Annual Report
FY 1991

Hot Dry Rock Geothermal Development Program

Los Alamos
NATIONAL LABORATORY

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Hot Dry Rock Heat Mining Geothermal Energy Development Program

**Annual Report
Fiscal Year 1991**

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PREFACE

The activities of the Hot Dry Rock Program at Los Alamos are reported in two volumes this year. This volume, in accordance with guidelines provided by the USDOE Geothermal Technology Division, reports our work in an objective/accomplishments format which stresses the relationship of our activities and accomplishments to the program objectives. Because it is designed to serve as a stand-alone document, some sections from previous reports are repeated herein for completeness with little change from previous years. This volume is intended to serve both as a functional report to HDR Program management personnel at the DOE and the Laboratory, and as a useful general reference document to provide a view of the status and accomplishments of the HDR program as of the close of FY91.

The companion volume to this report is a compendium of scientific and technical publications of the project staff during Fiscal Year 1991. The compendium is intended to provide the details of the technical information published in this program during Fiscal Year 1991.

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EXECUTIVE SUMMARY

This year marked a watershed in the course of HDR development. By the end of the fiscal year, construction of the surface plant at the Fenton Hill HDR site was essentially complete, and testing to demonstrate that the system could operate safely and reliably was well underway. The surface facility will make it possible to extract heat from the Phase II HDR reservoir over a long period of time under conditions simulating an industrial facility.

The long-term pressurization experiment, begun in 1989, continued to demonstrate that water losses from the Fenton Hill Phase II reservoir are very low even at static reservoir pressures as high as 19 MPa (2750 psi). Data collected during this long experiment were used this year to show that below a reservoir pressure of about 15 MPa (2175 psi) water storage is largely in the microcracks of the reservoir rock, but that at higher pressures storage occurs largely in the joints between the rock blocks. Since fluid transfer can occur much more rapidly in joints than in microcracks, this finding has important implications for the operation of HDR reservoirs.

Model development this year progressed to the point where a very good fit of the FRACNET model to actual reservoir behavior over a period of 100 days of static pressurization was achieved. We are moving closer to the time when models can provide realistic predictive information about the performance of HDR reservoirs. Seismic activities concentrated on improving the accessibility of the vast amount of data previously collected at Fenton Hill and developing techniques to use that data to give an increasingly accurate picture of the reservoir. Geochemistry and tracer work at Los Alamos was directed primarily toward preparations for water chemistry analyses during long-term flow testing. In addition, a new rock/water interactions program, initiated this year in conjunction with the Massachusetts Institute of Technology, should soon begin to provide data regarding the possibility of using novel water sources such as treated sewage, seawater, and natural brines as feed for an HDR system.

Technology transfer activities this past year included hosting over 200 official visitors, several meetings with groups of industry representatives, and extensive attention by the print and broadcast media. Early in the year, work began on Phase II of the Clearlake, CA, HDR initiative, funded by the California Energy Commission in the amount of \$225,000.

In spite of an extremely limited funding situation, the program moved forward in FY91 to the point where it will be possible to begin the long-awaited long-term flow test (LTFT) in FY92. This test will be initiated as soon as it is practical to do so. In the face of continuing funding constraints, however, the duration of the LTFT may not be long enough to truly demonstrate the potential of HDR technology. While intermittent testing on a limited budget will add valuable information to our store of knowledge about HDR, only an adequately funded and sustained LTFT effort will take HDR technology the next critical step toward commercial reality.

BACKGROUND

The Resource:

In such forms as hot springs, geysers, and erupting volcanos, there is clear evidence at its surface that the earth's interior is very hot. This heat is geothermal energy. It originates largely in the lower crust and mantle and in the decay of unstable elements that occur naturally in the upper crust.

The earth's surface is kept relatively cool by radiation of heat into space and, in most places, the outermost layers of the crust are kept at nearly the surface temperature by groundwater circulation. With increasing depth, however, the greater weight of soils, gravel, and rock above it reduces permeability and the rate of water circulation, and temperatures begin to rise. Finally, permeability and free-water content are extremely low – the typical "hot dry rock" situation – and heat flow toward the surface is entirely by thermal conduction. The rate of heat flow is determined jointly by the conductivity of the rock and the rate at which temperature increases with depth – which is called the "geothermal gradient."

As is illustrated by Figure 1, the geothermal gradient varies widely from place to place. In the United States, it averages about 17°F per thousand feet of depth (30°C per kilometer). However, where the crust is thin or it has been disturbed by volcanic activity or large-scale earth movements, it is often much higher than that.

The large earth movements that create earthquakes occur by the sliding of one part of the crust past another along a fracture called a "fault," usually accompanied by considerable fracturing of rock on both sides of the fault. Where the fractures have not been sealed by heat and pressure or mineral deposition, groundwater may descend through them deeply enough to reach hot rock. Expanding as it is heated, the water rises buoyantly and may reach the surface as hot springs or geysers or steam vents. However, it may instead be trapped in porous or fractured formations called "hydrothermal reservoirs." When these are large enough and hot enough, they can be economical sources of energy, but such occurrences are rare. At depths at which temperatures are high enough to be potentially useful, the usual geologic environment is hot dry rock (HDR).

At depths that vary with the local geology, HDR exists everywhere. Its heat content represents one of the largest supplies of energy that is available to man. If it is assumed that all heat above 25°C (77°F) is potentially useful, as is done in measuring the heating value of a fossil fuel; and that – at least to reach temperatures high enough to generate electricity – we can afford to drill geothermal wells to depths as great as 6 kilometers (19,700 ft, which is reached routinely in drilling for oil and gas); then the calculated useful heat content of HDR under the United States is about 10 million quads. (One quad equals 10^{15} or one thousand trillion BTU's.) In energy content, this is equivalent to about 1700×10^{12} or 1700 trillion

Figure 1. Geothermal gradient map of the United States.

barrels of oil, or approximately 60,000 times the energy in the proved US reserves of crude oil.

While much of this heat is at too low a temperature to be of any practical value, one fairly conservative estimate is that there are at least 500,000 quads of useful heat in hot dry rock at accessible drilling depths beneath the US. This is about 6000 times the total amount of energy used in this country in one year. Economical recovery of even a very small fraction of such heat would contribute significantly to the nation's energy future.

Heat Mining: A concept for recovering useful heat from this tremendous natural resource originated at Los Alamos National Laboratory. As illustrated in Figure 2, it involves drilling two holes down from the surface into the hot rock, connecting them within the rock by means of large cracks created by fluid pressure (hydraulic fracturing), and circulating water through this underground loop to extract heat from the rock and to transport it to the surface.

Background studies and field investigations showed that usefully hot rock is present at accessible drilling depths under most of the United States and that much of the technology required to construct the proposed system already existed in the petroleum and natural-gas industries. Accordingly, a Hot Dry Rock Geothermal Energy Development Program, sponsored by the Division of Geothermal Technology of the US Department of Energy and its predecessor agencies, was established at Los Alamos National Laboratory. The primary objective of this Program has been to develop the engineering technology and scientific understanding that will make commercial development of hot dry rock (HDR) geothermal energy systems practical and economical.

In his 1987 report on Energy Security,¹ Energy Secretary Harrington stated that "...the United States and the world will, in time, come to rely largely on energy sources that are essentially inexhaustible, possibly including advanced nuclear fission reactors, fusion, and many diverse sources that are commonly lumped under the term 'renewable energy'." This view is widely held, and HDR is indeed one of those essentially inexhaustible energy resources. Although HDR energy recovery involves mining heat from a body of subterranean rock, it is renewable in the sense that heat extracted from the rock will eventually be replaced by additional heat conducted to it from deeper in the Earth.

As the Energy Secretary pointed out, such resources are indigenous and not subject to politically induced disruptions. HDR is a secure, broadly distributed domestic energy supply, potentially capable of significantly reducing both US dependence on imported oil and the rate at which our own limited resources of fossil fuels are depleted. An HDR energy system is self-sufficient and therefore not subject to shutdowns as a result of interruptions in its fuel supply by storms, strikes, or political disturbances. Being completely contained, it will have little or no adverse environmental effect and, requiring no surface area for fuel or spent-fuel storage, waste dumps, or transportation facilities, its land use will be small. The broad distribution of the energy source provides great flexibility with regard to the location of HDR

Figure 2. A hot dry rock geothermal system.

energy systems. They can be built where there is little or no problem with land acquisition and where long distance transmission lines -- and the large land use and scenic disruption that they involve -- will not be necessary. To the environmentally concerned, HDR offers a welcome alternative to almost all other energy systems.

Finally, an HDR system does not have to be extremely large in size to be economically viable, and its surface system is relatively simple. It can be constructed rapidly in modular units almost anywhere that energy is needed. In a time of uncertainty with regard to future energy demand and cost, this can greatly reduce the financial risk otherwise incurred by construction of traditional power plants, which typically are very large and enormously expensive.

Costs of Energy from HDR: The economics of HDR systems remain to be demonstrated in long-term, large-scale operations. However, independent cost analyses have been conducted over a number of years and with varying criteria by Los Alamos, the Electric Power Research Institute, the Meridian Corporation, Bechtel National, Inc., the United Kingdom Department of Energy, and the Japanese. The results of all of these economic studies were used by Tester and Herzog of the Massachusetts Institute of Technology² to prepare a composite study of the economics of HDR heat mining. Their work showed that, with current technology, electric power could be generated from high-grade HDR resources at busbar costs of 5-6¢/kWh -- a figure which is generally very competitive with the cost of power from fossil fuels. Costs of electricity from moderate grade resources were calculated to be 8-9¢/kWh, which is marginally competitive with conventional sources. Finally, the study indicated that electricity from low grade HDR would cost 16-18¢/kWh at the present state of HDR technical development. High-grade HDR resources have been estimated to occur over more than 60,000 square miles and medium-grade resources over more than 300,000 square miles of the land surface of the US.

The work by Tester and Herzog also took into account the effect on costs of further advancements in HDR technology. As an example, the use of two or three production wells per injection well -- a concept which has been formulated and modeled, but not tested -- would lead to electricity costs in the range of 3.5¢/kWh from high-grade HDR resources and less than 5¢/kWh from moderate-grade resources.

Direct thermal applications of HDR energy may make even low-grade resources economically exploitable. The Tester and Herzog study showed that low-grade resources could provide thermal energy at less than \$20 per million British Thermal Units (BTU's) currently and that with advanced development these costs could drop to less than \$5 per million BTU's. Direct thermal heat at cost of \$5 or less per million BTU's is estimated to be obtainable from high-grade resources with today's technology, with the promise of costs in the \$1-2 per million BTU's range.

International Aspects of HDR: The abundant HDR energy supply is, of course, not confined to the United States. It is a worldwide resource and is attracting increasing international

interest. Japan currently has an HDR program with a budget twice the size of the US effort. The Japanese are conducting field work at three locations. While they do not have a reservoir comparable in size or quality to the Fenton Hill site, they are proceeding rapidly with novel drilling and fracturing work and plan to begin extensive flow testing in 1994.

The United Kingdom has been deeply involved in HDR research since 1978. Their experimental site in Cornwall has a relatively low thermal gradient of about 35°C/km. A recent conceptual design study concluded that the development of a commercial HDR system at that location would not be economically feasible with today's HDR technology. The British have thus decided to de-emphasize underground work in Cornwall and take a more active role in other western European HDR projects with an eye toward future participation in a major HDR development effort under the auspices of the European Community.

Both France and Germany are active participants along with the European Community in a drilling and fracturing program at Soultz, near Strausberg in northeastern France. Temperatures of 140°C have been reached in this project at a depth of 2000 meters where a small natural hydrothermal system has been accessed by the drilling and fracturing operations. Plans are to drill to deeper, hotter rock and conduct further fracturing experiments. Recently, renewed interest has also been shown in further development at Bad-Urach in Germany.

All of these activities are leading to the selection of a single site for a major HDR Program to begin in 1993-1994 with financing by the European Community. A consortium of German, French, and British companies have proposed a \$300 million program to be conducted over 10 years. It would be designed to demonstrate the viability of HDR in the areas of low thermal gradient that are typical of northern Europe.

Significant HDR work was also conducted in Russia during the past year. Drilling and fracturing operations were carried out at Timniaus near Elbrus in the Caucasus Mountains. The experimental work followed the Fenton Hill model with drilling to 3.6 km followed by fracturing operations at pressures up to 60 MPa (8700 psi). Mechanical problems led to abandonment of the deepest portion of the original wellbore, but sidetracking to another location at the same depth and further fracturing are planned. The Russian program could be greatly enhanced by some of the advanced technologies developed at Fenton Hill. Under the right conditions, joint US-Russian cooperation could lead to significant benefits for both parties.

Again quoting Secretary Harrington's report: "Renewable-energy technologies have excellent export potential in the developing countries. Penetrating these markets, and holding domestic markets in the face of rising foreign competition, depends on continuing technical progress driven by advanced research.... The development of a technology base upon which industry can build will involve a sustained research commitment well in advance of potential payoffs.... Continued research progress in key areas will speed the day when private sector initiatives make more renewable energy technologies competitive."

The nation or nations that are leaders in the development and commercialization of HDR will take a large step toward energy independence, make significant advances in solving their environmental problems without sacrificing vital energy consuming activities, and create a large domestic and foreign market for their drilling and services industries. For all of these reasons, the DOE-sponsored Hot Dry Rock Geothermal Energy Development Program is important to the United States and the rest of the world.

History of HDR Research

The Phase I System: Although other methods of energy recovery are potentially useful in other geologic environments or for other purposes, the Hot Dry Rock (HDR) Program has so far concentrated on the common case of hot crystalline rock of low initial permeability; the use of fluid pressure downhole (hydraulic fracturing) to create flow passages and heat-transfer surface within the rock; and the operation of a recirculating, pressurized-water loop to extract heat from the rock and transport it to the surface. At the surface, the useful heat is recovered through heat exchangers, and the cooled water is reinjected to recirculate through the fractured rock and recover more heat from it.

