temperature was monitored at 8500 ft for ~1 hour.
217	5/8-9/80	Br ⁸² Tracer Experiment in EE-1 and GT-2.	Fluid entrances and exits in the wellbores were determined.
None	5/13/80	TV Survey of Water Well III.	Data given to hydrologist.
217	5/20-28/80	Spinner/Temperature Surveys in EE-1, Temperature in GT-2.	Measured temperature recovery in EE-1 and GT-2. Data given to hydrologist.
217	5/22/80	Temperature Survey in EE-1 and GT-2.	Continuation of temperature recovery data.
217	5/27/80	Ditto 5/22/80.	Ditto 5/22/80.
217	6/9/80	Spinner/Temperature Survey in GT-2.	Spinner and temperature logs were obtained.
217	6/11-12/80	Geophone Tool in EE-2.	Arm motor on tool failed.
217	6/16/80	Geophone Tool in EE-2.	Cablehead failed at ~200°C.
217	6/23/80	Spinner/Temperature Survey in GT-2.	Spinner and temperature logs were obtained.
217	6/24-25/80	Geophone Tool in EE-2.	Downhole seismic data for Experiment 217 were obtained.
217	7/7/80	Temperature/Spinner Survey in GT-2.	Continuation of drawdown flow measurements.
217	7/21/80	Temperature/Spinner Survey in GT-2.	More spinner temperature data obtained.
None	8/12/80	Temperature Log, EE-2.	Log to bottom with new logging truck and cable. System performance was excellent; bottom-hole temperature recorded at 317°C.

APPENDIX B (Cont.)

<u>Exp. No.</u>	<u>Date</u>	<u>Description</u>	<u>Results</u>
217	8/26/80	Temperature/Spinner Survey in GT-2.	Continued drawdown measurements.
217	9/3-8/80	Br ⁸² Injection and Gamma-Ray Logging in both GT-2 and EE-1.	This experiment was performed to determine fluid residence time in the fracture system and check integrity of casing cement in bottom of EE-1.
217	9/9/80	Temperature/Spinner Survey in GT-2.	Additional drawdown data.
None	9/11/80	Caliper Log, EE-2.	Used the Laboratory 3-arm caliper to determine extent of altered zones and swelling clays if any. Caliper showed several altered zones but no swelling clays.
217	9/24-25/80	Br ⁸² Injection in EE-1 with Gamma-Ray Scan.	This experiment was performed to determine annulus leak in the EE-1 borehole system.

APPENDIX C

INSTRUMENT DEVELOPMENT EXPERIMENTS DURING FY80

<u>Exp. No.</u>	<u>Date</u>	<u>Description</u>	<u>Results</u>
ID-133	11/9/79	Calibration of Spinner Tool, GT-2.	Revealed the output of spurious signals from the spinner tool. Source was found and a new circuit and recording technique initiated.

APPENDIX C (Cont.)

ID-134 12/17/79	Caliper Tool Checkout, EE-1.	Two runs were made. Bottom of the casing was tagged decisively at 9609-ft cable depth. No problems were encountered.
ID-134 12/27/79	Test caliper tool in EE-1 and tag casing in EE-1 to calibrate armored cable.	Caliper tool operated well; casing tagged at 9609 ft.
ID-135 12/19/79	Collar Locator Checkout.	Locator functioned well. Armor can be utilized with very little noise exhibited on output. Leak occurred at 4500 ft down; data was obtained.
ID-136 1/9/80	To test the slimline temperature probe in GT-2 for checkout of tool in preparation for EE-2 cooldown.	Temperature was recorded in GT-2 from 6000 to 8870 ft. Probe functioned to design criteria.
ID-133 2/25/80	Test of collar locator in GT-2 to detect bottom of casing and exposure to high temperature.	Collar locator worked well locating casing collars as well as bottom of casing.
ID-137 3/19/80	Spinner/temperature survey in GT-2 to check out spinner tool and software. Tool had been modified to use dual switches.	Spinner tool had one set of switches fail. It had problems discriminating pulses. Finished survey with original set of switches.
ID-138 4/9/80	Checkout of Gamma Tool GT-2.	Trouble with electronics.
ID-138 4/21/80	Checkout of Gamma Tool in GT-2.	Tool checked OK.
ID-130 5/1/80	Checkout of both Gamma Tools and dry run for Br ⁸² Tracer Experiment.	Both tools checked out.
ID-141 7/22/80	Logging Truck Checkout, EE-2.	Conductor boots on cable-head leaked; cable problems at 8500 ft.

APPENDIX C (Cont.)

ID-142 7/28/80

High-Temperature Cable
Test, EE-2.

Soak test at 10,000 ft and
200°C. Cable performance
very good.

ID-143 7/30/80

Temperature Log to
15,000 ft, EE-2.

Successful temperature log
to 15,000 ft and 300°C.