This HDR geothermal energy concept originated at Los Alamos National Laboratory in 1970. Background and field investigations between 1970 and 1974 were encouraging with regard to the practicality of developing hydraulically fractured HDR systems and identified an area about 35 km (21 miles) west of Los Alamos by air that appeared to be well suited for large-scale HDR field experiments. At Fenton Hill, a convenient location within that area, the world's first HDR energy system was completed in 1977. It was enlarged in 1979 by additional hydraulic fracturing and operated successfully for more than a year.

This "Phase I" or "Research" system extracted heat from hydraulically fractured granitic rock at a depth of about 3000 m (9850 ft), where the initial rock temperature was around 185°C (365°F), and brought it to the surface in pressurized water at 135° to 140°C (275° to 285°F) and rates up to 5 MWt (thermal megawatts; about 17 million Btu/hr). Some of the heat was used to operate an experimental binary cycle power plant which produced 60 kW (kilowatts) of electricity that were used at the site. System operation was essentially trouble-free, and there was no detectable scaling, plugging, corrosion, or environmental effect.

Successful completion and operation of the Phase I system at Fenton Hill accomplished the original goal of the HDR Program. In a populated area, it could have heated several hundred homes for many years, and it demonstrated the engineering feasibility and commercial usefulness of HDR energy systems. However, it did not produce heat at a temperature or rate that would support economical operation of a commercial electrical-generating power plant in competition with fossil-fuel-fired or nuclear-energy plants. Since higher-temperature HDR systems had the potential to do so and a worldwide need existed for clean alternative energy supplies, the HDR Program was extended to attempt to meet those more demanding requirements.

The Phase II System: Under this new directive, construction of a larger, deeper, hotter "Phase II" or "Engineering" HDR system began at Fenton Hill in 1979. Two new wells about 50 m (150 ft) apart at the surface were drilled, the deeper one to a vertical depth of 4390 m (14,400 ft) where the rock temperature was 327°C (620°F). From hydraulic-fracturing theory and experience in creating the Phase I system, it was expected that hydraulic fractures produced in the Phase II system would be substantially planar and vertical, with an approximately north-northwest strike. Therefore, to provide the horizontal separation needed to thermally isolate a series of such fractures, the bottom 1000 m (3280 ft) of the first well was drilled toward the east-northeast and inclined at 35° to the vertical as illustrated in Figure 3a. The second well was then directionally drilled with its inclined section 380 m (1250 ft) vertically above that of the first well.

Hydraulic-fracturing experiments were conducted at various depths in these two wells during 1982, 1983, and 1984. Unexpectedly, the fracture systems produced were three-dimensional rather than planar, inclined rather than vertical, and did not meet each other or connect the two wells hydraulically. This fracturing behavior is probably the result of a joint pattern in the reservoir rock, related to the presence of a cooling magma body underlying a volcanic caldera a few kilometers east of Fenton Hill. Because it appeared unlikely that further hydraulic fracturing would establish the required connection, it was concluded that a more promising approach would be to redrill one of the wells directionally through a fracture system created from the other well.

The largest of the potential redrilling targets was the fractured volume produced in December 1983 by the Massive Hydraulic Fracture (MHF) Experiment during which 21,300 m³ (5.63 million gallons) of water were pumped at 48-MPa (7000-psi) pressure into an isolated section of the deeper well, EE-2, in the depth interval 3529 to 3550 m (11,580 to 11,650 ft). The target volumes were based on the locations of microearthquakes determined from analyses of records of the seismicity that occurred during the MHF Experiment.

Accordingly, during the spring of 1985 the upper well, EE-3, was sidetracked at a measured depth of about 2830 m (9285 ft) and completed at a final depth of 4018 m (13,182 ft), where the rock temperature was about 265°C (510°F). The sidetracked well, now identified as EE-3A, did intersect several of the fractures produced by the MHF operation, which provided good flow connections to well EE-2 from which they had been produced. These fractures and the two wells, EE-2 and EE-3A, constituted the Phase II underground heat-extraction loop. Well EE-2 was later redrilled as discussed below, to create the present Phase II system shown in Figure 3b.

Initial Flow Test of the Phase II Reservoir: After several preliminary experiments, an Initial Closed-Loop Flow Test (ICFT) of the Phase II system was conducted over a period of 30 days in May and June 1986. A total of 37,000 m³ (9.76 million gallons) of cool water was injected through well EE-3A, of which 66% was recovered through the production well EE-2 during the test, and an additional 20% was recovered during a subsequent venting of the system from

Figure 4. Results of the Initial Closed-Loop Flow Test of the Phase II HDR reservoir.

The Initial Closed-Loop Flow Test (ICFT) had been successfully conducted with the system in this impaired condition, but it was thought that the wellbore would continue to deteriorate during extended testing. Attempts to mill out the obstruction and re-enter the remaining liner were unsuccessful, and several other options for repairing the well were considered.

In accordance with the recommendations of a panel of drilling and well-completion experts convened in January 1987 by the Geothermal Technology Division of DOE, the option selected was to seal the casing leaks and add support to the upper part of the casing by cementing the annulus behind it and to sidetrack and redrill the well from a point above the region of casing collapse.

Accordingly, a drilling rig was mobilized over well EE-2 in early September 1987 to initiate these operations. The bottom of the well was plugged with cement to prevent interactions with the redrilled wellbore and provide a base for subsequent installation of the whipstock needed for sidetracking. The annulus behind the casing was filled with cement to the level of a lost-circulation zone at about 735-m (2410-ft) depth, and casing leaks and perforations were sealed with high-strength cement. A window for sidetracking the well was produced by milling out the casing from 2953 to 2971 m (9688 to 9747 ft). In FY88, a whipstock was installed and the well was successfully sidetracked. The redrilled wellbore has been redesignated as EE-2A. It required just 30 days to drill 800 m (2600 ft) of additional well, an average drilling rate of 27 m (87 ft) per day, which is 2-1/2 times faster than was achieved during the original drilling of the well in 1978 and 1979. As a consequence of this favorable experience, HDR researchers believe that if the entire well were redrilled today, its cost would be only \$4 million rather than the \$10 million actually spent. This brightens the future of HDR and other geothermal programs because a 60% saving in drilling costs corresponds to at least a 10-20% reduction of overall cost to generate electricity.

A potential major obstacle to the long-term testing of the Phase II system was resolved in 1989. The rate at which water is irrecoverably lost to the underground in the operation of HDR geothermal extraction systems has been a major source of concern in areas of the country where surface water is a limited resource and where the potential for earthquakes exists. At Fenton Hill, the rate of water loss which has been measured during transient flow tests, including the ICFT noted above, would be unacceptable for the long term operation of the Phase II system or others like it in the arid west. Measurements of water loss conducted under steady-state, equilibrium-pressure conditions have now shown that the water loss rate during long-term operation of the reservoir should be less than 10% of earlier estimates based on transient measurements.

Because hot dry rock represents an essentially inexhaustible supply of thermal energy almost everywhere, the US HDR Program has attracted international interest. As discussed earlier in this report, parallel and complementary programs have since been initiated in several other countries. Under an International Energy Agency (IEA) Agreement, agencies of the Governments of West Germany and Japan (KFA-Julich and NEDO) participated directly in the Fenton Hill Project during 1980-1986. This involved partial financial support, membership in its International Steering Committee, and long-term assignment of scientists and engineers from both countries to the HDR staff at Los Alamos. Under a bilateral agreement between the US DOE and the Italian Energy Agency (ENEL), a close relation with geothermal programs in Italy was established. There is continuing informal cooperation and information exchange with individuals and organizations in these and other countries.

Mandates for Continued HDR Development

In its 1985 "National Energy Policy Plan (NEPP) V," the US Department of Energy reiterated the Nation's policy that "...Americans should have an adequate supply of energy, available at reasonable cost. The basic strategies for holding to this goal are to ...promote a balanced and mixed energy resource system." In its plan, DOE explained that this includes renewable energy, for which research should "...address key, high risk, technical issues that will provide a scientific and engineering knowledge for industry...."

The HDR energy resource is one of the largest and most broadly distributed renewable energy supplies that is available to man. The DOE-sponsored Hot Dry Rock Geothermal Energy Development Program has already shown that practical means exist to recover useful energy from this secure supply, and ten years of environmental surveillance at Fenton Hill have shown that operation of an HDR energy system has no significant adverse environmental effect. The Program has concentrated successfully on the key, high-risk technical issues that will provide scientific and engineering knowledge not only to HDR developers but also to the geothermal industry in general, to the oil and gas industries, and to utilities. Transfer of this knowledge to industry has been prompt, continuous, and effective.

In 1984, the DOE Office of Program Analysis conducted an assessment of geothermal research. In its report,³ nine individual projects within the HDR Program were evaluated. Three were rated "outstanding," five were "strong projects deserving of continuing priority support," and one was simply "good."

In 1985, the DOE Office of Conservation and Renewable Energy determined that its priority for the HDR Program should be elevated because "its effectiveness scores are high based on addressing critical technology development objectives. Federal role scores were also high due to high technical risk."⁴

However, a 1986 review of geothermal energy programs by the Solid Earth Sciences Panel of the Energy Research Advisory Board⁵ suggested that both the HDR and the Magma Energy Programs should be terminated because geothermal energy would be limited to only a minor role in future energy use. (The panel evidently did not examine either the magnitude of the HDR energy resource or the fact that the HDR Program had brought HDR technology to the threshold of economic viability.)

The opposite view was expressed in 1986 by a panel of technical experts from private industry, national laboratories, and universities, which also reviewed the major DOE geothermal programs. That panel selected the HDR Program as its number one priority on the basis of its enormous resource base, its applicability to the production of heat either for direct use or for generating electricity, its recent technical successes, its promising economic estimates, the increased international interest in the technology, and its attainment of the later phase of engineering development.

In 1987, the Committee on Geothermal Energy Technology of the National Research Council reviewed the DOE geothermal programs. It reported⁶ that the HDR Program was well managed with reasonable and important technical goals directly addressing the program's objectives. It noted that budget cuts and the resulting loss of technical personnel had weakened the Program and recommended that DOE "stay the course" with adequate funding to maintain a vigorous HDR Program through FY88-91.

While agreement is not unanimous, the large majority of well-informed experts who have evaluated it agree that the HDR Program addresses the beneficial use of an extremely large energy resource whose utilization will have many advantages; that the existing program to develop the technology needed to recover and use that energy is well planned and is being well executed; and that, with the necessary Federal support, the HDR Program should be carried forward to a successful conclusion in the 1990s.

Technology Transfer

Industry has been directly involved in the HDR Program from its beginning. Approximately 40% of the total HDR budget has gone to drilling and service companies in a mutually

beneficial arrangement in which industrial and program personnel have learned from and with each other in advancing the technology of drilling, well completion, and hydraulic fracturing in a new and challenging underground environment. Drilling and coring bits, downhole motors, open-hole packers, and other equipment developed for the HDR Program are now used throughout the drilling industry. Instruments developed for use in the Fenton Hill wells are now also used both in conventional hydrothermal development and in the oil and gas industries. The seismic techniques developed for investigation of HDR reservoirs are being evaluated for use by those and other industries. These and other innovations and developments from the HDR Program will significantly increase the efficiencies and reduce the costs not only of future HDR systems but also of many other underground operations.

Representatives of industry and of State and Federal Government have participated in experiments at Fenton Hill. Plans for drilling, redrilling, well completion, hydraulic fracturing, and extended flow tests have repeatedly been reviewed and critiqued by experts from industry. An advisory committee regularly reviews the status, progress, and plans for the program and makes recommendations to its management. The Committee consists of representatives of Geothermal Resources International, Stone and Webster, Plains Electric of New Mexico, San Diego Gas and Electric, the State Energy Departments of California and New York, and private consultants. A conclusion of that committee is that completion of the long-term flow test, the final major milestone in the Fenton Hill Project, will provide the information needed for industry to undertake development of HDR energy systems on a commercial scale.

Possible applications of HDR technologies for the mitigation of the pressure decline at The Geysers came under investigation as a result of a California Energy Commission hearing held in Santa Rosa on September 21, 1989. The DOE requested that members of the Los Alamos staff be present to assess the problem in The Geysers in terms of the knowledge of the mechanical properties of fractured reservoirs that has been obtained through the years of research at Fenton Hill.

Recognition of the role that HDR systems can fill in the development of geothermal resources in regions for which hydrothermal development has not proved feasible came with the completion of one study and the request for a further study, both funded by the city of Clearlake under the auspices of the California Energy Commission. In the completed study, Los Alamos assembled and analyzed well-log, geophysical, and geological data available for the Clearlake region with the goal of identifying potential hot dry rock locations for the siting of a power plant for the municipality. Scientific data were compiled in a portfolio at the scale of 1:62,500 comprised of topography, gravity, aeromagnetic, resistivity, geology, thermal-gradient, and well-location sheets. Subsurface prediction of the location of hot dry rock environments was made by simultaneous interpretation of information assembled together in the portfolio. Two areas for the potential siting of a hot dry rock power plant were identified.

• Early in FY91 the city of Clearlake secured additional funds from the California Energy Commission for a greatly expanded study, citing Los Alamos as the sole source for HDR technology in the country and requesting Los Alamos direction of the study. Work has concentrated on the development of a conceptual and computational model to explain the assembled data on the basis of thermal history, temperature and hydrologic gradients, rock structure, and distribution of fracture permeability. Data from existing wells has been heavily relied upon in the development of the model. An analysis of the comparative merits of sites in the Clearlake area vis-a-vis current hot dry rock technology is also being completed. At the conclusion of this phase of the project, the stage should be set for site selection and initial drilling in connection with the development of the Clearlake HDR resource.

OBJECTIVES

The goal of the Hot Dry Rock Heat Mining Geothermal Energy Development Program is to demonstrate that HDR technology can be employed to provide a practical and economically feasible method to produce energy on a sustainable basis. In order to attain this goal, a primary objective has been formulated as follows:

Level I Objective:

Develop HDR technology sufficiently by 1997 to demonstrate that power can be generated from hot dry rock energy at costs in the range of 5-8¢/kWh.

The aim of this objective is to lead to the availability of the technical base by the year 1997, which will give industry the information and incentive it needs to develop commercial HDR power generation plants. In order to achieve this broad objective, it is necessary to examine and optimize the major factors in determining the viability of the hot dry rock resource as an energy source: quality, accessibility, environmental characteristics, and economics. These factors are the key elements of the subsidiary objectives of the program:

Level II Objectives:

1. Evaluate the performance of the Fenton Hill Phase II reservoir including predicted thermal lifetime, optimum system operating characteristics, required maintenance operations, sustainable energy production, and water consumption.
2. Improve the performance of drilling and completion technology under conditions typical of hot dry rock environments.
3. Determine the environmental characteristics of HDR technology.
4. Evaluate and optimize the economics of HDR energy production.

In order to attain the primary and subsidiary objectives in a timely manner, a set of working objectives has been developed. These are summarized below:

Level III Objectives:

- 1. Evaluate the large Phase II reservoir at Fenton Hill to determine its drawdown characteristics.**
- 2. Complete detailed reservoir analyses and confirm modeling of hydraulic and thermal performance of the Phase II system.**
- 3. Develop technology to monitor changes in reservoir volume and temperature and confirm monitoring data using tracers.**
- 4. Establish reservoir-mapping techniques to locate drilling targets for production wells.**
- 5. Conduct studies on water-rock interactions and their effects on flow through a hot dry rock reservoir.**
- 6. Verify that the environmental and social consequences of HDR development are acceptable.**
- 7. Determine whether the performance of the Fenton Hill Phase II reservoir, when considered as a unit reservoir in a commercial-scale project, could support production of electricity at an economical busbar cost.**
- 8. Determine means to locate accurately the intersections of fractures with the wellbore.**

The activities associated with this project during FY91 have been directed toward the accomplishment of the program objectives, within the work breakdown framework as illustrated in Figure 5. The expected accomplishments for this year, as stated in the FY91 Annual Operating Plan, are listed below.

FY91 Expected Accomplishments

- A. All aspects of procurement and installation of LTFT system components completed.
- B. Reservoir operation under high backpressure conditions field tested and evaluated.
- C. Water loss rates as a function of reservoir pressure at high reservoir pressures determined.
- D. Water rights, supply, and storage for LTFT assured.
- E. Required environmental activities carried out and safeguards implemented.
- F. Reservoir engineering, seismic studies, modeling, and tracer work utilized to develop LTFT experimental design and operational plan.
- G. All equipment and facilities maintained, and upgraded where necessary.
- H. Required interagency coordination carried on.
- I. Active program to publicize and transfer HDR technology pursued.

The HDR program consists of two main task areas: (1) Fenton Hill Site Operations and (2) Scientific and Engineering Support.

HDR Program Work Breakdown Structure

HDR Program Geothermal Energy Development Program

Fenton Hill Operations Task Area

Phase II Energy Extraction System Plant

- Commissioning
- Initial Operational Testing
- Long-Term Flow Testing
- Static and Limited Term Testing
- Logging

Phase II Ancillary Activities

- Water Supply
- Environmental, Safety, and Health Functions

Test Site Support

- Surface Plant Maintenance
- Equipment Maintenance and Upgrade
- General Site Work

Scientific and Engineering Support Task Area

Engineering and Development Activities

- Reservoir Engineering
- Modeling
- Seismology
- Geochemistry and Tracers

Technology Applications

- Technology Transfer Activities

Figure 5. HDR work breakdown structure.

Fenton Hill Site Operations Task Area

The Fenton Hill Site Operations Task Area is concerned with all activities at the Fenton Hill HDR site. These include all aspects of plant construction and commissioning, reservoir management and testing, site environmental and safety measures, procurement of utilities, and routine site maintenance.

Phase II Energy Extraction System

This project element entails all the preparations for and conduct of the long term flow test (LTFT) of the Phase II reservoir, as well as all preliminary work leading to this test and such limited testing efforts as may be necessary in funding-limited operational scenarios. It is directly concerned with the attainment of Level II objective #1. In addition, the data generated as part of this project element contributes substantially to all other program objectives. During this year, construction of the surface plant was essentially completed. Commissioning of the plant will be completed early in 1992, and initial flow testing will set the stage for a steady-state LTFT phase beginning in the second quarter.

With the funding allocation anticipated at the beginning of FY92, it will be possible to sustain the steady-state LTFT for only about 3 months. Supplemental funding is being sought to allow the continuous phase of the LTFT to be conducted for a period of a year or more. In the event this funding is not forthcoming, a program of static and low-cost intermittent testing will be implemented subsequent to the 3-month LTFT phase.

The goal of the reservoir testing effort is to obtain information about the thermal and hydraulic characteristics of the Phase II reservoir and provide a basis for studies of HDR technology in general. Geochemical analyses, tracer tests, seismic surveillance, and logging activities will be carried out during the test period to provide important supplemental technical data regarding system parameters and characteristics.

Phase II Ancillary Activities

The activities in the ancillary and support projects are essential for meeting safety, health, and regulatory requirements for operation of the LTFT and for assuring that the necessary water supply, utilities, and related facilities are in place. The ancillary activities at Fenton Hill contribute importantly to meeting Level 3 objective #6. This year, procurement of sufficient water to conduct the LTFT continued to be an important goal of this activity area.

Seismic, air, and water monitoring add to the store of data needed to verify the environmental characteristics of HDR development. In the long run, all the projects and activities in this task area will contribute significantly to the analysis of the performance of the Fenton Hill Phase II reservoir.

Site Support Activities

This activity area includes all the day-to-day work needed to keep the area running in a safe manner with adequate utilities and well-maintained equipment. Environment, safety, and health (ES&H) issues continued to be a major focus this year. As part of an intensive investigation of the state of ES&H efforts at the Laboratory, members of DOE "Tiger Team" spent about 80 hours reviewing relevant topics at Fenton Hill. Only a few minor deficiencies were found. It should be noted, however, that intensive ES&H work was completed prior to the visit by the "Tiger Team" at a highly significant cost in money, time, and the attention of key project personnel.

Scientific and Engineering Support Task Area

The object of the projects in the Scientific and Engineering Support Task Area is to provide the scientific and technical underpinning for the field work at Fenton Hill.

Engineering and Development Activities

The project includes a variety of activities aimed at developing a better understanding of the HDR reservoir at Fenton Hill, HDR reservoirs in general, and the geological phenomena associated with the development and operation of an HDR heat mine.

Reservoir Engineering: The various projects in the reservoir engineering task area provide the scientific and engineering basis for the development of HDR technology. Because HDR is a frontier energy production technology, no prototypes exist to guide the development. As a result, the basic science, the developmental engineering, and the applied engineering all have to be developed from scratch.

Reservoir engineering is concerned with understanding and manipulating HDR reservoirs. It draws heavily on the technology already developed in the oil and hydrothermal industries but must adapt the established principles from these areas to the peculiarities of HDR reservoirs. Reservoir engineering makes use of information generated by all the components of the Science and Engineering Support Area, as well as operating experience at Fenton Hill, to build a coherent picture of HDR-reservoir thermal and mechanical behavior. Reservoir engineering is primarily concerned with meeting level III objectives #1, #2, #3, and #7, which relate to overall system performance, but it draws heavily upon and interactively contributes to the information generated in meeting level III objectives #4, #5, and #8.

The reservoir engineering work this year has concentrated on further understanding factors involved in water consumption through the application of data from static pressurization tests and the use of static-test data to obtain a quantitative measure of the flow-connected volume of the Phase II HDR reservoir.

Seismology: Microseismic analysis activity is concerned with the application of advanced microseismic techniques to the problem of defining the size and shape of the reservoir, monitoring its growth, and establishing conditions which lead to reservoir creation and expansion. It directly addresses level III objectives #3, #4, and #8. Since this activity includes monitoring for potential seismic environmental effects of HDR experiments, it also contributes to the attainment of level III objective #6.

Modeling: Modeling activity is closely tied to overall reservoir engineering. It entails applying mathematical and physical concepts in an attempt to model and predict reservoir behavior. Modeling serves to explain the phenomena observed in experimental work and to point the direction for further experiments. It provides a framework for reservoir engineering work that gives added strength to experimental observations. Modeling is a key activity in the attainment of level III objectives #1, #2, #3, and #6 and has an important role in reaching objectives #7 and #8.

Geochemistry and Tracer Work: The geochemistry activities, including tracer studies, provide essential chemical data which can be used to measure the flow of fluid in the reservoir, the dissolution of minerals, dissolved or entrained gases, corrosive wear on system components, and other important system characteristics. This information is extremely important in monitoring the performance of the reservoir during testing and providing a basis for modeling and predictive studies. Potential environmental effects of HDR technology can also be accurately assessed using the data from geochemical analyses. Geochemistry work is an important contributor to the attainment of level III objectives #1, #2, #3, #5, #6, #7, and #8.

Technology Applications

Technology transfer activities are directed toward publicizing HDR technology in order to foster the growth of HDR in the private sector. These activities include visits to the Laboratory and the Fenton Hill site by industrial representatives, visits by HDR staff to industrial organizations, interactions with all levels of the media, attendance at professional and technical meetings, the presentation and publication of HDR technology in a broad variety of forums, and related actions. Technology transfer entails the dissemination of information related to all of the level III objectives. In fact, the ultimate goal of the program is to effectively transfer HDR technology so that it is adopted by US industry, and the objectives at all levels are directed toward this end. This coming year, in particular, every effort will be expended to encourage private sector participation in the flow testing effort at Fenton Hill. It is extremely important that the voice of private industry be heard in respect to the goals and conduct of all flow testing work.

ACCOMPLISHMENTS

The preceding section of this report stated the objectives of the HDR Program and related these objectives to the work carried out under each of the program elements. The work breakdown structure (Figure 5, page 24) also provides the framework for this summary of the accomplishments of the HDR Program during FY 1991.

Fenton Hill Site Operations Task Area

Phase II Energy Extraction System

Construction of the surface plant for the Phase II HDR reservoir was essentially completed by the end of 1991. Work performed prior to FY91 has been summarized in previous annual reports. Progress during the past year is summarized herein.

Figure 6, shows a simplified schematic of the surface facility. Key components include pumps for injection, supply water and makeup water, a separator to remove particles and gases from the circulating fluid, a heat exchanger to extract the thermal energy mined from the HDR reservoir, the wellhead assemblies, and piping to form the surface portion of the closed loop. Numerous valves, fittings, and minor components not shown in the figure complete the system.

Figure 6. Simplified schematic of the Fenton Hill surface plant.

The Injection Pumps: The two high pressure pumps designed to inject water into the reservoir were delivered to Fenton Hill at the end of the first quarter of 1991. Each pump package weighs about 70,000 lbs and includes a Caterpillar diesel engine, Allison transmission, a mounting skid, and a soundproof enclosure in addition to the pump itself. The enclosure is

heated to alleviate problems with freezing during the winter months. As illustrated in Figure 7, the pumps are 5-cylinder reciprocating units. Each unit is capable of delivering about 200 gpm of water at a maximum pressure of 5,000 psi.

Installation, hookup, and testing of the pumps continued throughout most of FY91 as portions of the surface facility were progressively brought on line. No outstanding problems were encountered in building the pumps into the loop, although a number of adaptations and modifications were necessary to alleviate minor problems brought to light during testing.

Figure 7. Cross-section view of a high pressure injection pump.

Initial start-up of the pumps at Fenton Hill occurred in March 1991, and shakedown operations continued throughout the spring and summer. The pumps were first put to beneficial use to inject water into the reservoir in September 1991. Early in FY92, a "clanking" noise was observed during operation of one of the pumps. It was attributed to an out-of-tolerance bearing housing, and the problem was rapidly corrected. During disassembly and inspection, some scratches and marks were seen on the sealing surfaces of the valves. The valves were refaced but, as of this writing, the significance of this corrosion problem has not been fully determined.

It is anticipated that only one pump at a time will be operated during most of the long-term testing program. This will permit continued operation of the system while maintenance is performed on the idle unit. A contract for up to 150 thousand gallons of diesel fuel to power the injection pumps was signed this year with Graves Oil Company of Farmington, New Mexico. The price is tied to the Oil Price Index. Fuel oil was delivered under this contract near the end of FY91 at a cost of about 70¢/gal.

The Makeup Water Pumps: Makeup water can be added to the system by either of two types of pumps. Several low pressure, high volume pumps purchased a number of years ago can rapidly fill the system by pumping more than a hundred gallons of water per minute into the loop. During operation, however, the circulating fluid is maintained at pressures up to 1,000 psi. To add water to the system while operating at these pressures, two high pressure, low volume pumps manufactured by the Rotojet Pump Company were ordered in 1990. Each of these units is capable of delivering about 25 gpm against a pressure head of 1,000 psi.

The Rotojet pumps arrived at Fenton Hill early in FY91. As part of the package, a duplex controller was supplied to start the pumps in sequence as required to meet predetermined pressure or flow values. The logic causes one unit to be energized to initiate pumping with the other pump coming on automatically when system demand exceeds the capacity of the first unit. The controller also includes a provision for reversing the order of operation of the pumps during cyclic pumping operations in order to equalize usage time and extend the life of seals and bearings.

The pumps were installed during the winter, and Rotojet personnel visited Fenton Hill for start-up and shakedown testing in February 1991. Although hydraulic and mechanical operations went smoothly, the electronic controls proved to be the Achilles' heel of the make-up water system. While the pumps were fully incorporated into the surface plant and repeatedly tested throughout the summer, the control logic problem was not finally corrected until early in FY92.

The Separator: The separator was the single significant piece of equipment which had not been procured by the beginning of FY91. The mechanical design and fabrication requirements for the separator were established early in the year, and an order was placed with Sivalis, a manufacturer of oil field separators in March 1991. The unit was delivered to Fenton Hill on July 18, 1991, and installation and hydrotesting were completed in late summer. The separator has been designed, built, and installed in accordance with the requirements of the American Society of Mechanical Engineers (ASME) boiler and pressure vessel code.

The Heat Exchanger: The condition of the heat exchanger, which has been on site since 1974, was closely evaluated and found to be satisfactory during FY90. Improvements in FY91 included the installation of new motor controllers to provide for more reliable operation of the cooling fans and bring the unit in compliance with the latest code provisions for the operation of large electrical equipment.