APPENDIX D

MICROCLIMATOLOGIC MONITORING
FENTON HILL - NOVEMBER 1979

Day	Wind Speed (m/s)			Wind Direction ^a (°)	Temperature (°C)				Relative Humidity (%)	Precipitation (mm)	Pressure (kPa)
	avg	max	min		avg	max	min	fuel ^b			
13	2.1	3.1	1.0	210	-0.8	2.7	-3.0	-27.1	13	0	71.89
14	2.0	3.6	0.6	328	-0.4	4.2	-5.5	-27.2	17	0	72.14
15	2.4	4.0	0.9	261	2.2	6.7	-1.0	-27.1	10	0	72.14
16	2.0	4.0	0.8	225	4.1	8.9	-1.0	-26.9	4	0	71.76
17	2.1	3.5	1.0	46	2.9	6.9	0.1	-26.9	7	0	71.16
18	4.9	8.3	1.2	91	-0.0	1.8	-2.1	-26.8	10	0	70.74
19	4.0	6.9	0.9	340	-1.6	-0.1	-5.0	-27.0	28	1	71.02
20	3.9	7.2	1.9	84	-9.8	-7.7	-11.4	-27.1	28	0	71.15
21	2.8	4.8	1.4	127	-9.9	-5.9	-11.6	-27.1	27	0	71.39
22	3.2	5.4	1.5	122	-9.7	-5.2	-13.2	-27.1	14	0	71.45
23	3.6	4.9	1.4	111	-7.4	-5.1	-10.5	-27.0	0	0	70.92
24	99.9 ^c	99.9 ^c	99.9 ^c	999 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	99 ^c	99.99 ^c
25	99.9 ^c	99.9 ^c	99.9 ^c	999 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	99 ^c	99.99 ^c
26	7.3	9.9	6.1	87	1.9	3.9	-0.8	-27.2	0	0	71.09
27	5.9	10.9	2.8	104	-5.5	-1.5	-8.9	-27.1	0	0	71.62
28	2.3	3.7	1.0	240	-8.6	-3.1	-11.9	-0.5	0	7	71.96
29	2.1	3.8	0.8	293	-8.2	-3.8	-12.1	47.6	0	0	72.00
30	3.4	4.6	1.0	181	-6.2	-1.0	-11.4	48.1	0	0	71.54

^aCompass direction from which wind is blowing.^bForest Service term. Fuel temperature = air temperature 6 in. above ground level.^cMissing data.

APPENDIX D (Cont.)
FENTON HILL - DECEMBER 1979

Day	Wind Speed (m/s)			Wind Direction ^a (°)	Temperature (°C)				Relative Humidity (%)	Precipi- tation (mm)	Pressure (kPa)
	avg	max	min		avg	max	min	fuel ^b			
1	2.4	3.5	0.5	184	-0.6	4.2	-4.7	99.9 ^c	99 ^c	0	71.93
2	3.0	4.9	1.3	110	0.8	6.1	-2.7	99.9 ^c	99 ^c	0	72.24
3	3.9	5.3	2.1	170	3.7	9.2	-0.6	99.9 ^c	99 ^c	0	72.70
4	2.9	4.9	1.1	123	5.5	11.8	0.5	99.9 ^c	99 ^c	0	72.83
5	5.3	8.0	1.6	110	-0.1	3.9	-5.0	99.9 ^c	99 ^c	0	71.47
6	4.2	8.4	1.0	113	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	0	71.33
7	2.9	5.0	1.2	331	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	0	71.79
8	2.7	4.3	1.3	89	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	3	72.21
9	3.0	4.9	1.6	148	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	3	72.27
10	3.7	7.6	1.7	111	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	0	71.57
11	4.0	9.1	1.4	79	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	0	71.27
12	2.4	4.1	0.0	129	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	0	68.67
13	2.8	4.8	1.2	210	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	0	72.00
14	2.8	4.1	0.9	165	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	0	72.03
15	3.7	5.0	2.3	143	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	0	71.84
16	2.8	4.7	0.7	240	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	0	72.21
17	2.7	3.8	1.7	165	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	0	72.52
18	2.5	4.2	1.2	168	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99	0	72.18
19	3.5	5.6	0.0	137	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	18	0	68.11
20	3.1	5.1	1.6	129	99.9 ^c	99.9 ^c	99.9 ^c	-2.1	42	0	71.61
21	4.2	7.3	0.9	76	99.9 ^c	99.9 ^c	99.9 ^c	-1.9	42	3	70.88
22	4.0	7.1	1.7	92	99.9 ^c	99.9 ^c	99.9 ^c	-6.2	43	0	70.46
23	3.3	4.3	2.0	136	99.9 ^c	99.9 ^c	99.9 ^c	-7.5	39	0	71.18
24	2.2	4.4	1.3	135	99.9 ^c	99.9 ^c	99.9 ^c	-1.4	42	0	71.86
25	2.4	4.9	1.3	104	99.9 ^c	99.9 ^c	99.9 ^c	1.3	41	0	71.86
26	4.5	7.6	2.2	293	99.9 ^c	99.9 ^c	99.9 ^c	-1.5	41	1	71.37
27	5.1	8.4	1.8	313	99.9 ^c	99.9 ^c	99.9 ^c	-2.7	42	6	71.12
28	1.8	2.6	1.2	234	99.9 ^c	99.9 ^c	99.9 ^c	4.5	41	0	71.58
29	2.9	4.4	1.5	134	99.9 ^c	99.9 ^c	99.9 ^c	-4.2	40	0	71.66
30	3.0	4.3	1.8	146	99.9 ^c	99.9 ^c	99.9 ^c	-4.3	41	0	71.62
31	3.3	5.4	2.1	139	99.9 ^c	99.9 ^c	99.9 ^c	-5.3	41	0	71.62

^aCompass direction from which wind is blowing.

^bForest Service term. Fuel temperature = air temperature 6 in. above ground level.

^cMissing data.