Data Acquisition and Control: The data acquisition and control (DAC) system, based on equipment purchased in FY90, was installed over the course of FY91. Figure 8 is a schematic showing the numerous points around the loop where data is acquired or control operations are performed. The system was brought on line gradually with frequent testing of individual elements. By the end of the year, it was fully functional. A complete back-up system was installed during the summer to provide 100% redundancy in all DAC functions.

Surface Loop Piping: All the piping strings in the loop have been designed and constructed in accordance with requirements of the American National Standards Institute (ANSI) power piping code. From a mechanical design standpoint, the piping is divided into three sections. The low pressure side of the system, which includes the separator, heat exchanger, and make-up water pumps as well as all the connecting piping, is designed for operation at pressures up to 1,100 psi. The production segment containing various pressure regulating equipment is capable of operation at up to 4,500 psi. Finally, the high pressure section, which delivers the output of the high pressure pumps to the injection wellhead can be operated at up to 5,000 psi. The high pressure injection line has been fabricated out of stainless steel, while all the lower pressure sections are constructed of carbon steel.

During this past year, all new sections of piping were fabricated, welded, inspected, and certified. Some sections of older pipe being included in the loop were also inspected radiographically. A number of defective welds were found. These were cut apart, rewelded, reinspected, and certified. Late in the year, the entire system was hydrostatically tested and verified to be sound. By the beginning of FY92, this mundane, but critical, aspect of the surface system was entirely in place and ready for use.

The Wellheads: Both the injection and production wellheads were largely rebuilt in FY90. This work was completed early in FY91 with the final installation of valves on the production wellhead. A pinhole leak detected in the injection wellhead casing during pressure testing was successfully repaired by a wellhead welding company.

Late in the year, a decision was made to install utilitarian structures around the injection and production wellheads. Each structure will consist of stairwells, ladders, platforms, and multiple landings to provide convenient access to the wellhead valves for operations and maintenance. Because sub-zero temperatures can be encountered at Fenton hill during the winter, the structures will be designed with a provision for protection of the wellheads from the elements. The structural members will be prefabricated to minimize field assembly work. Design and construction will comply with all applicable building code and OSHA requirements.

Site Safety: As part of the hazards review in preparation for the LTFT, the potential for the production of hydrogen sulfide gas during the test and our procedures for dealing with the release of this gas were evaluated this year. Seven (7) new fixed hydrogen sulfide detectors and 8 portable units were procured. Warning of this hazard has been placed both on the

Figure 8. Loop schematic showing data acquisition and control points.

perimeter and at the various possible source points. The signing has been designed to meet the standards of all the regulatory agencies legitimately concerned with this hazard at Fenton Hill.

An intensive evaluation of all environmental, safety, and health (ES&H) activities was conducted toward the end of the year by a "Tiger Team" appointed by the USDOE. The HDR site at Fenton Hill came under intensive scrutiny by 15 inspectors who spent a total of 80 hours auditing safety, environmental, and quality issues. They turned up 5 minor (OSHA, Category 3) violations and 1 compliance problem. None of the matters were significant from the standpoint of continued operations. Several have already been taken care of, and the others are being addressed in a prudent manner.

Design and Construction Review: A committee was formed in the summer of 1991 to review the design and construction of the surface plant. The committee was charged with evaluating the facility with respect to Laboratory policies and procedures in the areas of environment, safety, and health. The review was slated to cover mechanical design, operating controls, quality assurance, and construction practices. The review team is comprised of Laboratory personnel not associated with the HDR Program who have expertise in the areas of engineering design, safety, and quality assurance. The committee issued its first preliminary report in late summer. This report was being reviewed by HDR engineering personnel at the close of the fiscal year.

Reservoir Testing: The long-term pressurization study of the Fenton Hill HDR reservoir, begun in the spring of 1989, continued throughout FY91. Figure 9 shows the pressure profile of the reservoir as measured at the production wellhead over the course of the entire term of this test. The past fiscal year included extended intervals when the reservoir pressure was maintained at 10, 15, 17, and 19 MPa respectively.

This work has continued to demonstrate that it is possible to maintain the reservoir at a high pressure with very little water consumption and that the reservoir is aseismic (does not grow) even after prolonged periods of pressurization at up to 19 MPa. In addition, a wealth of other valuable information regarding reservoir characteristics has been derived from the data generated during this long experiment. Some of the most important findings of FY91 are summarized below:

10 MPa Pressure Plateau Study: After an 11-week shutin phase during which the reservoir was allowed to slowly vent down from 15 MPa (2175 psi) to 10 MPa (1450 psi), the pressure was maintained at 10 MPa for more than 9 weeks beginning on March 1, 1991. Water loss at the periphery of the reservoir was vanishingly small (about 0.0 to 0.1 gpm) during this 10 MPa pressure plateau period. The reservoir pressure had been significantly greater than 10 MPa for several months prior to the establishment of this plateau, and it is likely that a broad isobaric region extending well beyond the limits of the fractured reservoir was established during this test stage.

15 MPa Pressure Plateau Study: The pressure on the Phase II reservoir was raised from 10 MPa (1450 psi) to 15 MPa (2175 psi) in early May 1991. Based on prior experience early in this experiment, it was anticipated that this pressurization change would take about 3 weeks to complete and would consume 424,000 gallons of water. The process took only 7 days, however, and required only a net amount of 157,000 gallons of water.

The lower water consumption may be a consequence of more than 2 years of pressure maintenance. The rock mass surrounding the reservoir may have become much stiffer (considering its modulus) over the 2-year time span of the experiment during which it was internally pressurized and volumetrically expanded. As a result, smaller changes in joint dimensions would occur upon inflation of the reservoir from 10 to 15 MPa, and less fluid would thus be consumed in the process.

During this most recent 15 MPa pressure plateau in this multi-year test, water consumption declined with time from an initially high level on May 8, 1991, to 5.0 gpm during the period May 13-15, and still further to less than 4 gpm by the end of the month, when this phase of the experiment was terminated. These results are similar to those observed during previous 15 MPa pressure plateau stages of this experiment.

17 MPa Pressure Plateau Study: A 17 MPa (2465 psi) pressure plateau was established on July 8, 1991, and maintained until August 22, 1991, when equipment problems forced a cessation of this stage of the experiment. During this long steady-state pressurization stage, water consumption declined linearly with the logarithm of time, as usual, from an initial value of about 8.6 gpm to 4.5 gpm by early August. It then unexpectedly increased over a four day period to a level of 5.5 gpm. While this unanticipated increase coincided roughly with logging activity in the production well, that does not appear to have been the cause of it, and, in fact,

this aberration remains an unexplained phenomenon. Water consumption then resumed a declining profile for the few remaining days of this test phase.

19 MPa Pressure Plateau Study: Figure 10 shows a profile of the Phase II reservoir pressure during the November-December 1990 time period. During the latter part of November and early December the pressure was maintained at 19.0 ± 0.2 MPa (2755 psi) pressure. This was the second time during this long experiment that a 19 MPa pressure plateau had been established, the first being during May 1990. On December 10, the system was shut in due to equipment problems.

Figure 10. Reservoir pressure profile during November-December 1990.

The water loss rate profiles as measured during the two 19 MPa pressure plateau periods are shown in Figure 11. These two segments were separated by a six-month interval during which the reservoir pressure was maintained at an average value of about 15 MPa, but with short term variations to as low as about 10 and as high as 17 MPa.

The data clearly show that the rate of water loss during the second 19 MPa pressure plateau was significantly lower than observed during the first. This difference of about 1 gpm indicates that a pressure gradient was still developing at the periphery of the reservoir over the interval between the tests and that the somewhat higher far-field pressure during the second plateau period resulted in slower diffusion from the reservoir in November than in May.

The water loss data at 19 MPa are analogous to those observed for long-term pressurization at 15 MPa and provide further evidence that water losses decline significantly during extended

operation of the reservoir. These results bode well for the long-term flow test slated to begin in 1992. The mean pressure at the periphery of the reservoir is expected to be at or below 19 MPa during aseismic reservoir operation at injection pressures of about 25.5 MPa (3700 psi), although it may be somewhat higher in regions distant from, and lower close to, the production well.

Figure 11. Water loss profiles during 19 MPa pressure plateau periods.

Fluid Leak through the Injection Wellbore Annulus: A continuous water leak of a few gallons per minute from the injection well (the EE-3A well) has been observed for several years. The leak manifests itself as fluid returning to the surface in the annulus between the wellbore and the outermost casing. Analyses of water samples collected from the wellbore in 1990 indicated that it is probably reservoir fluid. It appears that a connection of the reservoir to the injection wellbore exists at some point above the cemented-in section which is supposed to seal off the reservoir from this exit pathway.

During this past year, automated monitoring of the bypass flow continued to indicate that the leak is in a steady-state condition. The flow rate has been found to change in response to changes in pumping schedules and reservoir pressures, but in a predictable manner. It has averaged 2-3 gpm over the entire 2 1/2-year course of the recent reservoir pressurization experiment. While this leak complicates some of the measurements and calculations regarding reservoir performance, it does not appear to be practical or expedient to repair it at this time. Instead, we intend to continue to monitor this situation closely.

Long-term Water Consumption: Some indication of the water requirements in operation of a HDR facility may be gained from the following summary of water usage in the extended pressurization experiment during calendar year 1990.

water injected:	3,174,000 gallons	12,020 m ³
water vented:	1,298,000 gallons	4,912 m ³
(through injection wellbore annulus)		
net water consumed	1,876,000 gallons	7,108 m ³
average water usage rate	3.57 gpm	0.225 kg/s
average reservoir pressure	2223 psi	15.32 MPa

The total water usage for reservoir pressurization at Fenton Hill during 1990 amounted to nearly 6 acre feet.

Logging: A temperature/gamma/collar log was conducted in the production wellbore on August 5, 1991, with the well at a pressure of about 17 MPa (> 2400 psi). This was the first logging activity at Fenton Hill in somewhat over 2 years, as well as the first time Los Alamos equipment has been used under high pressure conditions. Pressure control at the wellhead was provided by an outside service contractor, Oil Well Perforators of Casper, Wyoming.

The log shows that the temperature gradient between 10,860 and 11,560 ft is remarkably flat, with the shallow depths within this interval being above the virgin rock temperatures. From 11,560 ft to 12,186 ft, the gradient resumes the step-like temperatures profile expected for a reservoir that has been shut in for 30 months. The fractures that contribute to fluid production can be clearly seen over the latter depth interval.

Two hypotheses have been advanced to explain the appearance of the gradient between 10,860 and 11,560 ft. The first implies that flow has taken place from a fracture located at 11,560 ft into the EE-2A wellbore, up the well to 10,860 ft, and then out into a fracture at that depth. The second assumes that the temperatures measured in the EE-2A well are representative of the reservoir as a whole at those depths. If this is the case, there is little impedance to flow in the fractures comprising the reservoir, and buoyant forces are slowly driving a large scale convective system within it. No definitive conclusions have been reached as to which of these explanations is correct.

Phase II Ancillary Activities:

A comprehensive review of the design and construction of pressurized system components of the Fenton Hill system for circulation and treatment of reservoir fluids was initiated by a independent committee comprised of a safety engineer and 2 mechanical engineers. The objective of the review was to determine if the system as designed and as built meet the operations specifications that had been developed for the facilities. The review was well

underway by the close of the fiscal year and was scheduled for completion by December 31, 1991.

A technical safety appraisal was completed for the Fenton Hill installation and operations as required by DOE Order 5480.19. Included in the appraisal was a review of organization and administration, quality verification, operations, maintenance, training and certification, emergency preparedness, personnel protection, and worker safety and health compliance. Along similar lines, an assessment of risks to personnel and a review of current efforts to mitigate those risks was completed in a documented management review of Fenton Hill activities. Both the appraisal and assessment had the effect of increasing personnel and management awareness and response to the continuing Environment, Health, and Safety requirements of Fenton Hill operations.

A review of Federal and State regulations that affect operation of the Fenton Hill facilities was completed. Because hydrogen sulfide can be released during operation of the reservoir, a determination was required to be made of the status of the facilities with regard to the Federal and State of New Mexico Clean Air Acts. Based on the documented amount of gas released during past flow tests, the Laboratory's Environmental Management Division determined that the total annual release of hydrogen sulfide was well below the threshold at which Fenton Hill would qualify as a regulated source under those Acts. Similarly, because of the low volume of hydrogen sulfide released and its low concentration in the stream of released gases of which carbon dioxide is the principal constituent, Fenton Hill produces insufficient gas to be regulated as a public safety hazard by either the State of New Mexico or the Bureau of Land Management, the agency of jurisdiction for the Forest Service lands on which the Fenton Hill facility resides.

Nonetheless, since hydrogen sulfide is present on site, it represents a potential health hazard to operations personnel and visitors in the event that anomalously high concentrations of the gas are produced during operation of the reservoir or that were to concentrate in confined spaces or in low lying areas during still weather conditions. In this regard, regulations of the Occupational Safety and Health Administration (OSHA) for personnel protection apply. As a consequence, a comprehensive review was completed of risks to personnel, and mitigation of those risks, from the presence of hydrogen sulfide currently on site and from the anticipated production of hydrogen sulfide during upcoming flow testing of the Phase II reservoir.

Based on the results of that study, actions were undertaken and completed to improve personnel protection at Fenton Hill. Two (2) additional self-contained breathing units and 8 handheld, continuous-readout, digital hydrogen sulfide monitors were procured and made available for use by site personnel at the two locations at Fenton Hill from which emergency actions may originate. OSHA signs warning of the possible presence of poisonous hydrogen sulfide gas were posted at each potential location of hydrogen sulfide emissions as well as along the site perimeter fence. The fence around the 1-million gallon pond was also posted. A windsock was installed at a second location for a clear indication of low level air movement

close to the Phase II wellheads. Training dealing with the hydrogen sulfide risk, its detection, and consequent actions was given all Los Alamos and contract site personnel assigned to Fenton Hill.