APPENDIX D (Cont.)
FENTON HILL - JANUARY 1980

Day	Wind Speed (m/s)			Wind Direction ^a (°)	Temperature (°C)				Relative Humidity (%)	Precipitation (mm)	Pressure (kPa)
	avg	max	min		avg	max	min	fuel ^b			
3	3.4	4.9	1.6	117	99.9 ^c	99.9 ^c	99.9 ^c	-11.5	41	0	99.99 ^c
4	4.2	6.8	1.8	113	99.9 ^c	99.9 ^c	99.9 ^c	-6.8	40	0	99.99 ^c
5	3.7	5.9	2.2	116	99.9 ^c	99.9 ^c	99.9 ^c	-6.1	41	0	99.99 ^c
6	4.4	6.6	2.4	97	99.9 ^c	99.9 ^c	99.9 ^c	-5.1	41	0	99.99 ^c
7	4.5	7.3	2.5	86	99.9 ^c	99.9 ^c	99.9 ^c	2.8	37	0	99.99 ^c
8	4.2	5.7	2.0	90	99.9 ^c	99.9 ^c	99.9 ^c	-2.6	40	0	99.99 ^c
9	3.1	4.3	1.6	84	99.9 ^c	99.9 ^c	99.9 ^c	-2.4	37	0	99.99 ^c
10	7.6	11.0	2.7	71	99.9 ^c	99.9 ^c	99.9 ^c	-1.2	42	0	99.99 ^c
11	2.9	7.2	1.3	49	99.9 ^c	99.9 ^c	99.9 ^c	-1.8	41	0	99.99 ^c
12	3.9	5.6	2.5	98	99.9 ^c	99.9 ^c	99.9 ^c	-1.2	41	0	99.99 ^c
13	4.1	7.2	1.4	114	99.9 ^c	99.9 ^c	99.9 ^c	-9.2	40	0	99.99 ^c
14	3.1	5.1	1.1	82	-1.5	3.4	-5.0	-0.2	39	10	99.99 ^c
15	4.3	6.9	2.1	110	-2.0	0.6	-4.4	-0.1	40	0	99.99 ^c
16	3.4	5.7	1.8	122	-3.8	2.1	-5.1	-0.8	32	0	99.99 ^c
17	2.2	4.0	1.0	105	-2.1	2.7	-4.1	-3.1	26	0	99.99 ^c
18	3.0	4.6	1.3	321	-2.5	-1.0	-3.5	-2.7	35	0	99.99 ^c
19	6.2	8.4	4.0	298	-2.9	-1.2	-4.6	-1.2	31	0	99.99 ^c
20	2.6	5.5	1.2	265	-0.9	8.4	-6.1	-0.2	32	0	99.99 ^c
21	3.5	4.7	1.4	206	2.4	10.9	-3.4	-1.5	16	0	99.99 ^c
22	2.6	4.4	1.0	84	-4.6	1.0	-10.1	-1.9	26	0	99.99 ^c
23	2.9	3.3	2.5	156	-3.3	1.6	-5.3	-2.6	18	0	99.99 ^c
24	3.2	4.8	2.0	125	0.8	10.1	-6.3	-2.9	14	0	99.99 ^c
25	2.9	5.2	1.2	65	-0.7	6.7	-4.8	-2.8	17	0	99.99 ^c
26	4.2	7.9	2.3	82	-2.4	2.2	-6.3	-2.9	21	0	99.99 ^c
27	3.5	5.2	1.5	72	-2.0	2.9	-6.0	-2.9	17	0	99.99 ^c
28	4.0	7.2	1.8	77	-3.3	0.0	-4.6	-2.5	28	0	99.99 ^c
29	4.8	7.8	2.1	53	-2.9	0.3	-5.2	-1.8	34	1	99.99 ^c
30	3.7	5.1	1.9	97	-1.5	2.6	-3.5	-1.3	31	7	99.99 ^c
31	2.5	4.3	1.3	96	0.7	8.1	-4.7	-1.1	24	0	99.99 ^c

^aCompass direction from which wind is blowing.

^bForest Service term. Fuel temperature = air temperature 6 in. above ground level.

^cMissing data.