The State of New Mexico through the State Oil Conservation Division permits and regulates all injection activities in the State. The principal reason for this is to insure that aquifer waters are not contaminated by injected waters or mixed with them via breached casing. Before commencement of large scale operations, the hydraulic integrity of an injection well must be assured, and thereafter at 5 year intervals. Once injection begins, monthly reports of the amount of fluid injected must be filed. Since reservoir testing will require large volumes of fluid to be injected into well EE-3A, a permit application was prepared and filed with the State. As of the close of FY91, the permit had not been acted on by the State.

Site Support

About 60 truckloads of accumulated salvage material were removed from Fenton Hill. Similarly, roughly 10 truckloads of salvage were removed from the staging area for Fenton Hill at TA 33. The Cable Test Facility was dismantled and salvaged. Salvageable equipment was also removed from the Borehole Tool Test facility and the facility was mothballed.

In order to meet OSHA requirements, improvements were made in the electrical service at Fenton Hill. All of the electrical service to trailers supporting operations at Fenton Hill was replaced and the wiring was placed in conduit. Electrical service breakers and distribution boxes in the vicinity of the heat exchangers, as well as the heat exchanger controller, were replaced with a single distribution center in an all-weather, walk-in enclosure. Non-electrical improvements included identification and posting of confined and limited egress spaces, implementation of lockout tagout procedures, relocation of the antenna tower to improve emergency radio communications, construction of secondary storage for the diesel fuel tanks for the high pressure injection pumps, documentation preparation and training in safe operating procedures, an inventory of all hazardous chemicals and removal of those not in use, and the procurement and training in the use of air purifying respirators for personnel involved in chemical treatment of the water storage ponds.

Because of the great increase in interest in Fenton Hill, improvements were made in facilities to receive visitors. Space was remodeled in the operations building to serve as a conference room. The conference room also can be used as an information center by site personnel to follow the progress of testing. The status of operating parameters (flow, temperature, and pressure) and recent performance history of each component of the circulation loop can be displayed and reviewed through a computer terminal that accesses the main control and data acquisition computer for the system. A viewing stand was fabricated and installed next to the 1 million gallon pond at the west end of the site. Visitors can see all elements of the surface plant from the stand without entering potentially hazardous areas of the plant. Finally, a small area in front of the Operations Building was paved with asphalt for visitor parking.

Scientific And Engineering Support Task Area

Engineering and Development Activities

Reservoir Engineering: The reservoir engineering activities related to this project entail developing an improved understanding of the fracturing geometry and thermal flow characteristics of the Fenton Hill HDR reservoir, as well as the engineering work directed toward controlling all aspects of reservoir operation and performance. In addition, an effort is being made to develop engineering information relevant to HDR reservoirs in general. This activity area utilizes the results of geochemical, seismic, modeling, and logging work to advance the level of understanding of HDR reservoirs.

During this year, a great deal of reservoir engineering effort has been concerned with the pressurization experiments at Fenton Hill. The details of that work have been discussed earlier in this report. In addition, data generated during the pressurization experiments of the past year have been used to determine other important characteristics of the Fenton Hill reservoir as described below:

Fluid Storage Partitioning in Joints and Microcracks: The Fenton Hill Phase II reservoir was shut in from late May to early August, 1990. As shown in Figure 9 (page 35), the reservoir pressure declined from 19 MPa to 9.8 MPa during this time. This was primarily due to venting of reservoir fluid through the annulus leak in the injection wellbore. This shut-in phase was followed by rapid repressurization of the reservoir.

Figure 12 shows the reservoir pressure profile during the last five weeks of the shutin period and the first two days of the subsequent repressurization stage during August 1990. Over the last three weeks of the shutin period, the reservoir pressure was declining at a rate of 0.061 MPa (8.86 psi) per day. The outflow through the injection wellbore annulus during this time averaged 2.58 gpm. The initial rate of pressure increase during the subsequent repressurization step was 1.39 MPa (201 psi) per day at a fluid injection rate of 19 gpm. Thus the rate of pressure increase exceeded the preceding pressure decline rate by a factor of more than 20.

The above data can be used to separately determine the volume fractions of fluid storage within the dilated joints of the reservoir and in the microcracks of the reservoir at a mean reservoir pressure of 10.5 MPa, if the following assertions are employed: (1) during the very slow reservoir depressurization stage, fluid flowed from storage out of both the matrix microcracks internal to the rock blocks comprising the reservoir and the joints between these blocks in essentially a pressure equilibrated manner; and (2) during the initial part of the subsequent rapid reservoir repressurization, fluid was stored almost completely in the interconnected set of joints. Over a short period of time, these two assumptions would be expected to be valid due to the very large (at least several orders of magnitude) difference between joint and matrix permeabilities.

Figure 12. Reservoir pressure profile during July-August 1990.

On the basis of the data and assertions, the fraction of the reservoir fluid stored in the microcracks under steady state conditions at 10.5 MPa is calculated to be 0.73 while that in the joints is 0.27. Thus in what seems to be a counterintuitive result for a fractured HDR reservoir, almost three-fourths of the reservoir storage may be found in the microcracks.

As discussed in the FY90 HDR Annual Report, the flow-connected reservoir volume has been calculated to be about 20 million cubic meters for a measured fluid storage increase of 2,715 cubic meters. If 73% of the fluid is stored in microcracks, then the volume of the microcracks would be about 2,000 cubic meters or about 0.01% of the total reservoir volume. As a point of comparison, the measured rock porosity of cores taken during drilling at Fenton Hill at a depth of 2.9 km (the Phase II reservoir is centered at 3.6 km) was 0.013%! The agreement between these two results is quite remarkable.

While storage partitioning at pressures in the range of 10 MPa appears to be largely in the microcracks of the reservoir rock, different factors appear to control storage at higher pressures. Figure 13 is a detailed graph of the reservoir pressurization profile during November 1990. It consisted of a period of gradual increase in pressure, a rapid pressurization stage, a long period of gradual depressurization, and, finally, a period of rapid pressurization at the end of the month. The course of events was largely influenced by mechanical problems, but the information generated has proven to be of great value in understanding the nature of reservoir storage at pressures somewhat above 15 MPa.

Figure 13. Detailed profile of reservoir pressure during November 1990.

For purposes of this analysis, the important times are the period of slow reservoir depressurization during November 13-15 and the rapid repressurization stage on November 17-18. Relevant data from these two stages of the experiment are summarized in Table 1 below:

Table 1
Reservoir Pressure and Flow Data

	<u>Slow Deflation</u>	<u>Rapid Inflation</u>
Rate of Pressure Change, psi/day	4.3	134.4
Net fluid inflow or outflow, gpm	0.42	12.12
Pressure Change/Fluid Storage Change, psi/day/gpm	10.2	11.1

These results imply that, at reservoir pressures in the range of 15-17 MPa (2460 psi) (about 16.4 MPa [2380 psi] average), there is no appreciable difference in slow and rapid reservoir pressurization. This is in sharp contrast to the observations for reservoir behavior at a pressure of 10.5 MPa. The above data strongly suggest that matrix microcracks are not contributing to storage at reservoir pressures above about 15 MPa. That is, microcrack storage appears to saturate at a reservoir pressure of about 15 MPa or less.

Other experimental results as well as mechanical deformation models support the above conclusion. Table 2 shows the measured reservoir inflation data for three pressure intervals during the extended pressurization experiment.

Table 2
Measured Reservoir Volume Increases During Expt. 2077

<u>Pressure Range</u> MPa	<u>Stored Water</u> <u>Volume Increase</u> Cubic Meters (gallons)	<u>Press. Change/Vol. Change</u> MPa/Cubic Meter
0.0 to 7.5	2140 (566,000)	285
7.5 to 15.0	2715 (717,000)	362
15.0 to 19.0	618 (163,000)	155

As shown, the volume increase over the interval 15.0 to 19.0 MPa differs markedly from the trend set in the range 0.0-15.0 MPa. These data show that, up to about 15.0 MPa, the differential volume growth of the reservoir increases with pressure (the increase in volume over the range 7.5-15.0 MPa is greater than that over the range 0.0-7.5 MPa), a result which has been previously observed and which is a direct consequence of nonlinear, pressure dependent joint and microcrack dilation.

When the reservoir pressure is increased above 15 MPa, however, this trend does not continue. As indicated by the data in Table 2, a dramatic decrease in the rate of additional fluid storage occurs instead. This change in reservoir storage behavior by more than a factor of 2 supports the assertion that, at pressures greater than about 15 MPa, additional fluid storage is almost entirely in the joints, while microcracks are the predominant fluid storage medium below that pressure.

These findings have important implications for the operation of HDR reservoirs since the process of storing fluid in the microcracks is relatively slow while storage in joints can be effected rapidly. Thus in any type of cyclic operation of an HDR system, it would normally be desirable to keep the pressure on the low side of the cycle at a level high enough so that joint storage still predominates in order to maintain a tighter control over reservoir performance parameters.

Joint Spacing in the Fenton Hill Phase II Reservoir: The problem of determining the spacing between the open joints of an HDR reservoir is extremely important to an adequate understanding of the thermal and flow performance of the HDR system. Unfortunately, there is presently no adequate method for accomplishing this, and while estimates of the joint spacing in the Phase II HDR reservoir have been made in the past, they were based on conjecture and tenuous reasoning. As might be expected with such arbitrary input, they have ranged over several orders of magnitude.

Measurements obtained from the extended reservoir pressurization experiment during FY91 may provide a basis for a more rational quantification of joint spacing in the Phase II HDR reservoir. The starting point of such an analysis is the measured incremental fluid storage between the joints and microcracks discussed above. As stated there, at 10.5 MPa approximately 73% of the incremental fluid storage in the reservoir fills microcracks while only 23% goes into the joints.

If it is assumed that on average this storage partitioning holds true over the range 7.5-15.0 MPa, then the measured incremental storage of 2715 m³ for that interval would be distributed as 1979 m³ in the microcracks and 736 m³ in the joints.

Seismic analyses show that the Phase II reservoir is an oblate spheroid in shape. On the basis of this shape and a flow-connected volume of 20 million cubic meters, as determined experimentally in earlier phases of the extended pressurization experiment, a reservoir face (or side) area of 133,000 m² can be postulated. Using this face area in conjunction with the incremental volume, an incremental joint opening of 5.5 mm between pressures of 7.5 and 15.0 MPa can be calculated.

Unfortunately, there is no unambiguous way of assigning this total joint opening in the reservoir to one or more joints. Relevant tests of joint compliance reported in the literature have shown total deformations for loads up to 30 MPa ranging from 0.12 to 0.22 millimeters. Using this range in combination with a Gangi joint-opening law, and with assumptions on joint opening based on previous experience at Fenton Hill (some joints open at 15 MPa while others, perhaps equal in number, do not open until about 22.5 MPa), one can calculate that the most probable range of joint spacing in the Phase II HDR reservoir is 4-8 meters. Work now underway using the FRACNET model will enable us to better quantify the actual joint spacing in the near future on the basis of flow impedance and tracer data.

Modeling: Modeling enables us to predict the performance of HDR systems and aids in the selection of operating parameters for the conduct of various test programs. Modeling is perhaps the best method for "seeing" into the future. The development and implementation of realistic models is therefore critical to the sound evaluation of HDR resources, the design of HDR plants, and the operational plans for HDR facilities. Work this year has continued to emphasize the development of models which can explain reservoir behavior and testing of these models by application to the Fenton Hill Phase II reservoir and our experience with it.

The FRACNET Model: The FRACNET computer code simulates fluid flow and solute transport in fractured media. While this model was initially developed for steady-state conditions, recent work has been directed toward the simulation of transient fluid flow and transport. Early in 1991, a fracture network and rock matrix mesh was set up to simulate the extended reservoir pressurization experiment. This modeling study differed from previous work by explicitly treating the diffusion of fluid into and out of the matrix.

The fracture network model was then applied and modified until it yielded a fit to the production wellhead pressure data from the first 100 days of the extended pressurization test. During this time, measured wellhead pressures ranged from 0-15 MPa (0-2175 psi) (equivalent to actual reservoir pressures of 30-45 MPa [4350-6525 psi] after the inclusion of the hydrostatic head on the reservoir). As pointed out above, unlike previous work, this modeling study explicitly treats the diffusion of fluid into and out of the matrix.

This model has been formulated on the basis of the HDR reservoir concepts developed by Don Brown in previous work. Thus, simulations with it should be regarded as calibrations to these concepts rather than validation of them. The goals of these simulations are to determine the values of reservoir permeability parameters and evaluate their reasonableness, as well as to provide a more detailed and quantitative explanation of the flow characteristics observed during the extended pressurization experiment. After simulation of other phases of this experiment and of other tests at high flow rates, the model, by then well-calibrated, will be used to make performance predictions for operations of the reservoir under a variety of scenarios.

The two-dimensional fracture network employed in this model is similar to that used in previous work. The third (unmodeled) dimension is fixed at 350 m on the basis of seismic data acquired during fracturing at Fenton Hill. The fractured volume of 20 million m³ is similar to the value estimated by Don Brown using rock mechanics arguments. The fractures consist of two sets, which dilate according to Gangi's fracture opening law, but at different opening pressures due to differences in orientation. The fractures are truncated in each dimension so that only tortuous pathways exist from one end of the reservoir to the other.

Near each wellbore, a fracture cluster exists which connects it to the remainder of the network. In the future, the properties of the fractures in these cluster regions will be adjusted to account for the large pressure drops which occur as a result of converging and diverging flow fields near the wellbores. Injection occurs in a cluster near the center of the fracture region, while the monitoring well during the extended pressurization experiment, the production well, is located in a cluster region positioned in the southern half of the reservoir.

Overlapping the fractured region, and extending beyond it, is a finite difference grid in which matrix flow and interactions between fractures and matrix are simulated. The matrix properties of interest are permeability and porosity, both of which are pressure dependent and are given values to match the data. Figure 14 shows the match to the data for the first 100 days of the extended pressurization experiment. To achieve the match shown, the fracture and matrix properties were adjusted simultaneously, subject to all of the conditions specified by Brown's work of the last two years. The characteristics of interest, all of which are well simulated by the model, are as follows:

Rapid response of the production well to pumping at the injection well. (This was obtained in the model by adjusting fracture aperture parameters.)

Figure 14. Match of FRACNET Model results to experimental data.