APPENDIX D (Cont.)
FENTON HILL - FEBRUARY 1980

Day	Wind Speed (m/s)			Wind Direction ^a (°)	Temperature (°C)				Relative Humidity (%)	Precipitation (mm)	Pressure (kPa)
	avg	max	min		avg	max	min	fuel ^b			
1	2.9	4.8	1.6	120	-1.2	6.6	-5.3	-1.6	26	0	99.99 ^c
2	3.8	5.2	2.5	136	0.8	11.0	-5.1	-1.9	20	0	99.99 ^c
3	3.5	5.4	1.4	113	2.9	8.5	-2.4	-1.8	14	0	99.99 ^c
4	5.4	8.5	1.9	111	2.4	7.1	-1.5	-1.7	15	0	99.99 ^c
5	2.7	4.3	1.1	175	1.8	11.4	-4.7	-2.0	12	0	99.99 ^c
6	2.6	4.8	0.9	81	3.1	11.5	-1.6	-2.4	12	0	99.99 ^c
7	2.8	4.3	1.3	4	-0.5	4.9	-4.7	-1.9	21	0	99.99 ^c
8	2.6	3.8	1.2	306	-0.2	4.9	-4.8	-1.9	20	0	99.99 ^c
9	2.9	5.1	1.3	320	-5.8	4.3	-10.1	-1.3	32	0	99.99 ^c
10	2.5	3.9	1.1	29	-9.8	-2.4	-14.4	-1.4	29	0	99.99 ^c
11	2.3	3.9	1.1	207	-2.8	6.8	-8.3	-1.5	16	0	99.99 ^c
12	3.4	6.0	1.9	124	-1.3	8.1	-6.0	-1.8	8	0	99.99 ^c
13	3.1	4.7	1.5	69	-1.3	4.3	-6.3	-2.3	16	0	99.99 ^c
14	3.2	6.1	2.0	31	-0.6	1.1	-2.3	-1.8	46	0	99.99 ^c
15	4.3	6.2	1.7	99	0.1	2.2	-2.3	-0.5	49	0	99.99 ^c
16	2.8	5.8	1.1	97	-1.8	0.9	-3.4	-0.2	48	0	99.99 ^c
17	6.2	11.0	3.6	90	0.2	3.7	-1.9	-0.2	44	0	99.99 ^c
18	6.4	13.3	1.7	85	0.7	5.2	-1.4	-0.2	36	0	99.99 ^c
19	5.9	9.1	2.8	66	-2.5	-0.6	-5.0	-0.2	44	24	99.99 ^c
20	7.3	10.5	5.9	95	-4.6	-4.3	-4.7	-0.2	43	0	99.99 ^c
21	4.9	7.4	2.7	87	-2.8	-0.4	-5.5	-0.2	43	2	99.99 ^c
22	5.8	8.2	1.7	99	-2.5	1.2	-4.9	-0.2	34	3	99.99 ^c
23	4.4	8.7	1.4	109	-1.7	3.7	-5.6	-0.2	25	0	99.99 ^c
24	3.6	5.1	1.8	127	-2.8	3.7	-8.6	-0.2	16	0	99.99 ^c
25	2.5	4.0	1.0	305	-0.5	6.2	-6.8	-0.2	12	0	99.99 ^c
26	3.2	5.3	1.1	118	2.8	11.4	-3.0	-0.2	13	0	99.99 ^c
27	3.5	5.8	0.0	129	5.4	14.5	0.0	-0.5	11	0	69.65
28	3.7	6.2	1.3	112	6.4	11.4	2.6	-0.5	9	0	73.91
29	6.0	8.5	2.4	104	0.8	4.4	-3.9	-0.4	12	0	73.53

^aCompass direction from which wind is blowing.

^bForest Service term. Fuel temperature = air temperature 6 in. above ground level.

^cMissing data.

APPENDIX D (Cont.)
FENTON HILL - MARCH 1980

Day	Wind Speed (m/s)			Wind Direction ^a (°)	Temperature (°C)				Relative Humidity (%)	Precipitation (mm)	Pressure (kPa)
	avg	max	min		avg	max	min	fuel ^b			
1	2.5	4.3	1.3	296	-2.5	3.8	-7.9	-0.3	15	0	73.99
2	2.3	3.4	1.0	294	-0.7	7.5	-6.6	-0.6	13	0	73.86
3	3.7	7.5	1.7	66	-0.7	4.8	-3.9	-0.5	25	0	73.16
4	6.1	9.4	2.9	99	-3.2	-0.4	-4.9	-0.3	35	0	73.19
5	2.9	4.6	1.8	89	0.6	6.8	-5.4	-0.2	24	1	73.59
6	3.9	5.7	1.7	65	1.8	5.9	-2.9	0.2	17	0	73.19
7	8.1	10.4	4.9	84	-3.2	0.0	-6.3	-0.2	26	0	73.10
8	3.7	6.6	1.6	100	-2.9	3.7	-8.1	-0.4	16	0	73.60
9	4.6	7.4	2.6	110	-1.9	2.8	-5.9	-0.8	21	0	73.74
10	4.1	5.7	2.0	104	0.2	7.5	-6.3	-0.2	19	0	73.66
11	7.2	10.4	3.4	78	-2.2	3.9	-6.4	-0.2	27	0	73.02
12	4.5	8.3	1.9	101	-3.6	2.8	-7.9	-0.3	17	0	73.48
13	4.3	6.3	2.1	106	-2.0	3.5	-6.0	-0.7	19	0	73.72
14	4.5	6.7	2.0	116	-1.2	7.5	-6.3	-0.7	20	0	73.80
15	3.1	5.2	1.5	74	0.1	7.6	-4.2	-0.5	26	0	73.39
16	7.3	12.5	3.5	91	-2.6	-0.9	-4.5	-0.2	40	2	73.00
17	11.0 ^c	11.5 ^c	10.4 ^c	92	-2.1	-1.9	-2.3	-0.2	19	0	73.16
18	99.9 ^c	99.9 ^c	99.9 ^c	999 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	99 ^c	99.99 ^c
19	4.0	5.1	2.6	111	-2.4	1.3	-3.8	-0.2	31	0	73.25
20	4.4	7.5	1.6	97	1.1	6.7	-5.0	-0.2	17	0	73.77
21	4.1	6.5	1.7	345	3.2	8.3	-1.8	-0.2	15	0	73.50
22	5.2	11.1	2.5	13	0.6	6.8	-6.6	-0.2	21	0	72.90
23	5.3	8.6	2.6	102	-4.1	0.7	-8.1	-0.2	37	0	73.01
24	4.4 ^c	7.3 ^c	1.8 ^c	313 ^c	-1.0 ^c	4.8 ^c	-6.3 ^c	-0.2 ^c	31 ^c	0 ^c	73.34
25	99.9 ^c	99.9 ^c	99.9 ^c	999 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	99 ^c	99.99
26	2.3	4.0	1.1	96	0.5	2.8	-2.8	-0.0	33	0	73.26
27	3.6	6.2	1.3	90	0.0	3.3	-2.9	0.5	37	21	73.21
28	3.5	4.8	1.4	101	-2.0	3.0	-8.1	0.6	34	18	73.32
29	4.0	6.2	2.3	123	-2.3	4.0	-8.4	0.3	38	7	73.57
30	4.0	5.9	2.5	93	2.0	7.6	-5.5	0.1	18	8	73.35
31	5.1	8.6	2.6	84	-4.2	0.5	-10.7	0.1	30	12	72.90

^aCompass direction from which wind is blowing.

^bForest Service term. Fuel temperature = air temperature 6 in. above ground level.

^cMissing data.

APPENDIX D (Cont.)
FENTON HILL - APRIL 1980

Day	Wind Speed (m/s)			Wind Direction ^a (°)	Temperature (°C)				Relative Humidity (%)	Precipi- tation (mm)	Pressure (kPa)
	avg	max	min		avg	max	min	fuel ^b			
1	2.3	3.9	1.2	120	-0.6	3.1	-7.3	0.1	37	8	73.23
2	4.1	6.2	2.2	95	-0.1	3.6	-2.9	0.7	32	14	73.27
3	3.0	4.3	1.1	116	-0.0	8.0	-7.0	-0.1	37	1	73.95
4	2.7	4.3	1.3	321	5.9	11.8	-2.3	0.2	21	5	74.21
5	4.9	9.7	1.9	68	5.8	9.7	1.5	0.2	19	1	73.73
6	6.0	7.6	2.8	97	4.7	11.0	-2.0	0.3	22	7	73.64
7	4.4	9.7	1.9	108	-2.4	5.3	-7.2	0.2	46	2	73.65
8	2.6	4.2	1.1	145	1.6	8.0	-2.5	-0.1	27	1	74.10
9	3.0	4.3	1.4	51	7.9	11.8	2.9	0.0	14	1	74.08
10	3.8	8.1	1.1	88	8.7	11.2	2.8	-1.1	11	0	73.54
11	3.6	7.8	1.5	98	4.6	10.5	-2.0	-2.8	13	0	72.69
12	4.3	6.8	1.5	272	-2.4	7.4	-7.0	0.6	36	6	73.32
13	2.5	4.0	1.2	4	-5.6	-0.5	-9.7	-0.5	35	0	73.98
14	4.2	6.2	1.5	115	-0.7	7.5	-3.7	-2.8	16	0	73.75
15	3.7	5.3	2.1	107	6.1	10.2	1.5	-0.2	10	0	73.81
16	4.1	6.6	2.3	101	8.3	12.7	2.4	6.9	9	0	74.16
17	2.7	4.3	1.8	314	7.1	13.8	-0.4	6.0	13	0	74.64
18	2.3	3.7	1.1	300	9.6	16.4	2.2	8.6	12	0	74.53
19	2.5	4.0	1.2	309	11.3	17.7	5.7	9.9	10	0	74.41
20	3.5	5.5	1.7	2	11.7	16.9	6.6	11.1	10	0	74.30
21	2.9	3.8	2.1	53	6.8	13.8	-0.4	5.9	12	0	74.62
22	2.4	4.3	1.1	305	9.1	16.4	2.2	8.0	13	0	74.58
23	2.4	4.0	1.2	304	11.0	17.7	5.7	9.5	10	0	74.42
24	3.2	6.8	1.6	273	4.7	11.5	-3.0	1.9	20	0	73.86
25	3.4	6.9	1.2	240	0.0	6.0	-4.0	0.7	33	0	73.47
26	2.7	4.7	1.1	305	2.5	7.4	-3.1	2.8	31	0	73.93
27	2.7	4.6	1.4	282	4.3	9.7	-0.8	4.5	28	0	74.24
28	3.0	5.7	1.3	291	8.7	14.7	2.1	8.6	20	0	74.15
29	3.6	4.9	2.2	351	7.1	12.3	0.6	6.8	17	0	73.52
30	2.8	4.6	1.5	238	1.3	6.1	-1.8	1.9	32	0	73.70

^aCompass direction from which wind is blowing.

^bForest Service term. Fuel temperature = air temperature 6 in. above ground level.

^cMissing data.