A rate of pressure rise during constant injection which matches that observed during days 0-11 and 33-60 of the extended pressurization experiment. (This match required that the fracture and matrix parameters be set so that the proper pressure rise for the additional amount of fluid stored in the joints was continuously obtained as the pressure increased.)

An adequate simulation of the constant pressure plateau stages of the test during days 11-30 and 60-90. (Since it is presumed that no additional storage in the fractures took place, accurate modeling of the leakage into the rock matrix was essential to matching the model to observed results during these periods.)

An adequate simulation of the pressure decline during the short shut-in periods on days 33 and 60.

One additional constraint was imposed on the model: The fracture volumes at typical circulation pressures were fixed in the range which had been previously calculated on the basis of tracer measurements made during actual circulation tests. Finally, although permeability and porosity data taken on cores from the Phase II reservoir were not used to constrain these parameter values in the model, the relevant model values are consistent with the core data within the level of uncertainty associated with such measurements.

Figure 15 shows the initial stage of the extended pressurization experiment in more detail. The solid line is the average input flow rate schedule for the experiment. This flow is divided

into two portions, with the dashed curve representing the fluid going into storage in the fractures and the dotted curve depicting the fluid which leaks into the rock matrix. During the two periods of constant pressure (days 11-30 and 60-90), the fluid injection rate is in balance with fluid flow into the matrix, as expected. The flow rate into the matrix was still finite at the end of each pressure plateau stage, implying that the matrix had not yet been saturated in either case. During periods of increasing fracture storage (days 0-11 and 33-60), an initial increase in the flow rate into the matrix overtakes that going into fracture storage, thus illustrating the need for the model to account for fracture/matrix interactions. Clearly, allotting all the fluid injected during this period to fracture storage is incorrect.

Figure 15. Details of the initial stages of the extended pressurization test.

Based on the above considerations, an effort was made later in 1991 to use data from the next 200 days of the extended pressurization test to further evaluate the model. However, it did not accurately reproduce this additional experimental data. It is now being revised in light of the discrepancies between the experimental data and the model predictions for days 100-300, in an attempt to incorporate parameters into it that will maintain the excellent fit to the early experimental data and at the same time provide better agreement with the succeeding part of the experiment.

An enhancement to the model to incorporate solute transport was also developed this year. This feature will allow us to test the model by simulating the results of tracer and inert chemical species (such as the chloride ion) data collected in a variety of tests at Fenton Hill. It should show whether our view of the behavior of these species, which is based on chemical engineering considerations, is consistent with our current model of fluid flow. We know from our experimental observations that some inert dissolved species remain at high concentrations over long periods of time even when the reservoir fluid is being constantly diluted with make-

up water, in spite of the fact that the species should not be produced by rock-water interactions.

The current hypothesis is that a large source of concentrated fluid exists in the pores of the rock, and this is continually diffusing into the circulating water in the open joints. This new model is based on long residence time fracture paths and a fluid filled joint matrix. A match between the model and our experimental data could allow us to predict future concentrations of certain dissolved species of operational interest (such as dissolved gases) and provide valuable insight into the fluid flow and transport processes occurring in the reservoir. A working version of the new computer code modules has been produced, and the new model has been tested for transport in the matrix. The new code agrees with the results of an existing one-dimensional transport code for the case of an adsorbing solute in a steady-state flow field.

Modeling of the remainder of the extended pressurization experiment is continuing. It is important to determine fracture and matrix parameters appropriate for pressure increases above 15 MPa, as well as to generally develop further confidence in the adequacy of the model. When this has been done, data from the initial closed-loop flow test (ICFT) and other high-flow injection periods will be employed to fine-tune the parameters which are used to describe the fracture clusters directly connected to the wellbores, since these are not well-constrained by modeling the data from the extended pressurization experiment. Finally, the calibrated model, with an enhancement to simulate heat transfer, will be used to predict system performance as described above.

The GEOCRACK Model: Professor Daniel Swenson of the Mechanical Engineering Department has been leading an effort at Kansas State University to develop a finite element, fully coupled rock/fluid/thermal model of geothermal reservoirs that can be used as a tool in design and feasibility work on HDR systems. This modeling effort complements multiphase-flow and fluid-flow-in-fractures work being done at Los Alamos. During the summer of 1990, a graduate student from KSU worked at Los Alamos to apply this model, which has been given the name "GEOCRACK," to a variety of problems and adapt it to the SUN computer work-station used by Los Alamos. This past year, another graduate student became involved in the effort.

The model utilizes a discrete approach wherein each joint and rock block, including the deformation of the rock and connecting joints, is separately considered. Two analyses, structural and fluid, are separately calculated. Information is sequentially transferred between the two calculations in an iterative manner until the calculated results converge. Coupling of the analyses is appropriate because the flow of the fluid depends on the opening of the joints, but the opening of the joints depends on fluid pressure. This coupling is highly nonlinear since the permeability of the joints is a cubic function of joint opening. In addition, other nonlinear terms arise from joint opening stiffness and boundary conditions applied in the fluid analysis portion of the model.

Experience has demonstrated that for steady-state problems convergence generally occurs within five iterations. The model is now being applied to calculations of transient situations (injection of fluid into a geothermal reservoir, for example) where convergence is much more drawn-out due to the additional terms that must be included in the calculations. Development has now proceeded to the point where verification analyses are underway. Initial results show good agreement with earlier analytical solutions for one-dimension fluid flow in a single loaded joint. This means that application of the technique to the more complicated situation of a realistic HDR reservoir can now proceed with some confidence.

Seismology: Seismic science has been a key element in determining the size, location, and orientation of the Fenton Hill Phase II HDR reservoir and in ascertaining the conditions which lead to reservoir growth. Seismic surveillance is one technique for continually monitoring the reservoir and assuring that no detrimental environmental effects result from the work at Fenton Hill. Seismology will also play a critical role in the development of future HDR systems by providing a means to accurately map reservoir formation and locate drilling targets.

No new seismic data was collected during this past year, but seismic monitoring continued at Fenton Hill, some equipment upgrades were implemented, and significant work was carried out to improve the accessibility, quality, and usefulness of the vast amount of data collected in earlier experiments. The monitoring effort confirmed that the reservoir continues to be aseismic at pressures as high as 19 MPa (2750 psi) or more.

As part of the effort to make seismic information more manageable and available, transfer of the data collected during the massive hydraulic fracturing (MHF) operation to optical disk from the magnetic tape media on which it was originally stored continued. As of the end of the year this massive task had still not been completed. The data is still used extensively for waveform analyses and reservoir definition work by increasingly sophisticated analytical techniques.

High quality seismic locations were selected for incorporation into a new video which will show the temporal and spatial evolution of the seismic zone during the MHF. The arrival time of selected seismic events from the MHF was also reassessed by taking advantage of faster computers that permit an analyst to look at the data in more detail. Continued work in this area is producing an ever-clearer seismic picture of the Phase II HDR reservoir. In addition, a reexamination of the locations of the microearthquakes associated with early hydraulic fracturing work in the Phase II HDR reservoir at Fenton Hill, as determined from hodogram information, was begun in an attempt to find a structure that might be embedded in the earthquake locations, but which may have been undetected in earlier analyses of the data.

Reservoir Imaging: Imaging the reservoir using tomographic techniques, which have led to significantly improved reservoir definition, continued this year. One area of interest has been the degree to which the smoothing imposed on the final velocity model during the tomographic inversion affects the final results of the inversion process. Smoothing is imposed during the

inversion to provide a more realistic model of the reservoir and to help reduce the degree of non-uniqueness in the inversion.

As part of this effort, we made plots of tomograms obtained from results of inversions that used constraints requiring a highly smoothed model as well as results from inversions made using constraints that employ relatively little smoothing. Plots of the reservoir structure at seven horizons located 100 meters apart in depth were constructed. The major features of the structure appeared in both tomograms. In fact, the similarity of the two sets of tomograms was quite remarkable, leading to the conclusion that smoothing to the inversion calculations does not significantly affect the results.

Work was then concentrated on developing methods to constrain the velocities determined by tomographic techniques from micro-earthquake signals. Because the data are obtained from only a few seismic stations, as many reasonable constraints as possible must be applied to the final model to limit the degree of non-uniqueness. The constraints that had been used previously included a penalty for velocities above the velocity in the unfractured rock and a penalty for spatially rough velocity models.

Previous results had physically unrealistically low P-wave to S-wave velocity ratios (V_p/V_s). These may have been the result of anisotropy in the rock, but more likely were due to the P wave velocities being poorly resolved. The best way that has been found to constrain V_p/V_s to physically realistic values has been to constrain the ratio in the inversion process by use of a penalty function. The penalty that was implemented is similar to the one used to constrain velocities to below a predetermined maximum value.

This new penalty technique has been found to work very well. The overall decreases in the velocities determined with this new function are physically more plausible, and the P and S wave velocity models show more correlation than was obtained without the constraint.

We also calculated the volume of the portion of the reservoir in which the velocity was below a specified value. This is a measure of the volume of reservoir rock which has been disturbed by fluid injection. We found that these volumes were about the same regardless of the amount of smoothing imposed on the inversion.

In an effort to improve data quality, a method to evaluate the quality of micro-earthquake location to allow the selection of the best located events for use in tomographic analyses was investigated this year. Using criteria developed on this basis, approximately 4,000 events have been selected as having the best defined locations from a pool of 11,000 initial event locations. The spatial distribution of these selected locations is now being evaluated.

Tomographic work in the area of seismology was supported at the Laboratory during 1991 by funding from the DOE Office of Basic Energy Sciences under Bill Luth. It is reported here

because it uses data generated in the HDR Program and is of interest as a means to increase our capability to quantify HDR reservoir characteristics.

Waveform Stacking: Early in the year, the first results were obtained from a novel form of waveform stacking that can be used to determine detailed velocities of seismic signals from microearthquakes in small volumes of an HDR reservoir. A set of 50 microearthquakes was used for this initial study. These were selected from 80 that occurred in a cube, 100 meters on each edge, during a period of about 1.5 hours in the early part of the massive hydraulic fracturing experiment in December 1983.

Initial results of the stacking method showed a P wave velocity of 5.2 km/sec and an S wave velocity of 3.2 km/sec in the 1 million cubic meter cube. These are considerably lower than the intact rock velocities of 5.9 km/sec and 3.5 km/sec expected for P and S waves, respectively.

Later in the year, work was directed toward stacking of seismograms to identify signal scattering features in the HDR reservoir at Fenton Hill. The goal of this effort was to identify scatterers that may be fractures. The first imaging of seismic scatterers in the interior of a hydraulically stimulated rock volume using seismogram stacking techniques has now been accomplished. Stacking was done at points 10 meters apart throughout a cube 1 km on a side using seismograms from 90 microearthquakes. The microearthquakes were selected for similarity of waveform character, and their locations were widely distributed through the volume of the stimulated rock. This stacking is a form of seismic migration, with arrivals moved to the positions of possible scatterers. Stacking with a grid of points is envisioned as a reconnaissance step in which planer scatterers can be roughly identified so the microearthquake positions and orientations can be more fully determined by subsequent stacking along planer scatterers.

The presence of planer scattering features was expected since several event planes had been identified previously in this data set by statistical analysis of micro-earthquake locations. The images, however, show more tubular features than anticipated, suggesting that joint intersections may play a prominent role in the conduction of fluids in the reservoir. Although contamination by processing artifacts has been partly ruled out, some problems of this nature may still affect the current images. Test images using synthetic data will help to further elucidate the possible role of artifacts.

Geochemistry and Tracers: Geochemical analysis provides an important means for monitoring the quality of the circulating geofluid and assessing the interactions of the circulating water with the reservoir rock. Tracers are used to estimate the size of the reservoir, to obtain information about fluid flow paths, and to provide experimental data on which to base predictions of the thermal lifetime of the reservoir. Geochemical and tracer work at Los Alamos this year has been concentrated on preparing for the long-term flow test.

In addition, a program to study rock-water interactions in simulated HDR systems was initiated at the Massachusetts Institute of Technology (MIT).

Preparations have now been completed for the collection of geochemical samples and on-line geochemistry data acquisition during the long-term flow test of the Phase II HDR reservoir. These have included the following:

- * Installation of software and hardware/software interfaces for the collection of radioactive tracer data.
- * Acquisition and calibration of on-line measurement probes for pH, electrical conductivity, etc.
- * Construction and testing of a system for measuring gas and liquid flow rates in a small side-stream of the surface loop. This will facilitate the determination of the fractions of gas and liquid in the circulating fluid.
- * Installation of software for general chemical data acquisition and provision for transmission of this data to the central data acquisition facility.
- * Acquisition of specialized software for converting the raw data from gas chromatographic analyses to a more useful form.
- * Production of drawings of the geochemical sampling equipment.
- * Revamping of the equipment for injecting radioactive tracers to allow its operation under the conditions of high pressure injection anticipated during the long-term flow test, including the revision and formal approval of the standard operating procedure (SOP) for this work.

Temperature-sensitive tracers especially designed for use in circulating geothermal fluids were developed at Los Alamos several years ago. During the past year, the detection limits for these tracers were reduced even further to levels of well under 1 part per billion. We anticipate that the first field applications of these tracers will take place in 1992 as part of the analysis program implemented during the long-term flow test.

Samples of storage pond water were collected and analyzed this year in support of the Fenton Hill environmental and water quality surveillance effort.

MIT Work on Rock-Water Interactions: Early in the year, the Massachusetts Institute of Technology began a study of rock-water interactions to determine the reactions of typical HDR reservoir rock with water at a variety of temperatures, pressures, and pH values. The aim of this work is to better understand the effects of circulating water on the HDR matrix rock by

simulating realistic reservoir conditions in laboratory experiments. Eventually it is hoped to evaluate specialized water sources such as treated sewage and ocean waters, for example, to determine their suitability for use in HDR systems.

Much of the year was spent putting together the equipment necessary to perform dynamic dissolution experiments under high pressures and temperatures and in obtaining baseline data. Initial work confirmed that quartz dissolution rates determined in the apparatus built for this work are in agreement with earlier data. These first experiments were carried out using de-ionized water at relatively low temperatures. The results have been added to the existing data base and have set the stage for tests at higher temperatures and in different media. Recently, experiments have been initiated to explore the effect of pH on quartz dissolution. This work should provide experimental data on the suitability of water from a variety of novel sources for use in HDR systems.