APPENDIX D (Cont.)
FENTON HILL - MAY 1980

Day	Wind Speed (m/s)			Wind Direction ^a (°)	Temperature (°C)				Relative Humidity (%)	Precipitation (mm)	Pressure (kPa)
	avg	max	min		avg	max	min	fuel ^b			
1	2.4	4.6	0.8	262	3.0	8.8	-1.3	2.3	38	0	74.12
2	2.6	5.7	1.5	289	4.8	11.6	0.8	5.1	44	2	74.20
3	2.1	4.1	0.8	109	6.3	11.3	0.7	5.7	40	1	74.20
4	2.3	4.3	0.7	262	7.3	13.5	3.5	5.9	31	0	74.17
5	1.7	3.9	0.5	238	7.5	12.2	3.2	6.8	57	0	74.05
6	99.9 ^c	99.9 ^c	99.9 ^c	273	8.6	14.1	4.2	9.9	99 ^c	0	73.97
7	99.9 ^c	99.9 ^c	99.9 ^c	276	2.8	4.1	1.9	2.2	99 ^c	0	73.99
8	99.9 ^c	99.9 ^c	99.9 ^c	286	6.5	11.1	1.3	6.7	99 ^c	0	73.89
9	99.9 ^c	99.9 ^c	99.9 ^c	298	7.5	12.0	2.8	8.4	99 ^c	0	73.56
10	99.9 ^c	99.9 ^c	99.9 ^c	298	8.6	14.1	4.0	9.3	99 ^c	0	73.38
11	99.9 ^c	99.9 ^c	99.9 ^c	299	6.7	11.2	-1.7	7.3	99 ^c	0	73.43
12	99.9 ^c	99.9 ^c	99.9 ^c	325	1.8	7.2	-4.8	3.8	99 ^c	0	73.63
13	99.9 ^c	99.9 ^c	99.9 ^c	280	6.7	11.2	0.5	7.9	99 ^c	0	73.87
14	99.9 ^c	99.9 ^c	99.9 ^c	286	3.3	5.7	0.0	3.4	99 ^c	0	69.48
15	99.9 ^c	99.9 ^c	99.9 ^c	284	1.5	6.3	-0.4	2.1	99 ^c	0	73.25
16	99.9 ^c	99.9 ^c	99.9 ^c	318	4.2	9.6	-0.4	4.2	99 ^c	0	73.67
17	99.9 ^c	99.9 ^c	99.9 ^c	292	4.4	7.2	3.7	4.2	99 ^c	0	73.49
18	99.9 ^c	99.9 ^c	99.9 ^c	279	2.0	5.6	-0.4	2.8	99 ^c	0	73.29
19	99.9 ^c	99.9 ^c	99.9 ^c	328	2.6	8.3	-0.4	3.1	99 ^c	0	73.49
20	99.9 ^c	99.9 ^c	99.9 ^c	298	6.6	9.9	3.8	7.1	99 ^c	0	73.85
21	99.9 ^c	99.9 ^c	99.9 ^c	266	7.2	12.8	1.7	8.4	99 ^c	0	74.15
22	99.9 ^c	99.9 ^c	99.9 ^c	289	8.1	14.4	2.1	9.3	99 ^c	0	74.33
23	99.9 ^c	99.9 ^c	99.9 ^c	291	11.4	15.3	7.6	11.6	99 ^c	0	74.23
24	99.9 ^c	99.9 ^c	99.9 ^c	295	16.2	17.5	14.2	22.5	99 ^c	0	62.62
25	99.9 ^c	99.9 ^c	99.9 ^c	305	11.8	15.2	0.0	17.6	99 ^c	0	63.30
26	99.9 ^c	99.9 ^c	99.9 ^c	298	9.1	13.9	6.9	4.6	99 ^c	0	73.94
27	99.9 ^c	99.9 ^c	99.9 ^c	299	12.5	14.4	9.8	21.9	99 ^c	0	74.06
28	99.9 ^c	99.9 ^c	99.9 ^c	280	11.2	15.3	6.8	11.5	99 ^c	0	74.02
29	99.9 ^c	99.9 ^c	99.9 ^c	302	11.9	16.6	4.5	13.9	99 ^c	0	74.01
30	99.9 ^c	99.9 ^c	99.9 ^c	304	11.8	17.6	6.8	13.3	99 ^c	0	73.95

^aCompass direction from which wind is blowing.

^bForest Service term. Fuel temperature = air temperature 6 in. above ground level.

^cMissing data.

APPENDIX D (Cont.)
FENTON HILL - AUGUST 1980

Day	Wind Speed (m/s)			Wind Direction ^a (°)	Temperature (°C)				Relative Humidity (%)	Precipi- tation (mm)	Pressure (kPa)
	avg	max	min		avg	max	min	fuel ^b			
1	2.4	4.4	0.6	334	15.8	21.1	10.5	20.1	99 ^c	1	74.69
2	3.7	4.9	2.9	109	14.4	20.1	11.1	19.0	99 ^c	1	74.48
3	3.4	5.3	1.0	10	10.6	12.6	8.0	12.0	99 ^c	0	74.37
4	4.1	5.9	1.7	107	14.4	19.4	10.3	18.7	99 ^c	0	74.03
5	4.1	6.1	2.5	110	15.0	20.2	9.1	19.7	99 ^c	0	74.11
6	3.5	5.9	2.1	286	11.6	18.0	8.7	13.9	99 ^c	0	74.50
7	2.0	4.3	0.4	313	12.1	19.0	9.0	15.2	99 ^c	5	74.57
8	2.4	5.4	0.4	253	11.2	16.6	6.9	16.4	99 ^c	11	74.50
9	2.5	4.6	0.8	129	12.5	18.7	6.3	16.2	99 ^c	3	74.40
10	2.4	3.8	0.5	271	14.1	19.7	9.8	16.6	99 ^c	0	74.35
11	3.0	5.5	1.0	322	12.1	16.6	6.3	17.2	99 ^c	2	74.60
12	2.7	3.2	2.0	295	6.7	8.4	6.0	8.1	99 ^c	0	74.62
13	2.3	3.1	1.6	330	13.4	17.6	10.5	15.1	99 ^c	0	74.17
14	1.0	2.8	0.4	153	9.3	13.2	7.0	13.4	99 ^c	0	74.08
15	2.3	3.1	1.6	330	13.4	17.6	10.5	15.1	99 ^c	0	74.17
16	1.0	2.8	0.4	153	9.3	13.2	7.0	13.4	99 ^c	0	74.08
17	99.9 ^c	99.9 ^c	99.9 ^c	999 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	99 ^c	99.99 ^c
18	99.9 ^c	99.9 ^c	99.9 ^c	999 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	99 ^c	99.99 ^c
19	99.9 ^c	99.9 ^c	99.9 ^c	999 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99.9 ^c	99 ^c	99 ^c	99.99 ^c
20	0.9	1.8	0.4	148	9.0	11.9	7.4	7.7	99 ^c	0	74.46
21	2.5	4.0	0.6	317	11.9	16.8	6.7	17.0	99 ^c	0	74.57
22	2.5	4.9	0.4	325	10.8	15.6	7.2	17.1	99 ^c	0	74.66
23	0.6	1.5	0.4	322	11.2	16.6	6.0	17.4	99 ^c	2	74.74
24	1.7	3.8	0.4	332	8.5	13.0	5.9	13.2	99 ^c	0	74.68
25	1.7	3.1	0.4	133	9.5	14.0	4.8	13.9	99 ^c	1	74.60
26	1.0	3.5	0.4	163	10.5	14.8	6.5	13.8	99 ^c	0	74.66
27	0.6	1.1	0.4	324	10.1	15.9	5.4	13.4	99 ^c	0	74.65
28	1.8	4.7	0.4	101	11.5	16.6	5.3	16.1	99 ^c	0	74.70
29	4.4	8.1	2.4	107	11.6	15.3	8.3	15.4	99 ^c	0	74.63
30	4.7	7.8	1.9	97	11.2	15.5	6.5	15.1	99 ^c	1	74.36
31	4.6	8.6	2.1	104	10.4	15.5	5.2	15.3	99 ^c	0	74.17