Technology Applications

Technology Transfer Activities: A concerted effort was undertaken in 1991 in working with industry, the media, the public sector, and other relevant parties to disseminate information about HDR and to promote the transfer of the technology to private industry. A total of about 200 official visitors from outside the Laboratory were briefed on the program during the year in 43 separate visits. There were 22 foreign visitors from 7 countries, including Japan (5), England (3), Germany (2), France (6), The Netherlands (1), Italy (3), and Switzerland (2).

Industrial Interactions: Two industrial reviews of the design of the long-term flow test program were conducted to assure that this experiment would be carried out in such a way as to provide the maximum amount of useful information from an industrial viewpoint. One meeting was set up by the National Geothermal Association; it included attendees from a number of geothermal companies, utilities, The Electric Power Research Institute (ERPI), and the California Energy Commission.

The second review was carried out by the Hot Dry Rock Program Development Council. This group meets periodically to discuss the status and future of the Los Alamos HDR Program. It consists of a number of representatives from industry and regulatory boards, as well as several members of the academic sector. In response to the advice received during these two reviews, the long-term flow test plan has been significantly modified in order to emphasize continuous production of energy under commercially realistic conditions.

A number of industrial representatives visited Los Alamos during the year to discuss HDR, and most of them toured the Fenton Hill site. Two groups of visitors are of particular note. In September, five members of the International Association of Drilling Contractors spent a day at Fenton Hill reviewing all aspects of HDR and its potential for reviving the drilling and services industry. We have been in subsequent contact with the organization and have made further presentations. During July and August, the Energy and Minerals Field Institute of the

Colorado School of Mines brought a total of 55 visitors to Fenton Hill. These included a substantial number of high level industrialists as well as media people, academicians, and public officials.

The program also hosted a number of individual visits from private industry interested in finding out more about HDR. These included people from oil drilling and service companies, utilities, large construction organizations, and the only private company actively working in HDR that we are aware of.

Media Interactions: Numerous fruitful interactions with a variety of media representatives this year resulted in widespread publicity for the HDR Program. Five (5) print and five (5) broadcast people visited Los Alamos and Fenton Hill, and telephone interviews were conducted with a dozen other reporters. Upon request, printed materials and visuals were sent to numerous organizations.

Stories about HDR were run in at least a dozen widely distributed popular and trade publications. Discover magazine featured HDR in a two page story in its "Energy Watch" section. The Denver Post used HDR as a lead article in one of its Sunday business sections. The Electric Power Research Institute Journal touted HDR as the predominant renewable resource in the west in a long article on renewable energy. Significant stories on HDR also appeared in Business Week, Science, Mechanical Engineering, Oil Daily, Electric Power and Light Bulletin, Geothermal Resource Council Bulletin, California Division of Oil and Gas Hot Line, and an Ingersoll-Rand Company publication. Undoubtedly, there were a number of other articles on HDR during 1991 that have not come to the attention of the HDR Program Office.

Segments about HDR were featured on two Albuquerque television stations this fiscal year. Several of the visitors and interviewers from the broadcast industry were from outside the state and the nation, so it is likely that stories including segments on HDR were also aired at other places around the world. A new video discussing HDR was produced toward the end of FY91. It has since been distributed to several organizations for their use in putting together programs on HDR.

Education and Academia: The HDR Program was also active in the educational and academic areas this year. A group of 11 Kellogg Fellows, selected from around the nation for their leadership in education, were briefed on HDR and visited the Fenton Hill site. College students working at the Laboratory as part of the DOE sponsored Science and Engineering Research Semester were also exposed to a half-day of HDR, as were high school students participating in project SEED, an educational effort of the American Chemical Society. In addition, faculty members from a number of universities were briefed on HDR during Laboratory visits.

Governmental Interactions: HDR was one of the topics addressed in the congressional hearing and town meeting sponsored by the office of Senator Jeff Bingaman of New Mexico in Albuquerque, NM, on November 1, 1990. Early in 1991, HDR was featured in a New Energy Technologies Reception put on by the California Division of Oil and Gas in Sacramento, CA. As part of its annual meeting in September 1991, The Energy Council featured an exhibit on HDR and a field trip to the Fenton Hill HDR site. The tour group of approximately 40 people included numerous state legislators and other public officials from a number of energy producing states in the southern and western parts of the country.

A number of visitors from federal and state government agencies visited the Fenton Hill HDR site both individually or as members of the Energy and Minerals Field Institute group mentioned under industrial interactions, above. DOE visitors included Cherri Langenfeld, Director of Technology and Analysis and Acting Director of Technology Utilization; Marvin Brook, Office of Technical Coordination; Jerry Bellows, Manager of the Los Alamos Area Office; Ron Kessler, Director of the Office of Renewable Energy Conversion; and Alan Jelacic and Gladys Hooper of the Geothermal Technology Division. Several visitors from other national laboratories were hosted by the HDR Program at various times during the past year,

Papers and Presentations: Numerous presentations reporting HDR research and development efforts were made at conferences around the world during the past year. These ranged from highly specific technical presentations to broad program overviews. Specific topics and authors are listed elsewhere in this report.

Clearlake, CA HDR Initiative: There has been a longstanding interest in the potential for the development of HDR in the vicinity of the city of Clearlake, CA, which is located northeast of The Geysers hydrothermal field in northern California. A preliminary study in 1987-1988 indicated that an in-depth resource assessment was warranted. Funds for a more complete resource assessment were allocated by the California State Legislature during the summer of 1989. It was not until January 1991, however, that formal approval to proceed with this effort, known as Phase II of the Clearlake HDR Project, was received from the Albuquerque Area Office of the DOE.

A \$225,000 contract, financed by the California Energy Commission (CEC) and implemented through the city of Clearlake, California, provided the funding for the project. The work entails an intensive investigation of the region to examine the potential for the development of HDR resources in the area. Thermal gradients, geologic structures, geohydrology, seismology, surface hydrology, and comparative geothermal regimes are being evaluated. A decision on whether to provide an additional \$55,000 in CEC funds for supplementary well log analyses work was still pending at the close of the fiscal year.

Kerry Burns of Los Alamos is leading this program. The work, which will continue into FY92, will culminate in the issuance of a detailed report on the HDR resources in the

Clearlake area. Phase II of this project may be followed by subsequent stages involving test drilling, reservoir development, and, eventually, construction of a practical HDR facility.

The Clearlake Project provides a good example of local initiative being employed to put technology developed by the DOE to practical use. If successful, it will lead to the development of the local geothermal resource and enhance the economy of the area.

MANAGEMENT

Organization

As shown in Figure 16, the HDR Program continues to be field managed jointly by the Los Alamos National Laboratory (LANL) and the DOE Albuquerque Operations Office (DOE/ALO) under the overall purview of the Geothermal Technology Division of the DOE (DOE/GTD). Gladys Hooper is the DOE/GTD Program Manager, George Tennyson is the DOE/ALO Field Manager, and David Duchane is the Los Alamos Program Manager. The Program Development Council (PDC), chaired by Robert Greider, meets periodically to offer industrial and academic perspectives on the course of the program.

Figure 16. HDR Program Management Structure.

Frequent contact is maintained among the organizations involved in managing the HDR Program in Los Alamos, Albuquerque, and Washington. At Los Alamos, David Duchane became Program Manager for the HDR Program in February 1990. He works closely with the Associate Directorate for Energy Technology, the EES Division Office, and the EES-4 Group Leader in directing the Los Alamos effort. Los Alamos management entails both direct program management and management support and services.

Direct program management involves the responsibility for overseeing, controlling, representing, and communicating on behalf of the HDR Program in both the technical and administrative areas. Responsibilities in this area include the following activities:

- Providing day-to-day programmatic direction to functional personnel.
- Carrying out technical and fiscal planning including preparation of the Annual Operating Plan (AOP), plans for the LTFT and for major experiments, and budgetary accounting analyses.
- Communicating program information both informally and by means of written reports and semiannual presentations to the DOE/GTD.
- Supporting requests from the DOE/GTD for programmatic information or other input.
- In concert with DOE/ALO, interfacing with and providing required reports to state and local government agencies and local offices of other federal agencies including the USGS, US Forest Service, EPA, BLM, New Mexico State Engineer's Office, and New Mexico State Bureau of Economic Geology.
- Assisting the Los Alamos Area Office of DOE in the processing and approval of major subcontracts and procurements and supporting that office in the settlement of any claims or labor disputes arising in connection with the HDR Program.
- Maintaining liaison with other HDR-related programs and relevant industrial organizations.
- Fostering the transfer of HDR technology to industry.
- Providing information and tours to governmental, industrial, and institutional visitors as appropriate.
- Conducting reviews of the HDR Program with the HDR Program Development Council.
- Coordinating the HDR Program with other LANL Programs.
- Representing the HDR Program to LANL upper management and other Laboratory organizations.

Management support and service functions include:

- LANL upper management attention to HDR Program matters, as required.
- Procurement, personnel, security, and legal services.
- Editorial and publication support.
- Fiscal and accounting support.

Interfaces

As described above, Los Alamos management interfaces with the DOE at several levels, as well as other federal agencies including the USGS, US Forest Service, Environmental Protection Agency, Bureau of Land Management; state government organizations such as the New Mexico State Engineer and New Mexico State Bureau of Economic Geology; and local governments.

Frequent interfaces with business, industry, and the press arise out of technology transfer activities, which may take the form of visits, phone calls, written correspondence, etc. These activities also lead to interfaces with a variety of governmental entities not specifically mentioned above on an ad-hoc basis, as well as a significant number of international contacts. The relationships developed with the city of Clearlake, CA, and the California Energy Commission are particularly noteworthy in this regard.

Attendance at professional meetings, the presentation of papers and talks, program reviews, and meetings of advisory groups such as the Program Development Council entail further interactions with wide segments of the business, technical, governmental, and professional communities. Finally, as described above, intralaboratory interfaces are an important component of the HDR effort.

Contacts

International: Professor Haruo Sato of the Geophysical Institute, Tohoku University, Sendai, Japan, visited Los Alamos during the week of November 26 to confer with Laboratory seismologists.

Dr. Koji Kishida, a research fellow with the Planning Department & New Energy Information Center of NEDO in Tokyo, Japan, visited the Laboratory in late November.

Dave Duchane and Don Brown participated in a Hot Dry Rock Geothermal Energy Forum held in Nurnberg, Germany, on June 13-14. The meeting brought together approximately 50 participants from ten countries around the world to discuss all aspects of geothermal energy production from HDR.

On June 11, prior to the HDR Forum in Nurnberg, Don Brown and Dave Duchane visited the European HDR site at Soultz to get a first-hand look at the status of the HDR Program there. After the meeting, on June 15, they both participated in a tour of the German deep scientific drilling project site (the KTB site), which is located about 60 miles northeast of Nurnberg.

Dr. Minoru Oda visited the Laboratory on March 6 to review Laboratory Programs in energy, space, and environmental research. He was given a briefing by Dave Duchane on HDR developments both at Los Alamos and worldwide.

Ron Stewart, a seismologist with the British HDR Program, visited Los Alamos on July 15. He discussed relevant issues with members of the HDR staff and presented a talk on the state of HDR in Britain.

Dave Duchane attended an International Symposium on Energy and Environment in Espoo (Helsinki), Finland, during the last week of August, and presented a paper entitled "Hot Dry Rock: An Alternative Energy Progress Report."

Industrial: On November 27, Wes Myers, EES Division Leader, met with A. Lee Hunt, President, and Ed McGhee, Executive Vice President (Retired), of the International Association of Drilling Contractors at their office in Houston.

Mr. Ed James of Crutcher-Tufts Corporation visited Los Alamos on January 3 for a briefing on the HDR Program followed by a tour of the Fenton Hill HDR site.

Brian Drakely and Michael Carmody of Baker Oil Tools visited Los Alamos on March 6.

Texas Utilities Electric Company is doing an evaluation of HDR technology. At their request, the Los Alamos HDR Program Office sent them information in April to aid them in this task.

On June 6, Dave Duchane joined Alan Jelacic and Gladys Hooper of the DOE Geothermal Technology Division, Nyles Lackey of the DOE Albuquerque Area Office, John Sass of the U.S. Geological Survey, and Ed Kaufman of Kaufman Associates on a visit to a potential HDR site at Nutrioso, Arizona. The local landowner, Harris Crosby, joined the group at the site.

Ed Kaufman of Kaufman Associates visited Los Alamos on July 1 to discuss the outlook for HDR development around the world as reflected at the recent European HDR Forum and the progress of all aspects of HDR in the US.

Brian Wenning, a Senior R&D Engineer with Texas Utilities Electric Co., (also on an advisory committee of the Electric Power Research Institute), visited Los Alamos on July 16 for a tour of the Fenton Hill HDR site.

Bob Taussig, Business Development Manager: Research and Development of Bechtel Corporation, met with Dave Duchane on August 12 to discuss the current state of HDR work at Los Alamos.

A number of representatives from the International Association of Drilling Contractors (IADC) visited the Fenton Hill HDR site on September 16 for a tour and an overview of the HDR Program. Attendees included Mike Killalea of the IADC, Mike Chaney of Ziadrill (Hobbs, NM), Scott Taliaferro of Texas Drilling Co. (Abilene, TX), Gary Hogatt of True Drilling (Casper, WY), and Robert Ritchey of Service Drilling (Tulsa, OK).

Governmental: Dave Duchane presented a review of the potential contributions of HDR to the energy supply of Arizona at hearings of the Arizona Committee on Energy Policy and Planning on October 4 at Tempe, AZ, and, again, on October 18 at Prescott, AZ.

Marvin Brooks of the DOE Fossil Energy Office of Technical Coordination visited the Laboratory on November 6 for discussions on a wide variety of energy efforts carried out at Los Alamos.

Hot Dry Rock was among the energy topics addressed at a congressional hearing and town meeting in Albuquerque, NM, on November 1, sponsored by the office of New Mexico Senator, Jeff Bingaman.