^aCompass direction from which wind is blowing.

^bForest Service term. Fuel temperature = air temperature 6 in. above ground level.

^cMissing data.

APPENDIX D (Cont.)
FENTON HILL - SEPTEMBER 1980

Day	Wind Speed (m/s)			Wind Direction ^a (°)	Temperature (°C)				Relative Humidity (%)	Precipi- tation (mm)	Pressure (kPa)
	avg	max	min		avg	max	min	fuel ^b			
1	3.2	5.4	1.5	126	11.2	16.2	6.0	16.2	99 ^c	1	74.37
2	2.8	4.9	0.0	332	13.3	17.9	8.9	17.8	99 ^c	0	74.49
3	1.7	3.3	0.0	147	11.4	17.1	0.0	14.3	99 ^c	2	74.50
4	2.8	6.1	0.4	298	12.8	18.3	7.6	16.6	99 ^c	2	74.69
5	3.7	6.4	2.1	304	9.6	13.0	6.7	13.5	99 ^c	0	74.89
6	3.0	4.1	2.2	323	7.4	11.2	5.6	11.9	99 ^c	0	74.76
7	2.1	4.3	1.1	307	9.5	13.6	5.7	13.8	99 ^c	1	74.48
8	2.3	4.4	0.5	282	9.9	15.6	6.2	13.9	99 ^c	19	74.55
9	2.4	7.3	0.4	295	6.3	6.7	5.9	9.3	99 ^c	2	74.81
10	3.5	6.8	1.1	345	5.8	8.1	4.4	9.8	99 ^c	12	74.63
11	2.5	5.2	0.6	141	6.9	10.4	4.3	10.2	99 ^c	4	74.37
12	2.1	4.1	0.4	113	8.8	13.4	4.9	12.7	99 ^c	0	74.33
13	2.9	5.5	0.4	326	9.8	14.0	6.3	14.2	99 ^c	0	74.52
14	1.7	3.1	0.4	355	8.8	13.8	4.3	12.3	99 ^c	0	74.66
15	1.9	4.9	0.4	133	99.9 ^c	99.9 ^c	99.9 ^c	13.4	99 ^c	0	74.51
16	2.6	5.4	0.6	122	99.9 ^c	99.9 ^c	99.9 ^c	14.5	99 ^c	0	74.27
17	2.1	6.3	0.4	140	99.9 ^c	99.9 ^c	99.9 ^c	14.4	99 ^c	0	74.35
18	2.3	4.8	0.7	201	99.9 ^c	99.9 ^c	99.9 ^c	11.5	99 ^c	0	74.61
19	3.7	6.9	1.7	85	99.9 ^c	99.9 ^c	99.9 ^c	16.2	99 ^c	0	74.59
20	3.9	6.7	0.5	83	99.9 ^c	99.9 ^c	99.9 ^c	14.4	99 ^c	0	74.17
21	1.5	6.9	0.4	87	99.9 ^c	99.9 ^c	99.9 ^c	13.8	99 ^c	0	74.04
22	1.6	5.4	0.4	334	99.9 ^c	99.9 ^c	99.9 ^c	12.1	99 ^c	0	74.36
23	2.7	5.4	0.6	355	99.9 ^c	99.9 ^c	99.9 ^c	17.4	99 ^c	0	74.35
24	0.9	3.6	0.4	135	99.9 ^c	99.9 ^c	99.9 ^c	13.8	99 ^c	0	74.25
25	0.5	0.5	0.5	306	14.3	19.9	7.9	20.2	99 ^c	0	74.54
26	0.5	0.5	0.5	317	14.9	18.4	10.3	20.6	99 ^c	0	74.65
27	1.7	4.9	0.4	292	99.9 ^c	99.9 ^c	99.9 ^c	8.2	99 ^c	1	74.65
28	2.0	4.9	0.5	288	99.9 ^c	99.9 ^c	99.9 ^c	10.5	99 ^c	1	74.37
29	1.9	4.5	0.4	202	99.9 ^c	99.9 ^c	99.9 ^c	8.3	99 ^c	1	74.33
30	1.4	3.4	0.4	205	99.9 ^c	99.9 ^c	99.9 ^c	12.7	99 ^c	0	74.63

^aCompass direction from which wind is blowing.

^bForest Service term. Fuel temperature = air temperature 6 in. above ground level.

^cMissing data,

APPENDIX E
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APPENDIX F

SUMMARY OF APRIL 3, 1980, REVIEW MEETING AT THE WESTERN GEOPHYSICAL OFFICES IN ENGLEWOOD, COLORADO

by

W. M. Dolan

Introduction. Bob Weinraub has requested that I offer for the study group's consideration my independent impressions. The reason for this is that I also sit on the executive committee of the Hot Dry Rock Program Development

Council and am consequently viewed as being slightly better informed on matters than the study group.

Terms of Reference. The items agreed upon were: (1) determine the level of success of the recent HDR experiments; (2) determine the necessity of thermal-stress cracking to the HDR concept; (3) discuss the economic feasibility of the HDR concept; (4) are the goals and objectives of the program clear and reasonable? (5) is the pace of the program nominal? (6) is the balance of the major program elements appropriate, e.g., reservoir assessment 14%, Fenton Hill experiment 86%? I also added a seventh item for discussion. That was the question, "Is the program properly integrated with other related programs, e.g., Sandia's high-temperature instrument development?"

Impressions.

1. An excellent presentation by Jeff Tester was convincing as to the level of success achieved during the second stage of development of the Phase I reservoir, i.e., they achieved greater than 45 000 m² of heat-transfer area. Jeff also made a convincing case that the Phase II reservoir currently under development has a finite chance of success.

2. Jeff also asserted that thermal-stress cracking is not necessary to the concept but is a possible bonus to come.

3. At present, the economic feasibility of the HDR concept is not too attractive. Crude calculations made at the meeting suggested approximately \$3000 per installed kilowatt of capacity. As far as we know, that is competitive only with solar. That observation prompted an urging initiated by Carel Otte that the Site 2 selection should contemplate a much shallower heat reservoir situation than Site 1 with the hope of experiencing some competitive or nearly competitive costs for purposes of demonstration. The study group generally concurred with that thought.

4. The goals and objectives of the program have previously contemplated the possibility of Site 2 being a nonelectric situation, i.e., temperature less than 350°F. Benny DiBona indicated that this would not be the case and that high temperature is the objective at Site 2. Carel Otte volunteered that it might be possible to select the second site inside the Valles Caldera, recognizing a possible fallback position in that if it does not prove to be hot dry rock then it might support a hot wet system. The overall goals and objectives of the program seem to be proceeding from rational analyses of prior experience and are difficult to criticize, particularly at Fenton Hill.

5. The pace of the program appears to be approximately correct. There were no obvious areas identified where an acceleration could work. In fact, the group cautioned against force feeding the program with money to accelerate it.

6. The balance of the major program elements appear to be essentially correct at this time. However, after a second site is selected and Fenton Hill moves toward a completion stage, the subject should be reassessed. It was understood that Site 2 will be handled by contractors with much less direct involvement by the Laboratory staff. No one present disputed that judgement.

7. As to the question of appropriate amounts of liaison with other laboratories and agencies taking place, the answer was that it was getting better. It is obvious that in the early stages of the HDR project that they had to establish some level of self sufficiency in instrumentation and drilling technology development to proceed with the program. However, there is a far broader scope and accelerated program in those areas of technology development taking place in Sandia and this should cause a continued reduction in the Laboratory's comparable facilities coupled with a determined effort to draw on Sandia's services. It was not made clear whether that is happening as fast as it should.

Additional Comments. We were advised by Larry Germain that Don Kerr, since taking over the Laboratory, has installed matrix management. That was pleasing to all of us that are concerned with too many scientists being attached to an individual project like HDR resulting in a staff budget that is disproportionate to the mission. We were assured by Benny DiBona that matrix management is working and the staff allocation is as correct as you can make it under the circumstances.

The economic study that is ongoing, with the prime contractor being Bechtel, is expected to take 2 years. Two task reports have been received.

Grant Heiken indicated that within the zone outside the western boundaries of the Valles Caldera that their calculations indicate that, to a depth of 6 km, 62 well pairs would correspond to 2 quads of energy. The consensus of the study group was that 6 km was too deep for HDR to be competitive in a near or even far time frame.

Carel Otte opined that the HDR program has a good team now, after dubious beginnings, who seems well equipped to carry out the objectives.

Carl Savit forcefully opined that demonstrating economic feasibility is vital to the program now and of course supports the various remonstrations in favor of seeking a shallower heat source at Site 2.

Dolan raised the question of what is being done about pursuing wells of opportunity. The answer was that the program is finally under way after many delays.

It was ascertained that the FY81 budget is primarily dedicated to Phase II reservoir development at Fenton Hill. We were also advised that Phase II is forward committed partly because of the existing FRG potential Japanese support.

Greg Nunz advised the group that the Phase I Fenton Hill site is to remain dedicated to high risk experiments. The consensus was that this was very logical.