Dave Duchane of Los Alamos and Ed Kaufman of Kaufman Associates met with the Board of Directors and some staff personnel of the Navopache Electric Cooperative at Lakeside, AZ, on November 28. Dave gave the board an update of the Los Alamos HDR program and plans for future experiments at Fenton Hill, while Ed presented the outline of potential HDR development in the area of Nutrioso, AZ.

Jerry Bellows, Manager of the DOE Los Alamos Area Office, was given a briefing on the HDR Program on December 12 by Dave Duchane and Ray Ponden. Jerry then toured the Fenton Hill Site along with John Whetton, Los Alamos Associate Director for Energy Technologies.

Dr. Jane Negus-de Wys of the Idaho National Engineering Laboratory (INEL) visited the Fenton Hill HDR test site on March 27 to get a first-hand look at progress in construction of the surface plant. Dr. Negus-de Wys is associated with the Geopressed Program at INEL.

Alan Jelacic and Gladys Hooper from the Geothermal Technology Division of the Department of Energy visited the Laboratory on June 5. They reviewed the overall HDR Program and discussed the plans being developed for the conduct of the LTFT.

Ron Kessler, Director of the DOE Office of Renewable Energy Conversion, visited Los Alamos on June 19 for an overview of the HDR Program.

Cherri Langenfeld, Director of Technology Analysis and Acting Director of Technology Utilization for the USDOE, visited the Fenton Hill HDR site on August 13 for an in-depth tour and review of the HDR Program at Los Alamos including plans and goals for the LTFT.

A DOE Tiger Team evaluation of operations at Los Alamos was conducted during September. As part of this effort, an occupational safety and health (OSHA) inspection of the Fenton Hill HDR site was conducted by a group representing industrial safety on September 26.

Dave Duchane, Jim Albright, and Ray Ponden of LANL presented a review of progress in the HDR Program to an audience of about 15 people at the DOE on October 31.

Non-Profit Organizations and Professional Societies: Mike Foley, Director of Financial Analysis for the National Association of Regulatory Utility Commissioners, met with Dave Duchane on December 15 to discuss possible Laboratory visits in connection with their meeting in Santa Fe during the second week of April 1991.

Kerry Burns presented an overview of the HDR Program at Los Alamos to a meeting of the Los Alamos Rotary Club on March 21.

Lori A. Cameron, executive director of the South/West Energy Council, visited the Laboratory on March 1 along with Norman Falk of the New Mexico Engineering Research Institute at the University of New Mexico. As one part of the Laboratory visit, Dave Duchane presented an overview of the HDR Program to Ms. Cameron and Mr. Falk. Ms. Cameron expressed an interest in making HDR part of the next annual meeting of the South/West Energy Council.

The annual conference of the National Association of Regulatory Utility Commissioners (NARUC) was held in Santa Fe, NM, on April 8-10. Dave Duchane spoke briefly to the conference attendees. A group of 9 conferees from the meeting visited Fenton Hill on Wednesday afternoon, April 10, at the conclusion of the meeting.

A Rotary exchange group consisting of six French visitors was given a tour of the Fenton Hill HDR site on April 15.

On Sunday, August 11, a group of 31 people from the Energy and Minerals Field Institute (EMFI) of the Colorado School of Mines visited the Fenton Hill HDR test site. The group included representatives from the DOE, the Office of Technology Assessment, various other federal agencies, congressional staffers, state agency people, and local government officials.

The South\West Energy Council held its annual meeting in Albuquerque during the first week of September, along with a concurrent symposium on Environmentally Significant Energy Technologies. About 40 attendees participated in a field trip to the Fenton Hill HDR site.

Stewart Udall, former US Secretary of Interior, and Paul Parker, Vice President of the Center for Resource Management, met with Laboratory management of September 17 to discuss the organization of a conference to explore alternative energy technologies with a focus on HDR.

Academic: Dr. Alan Sweedler, a professor at San Diego State University and an affiliate of the Institute on Global Conflict and Cooperation, visited Los Alamos on March 14 to discuss the development of environmental and energy initiatives in the countries of Eastern Europe.

Professor Daniel Swenson of the Kansas State University Department of Mechanical Engineering and two of his students, Mel Beikmann and Robert Du Teau, visited the Laboratory on February 14-15. They discussed the continuing development of the GEOCRACK modeling code for HDR by Kansas State and plans to implement it in modeling relevant flow tests at Fenton Hill and in simulating cyclic operations.

Darold D. Holton, Acting Dean of the Graduate Division and Research at the University of California Riverside, visited Los Alamos on April 22 and was given an overview of the HDR Program by Dave Duchane.

Dave Duchane met with Paul Kruger at Stanford University on May 8 to discuss a variety of issues related to the development of HDR in general and proposals for joint USSR-US HDR programs in particular.

A review of HDR technology and the Los Alamos HDR Program was presented to 18 DOE SERS (Science & Engineering Research Semester) students at Los Alamos by Dave Duchane on May 1. This was followed by a tour of the Fenton Hill HDR facility.

A group of 10 high school juniors and seniors visited the Fenton Hill HDR site on August 1 for a tour arranged by the Laboratory Educational Outreach Office. The students spent the summer at Los Alamos as part of Project SEED, a program sponsored by the American Chemical Society to encourage interest in math and science.

Intralaboratory: On January 9, Dave Duchane presented an update of the HDR Program to the staff of the Los Alamos Science Museum.

An overview of the HDR program was presented to the Earth and Environmental Sciences (EES) Division External Advisory Committee by Dave Duchane on May 13.

On May 14, Don Brown reviewed recent progress in HDR reservoir engineering for the EES Advisory Committee

Media: Maura Reynolds, a reporter for the Los Angeles Times, interviewed Dave Duchane regarding HDR Technology on October 22, by telephone, for a story about alternative energy including geothermal energy.

Richard Twarog, a scriptwriter working for the Los Alamos National Laboratory Museum, was given an overview of the HDR Program and a tour of the Fenton Hill site by Dave Duchane on October 26.

Ray Ponden, Dave Duchane, and Jim Albright were interviewed via a number of phone calls early in December by Mr. Michael Valenti, a writer for the periodical, Mechanical Engineering, which is published by the American Society of Mechanical Engineers.

Steve Conner, a science reporter for the Independent on Sunday, a London, England, newspaper with a circulation in excess of 300,000, visited the Laboratory on November 1 as part of an extended trip to a number of research institutions in the United States. He was briefed on HDR and given a tour of Fenton Hill.

On December 7, Wes Myers, Don Brown, and Dave Duchane participated in a telephone interview with Jim Drummond, a writer for "Oil Daily," a daily publication which reaches a wide audience of oil company managers and executives.

An article on HDR appeared in the "Tech News" section of the January 1991 issue of Mechanical Engineering Magazine, a monthly publication of the American Society of Mechanical Engineers.

Christine McGourty, a reporter for the London Daily Telegraph, conducted a short telephone interview with Dave Duchane on Friday, February 1.

Dan Sterling, an assignments reporter for KOAT-TV in Albuquerque, NM, visited the Fenton Hill HDR site on February 7, to prepare a segment on HDR as part of a series of reports on energy. The story was broadcast shortly thereafter.

Mariel McEwan of The Foundation for the Advancement of Science and Education contacted the Laboratory on February 12 regarding possible participation in one of their projects.

A story on the Clearlake HDR Initiative was prepared by the Laboratory Public Affairs Office and appeared in February 15 issue of the Los Alamos News Bulletin.

John Carey of Business Week Magazine conducted a telephone interview with Dave Duchane on February 22. Mr. Carey was interested in the Clearlake HDR Initiative and the potential for development of HDR at that location.

Bas den Hond, a reporter for the Dutch science publication "Trouw," visited the Laboratory on February 27. He was given an overview of the HDR Program by Don Brown.

Ed Messit, a reporter for the KOB television station in Albuquerque, visited the Fenton Hill HDR site on March 6 to film a story on the HDR Program. The segment was broadcast during the week of March 11.

David Fishman of Discover Magazine conducted a long telephone interview with Dave Duchane on March 5. He subsequently spoke with Don Dreesen regarding HDR drilling technology.

Helen Thomas of the British Broadcasting Corporation conducted a telephone interview with Dave Duchane on March 26. Ms. Thomas was preparing a segment on HDR for the BBC television program "Tomorrow's World."

Frank Pittman of Electric Utility Week called in March to ask a few questions about HDR in response to a news release by the Laboratory on the subject of our new HDR work at Clearlake, CA.

A short article on the HDR Program appeared in the March 11, 1991, issue of Business Week magazine.

Ms. Maura Schafer of Bozell Public Relations contacted the HDR Program Office in April for information regarding HDR and geothermal energy in general. They prepare publications for Ingersoll-Rand.

Information regarding the HDR Program was forwarded to Rock Products Magazine in April at their request.

Several color slides depicting various aspects of HDR technology were forwarded to Discover Magazine during April to be used in conjunction with an article they were preparing on the subject.

An article entitled "Underground Electricity Production Explored in California" appeared in the May, 1991 issue of the Magazine, "Electric Power and Light."

The July issue of Discover magazine featured a story on HDR in its "Energy Watch" section.

An article on International Programs in Hot Dry Rock appeared in the May issue of the Geothermal Resources Council Bulletin.

A series of stories on HDR development in various parts of the work were included in the January 1991, issue of the Geothermal Hot Line published by the California State Division of Oil and Gas.

A story on geothermal energy in the July 12 issue of Science magazine discussed HDR in a sidebar feature as one of the potentially large geothermal energy sources of the future.

A feature article on the front page of the business section of the Denver Post of Sunday, July 28, 1991, described the potential of HDR as a future energy source. The article was written by Adriel Bettelheim, a business reporter for the Denver Post, who visited Los Alamos and the Fenton Hill site on July 14 as part of a field trip by 24 participants in the Energy and Minerals Field Institute (EMFI) of the Colorado School of Mines.

Walter Friedenbergl, Executive Editor, and Bill Waters, Editorial Page Writer and Director of the Santa Fe New Mexican newspaper, were briefed on the HDR Program during a visit to the Laboratory on the afternoon of Friday, July 19.

An article in the second quarter 1991 issue of the Ingersoll-Rand World Report described the HDR Program at Los Alamos in some detail and highlighted the role of Ingersoll-Rand pumps in the surface plant being constructed at Fenton Hill.

The June 1991 issue of the EPRI Journal carried a long article entitled "Renewables on the Rise" which discussed the prospects for renewable energy sources and the preparation of an EPRI "Green Plan" for participation in the development and deployment of renewable energy technologies. It strongly endorsed HDR as the geothermal energy source of the future.

Raffaello Siniscalco of RAI News visited Fenton Hill on September 4 with a camera crew to film material for presentation on Italian state television. Mr. Siniscalco conducted interviews for broadcast. While at Fenton Hill the crew did extensive filming of the surface plant.

Dan Metger, a freelance journalist, and Birget Schneider, a photographer, conducted an intensive interview and did extensive photographing as part of a tour of the Fenton Hill HDR site on September 11. They prepare articles for German language publications in Germany and Switzerland.

Video material on HDR was sent to Lauren Millar of The Science Edition at TV Ontario in Toronto, Canada, for incorporation into a broadcast she was putting together.

Information about HDR was sent to Eric Brus of World Information Systems in September for inclusion in a book about alternative energy sources.

A short article on HDR has been prepared by a writer for "Super Science," a children's magazine. It will be published in the January 1992 issue.

Meetings

Dave Duchane attended a symposium on the topic of the underground injection of geothermal fluids, sponsored by the Underground Injection Practices Council and the U.S. Environmental Protection Agency at Santa Rosa, California, on October 29.

Kerry Burns attended a seminar in San Francisco on the broad subject of financial management of geothermal projects on November 16-18. The meeting was presented by Infocast, Inc. and sponsored by the Geothermal Resources Council.

On January 23-25 Don Brown and Dave Duchane attended the Sixteenth Annual Workshop on Geothermal Engineering at Stanford University.

Hot Dry Rock was the focus of a "New Geothermal Technologies" reception sponsored by Beverly Hanson, assemblywoman from the eighth district of the California Legislature on January 22.

Dave Duchane attended a Utilities Sector Field Planning Workshop at the Solar Energy Research Institute on February 25-27.

A number of representatives from Los Alamos attended the DOE Geothermal Review IX meeting in San Francisco on March 19-21. Dave Duchane, Ray Ponden, and Don Brown presented papers entitled "Moving HDR Toward Commercialization," "The Design and Construction of a Hot Dry Rock Pilot Plant," and "Progress in HDR Reservoir Engineering," respectively.

On March 19, Dave Duchane attended a workshop in San Francisco on the subject on implementing public policy for geothermal energy. The meeting was sponsored by the National Geothermal Association.

Dave Duchane and Ray Ponden attended a course on power generation from low temperature geothermal resources held at Reno, Nevada, on May 6-7. A variety of low temperature power plants (primarily based on binary technologies) were described and discussed.

On May 9, Dave Duchane attended a workshop on the potential for geothermal energy development in the 21st Century. The program centered on the prospects for development of hydrothermal resources, but many of the issues raised were also relevant to the further development of HDR.

On July 18, Dave Duchane, Jim Albright, Don Brown, and Ray Ponden of the Laboratory HDR staff, and Charryl Berger of the Laboratory Industrial Applications Office met with industrial representatives at the Clarion Hotel in San Francisco to review the HDR long-term flow test plan.

The Program Development Council meeting was held in Albuquerque on July 25. A visit to the Fenton Hill HDR on July 24 preceded the formal session.

Mike Fehler attended a Society of Exploration Geophysicists Workshop on "Relating Elastic Properties to Lithology at all Scales" in St. Louis from July 28-August 1. He made a presentation entitled "Characterizing Hydraulically Fractured Reservoirs Using Induced Microearthquakes" which drew heavily on experience with the HDR reservoir at Fenton Hill.

Publications

The following papers were published or accepted for publication during 1991. While all are pertinent to HDR technology they originated from work by a variety of sponsors as shown below:

Work Supported by USDOE Geothermal Technology Division through the Hot Dry Rock Geothermal Energy Development Program.

Brown, D. W., "Recent Progress in HDR Reservoir Engineering," Proceedings of the DOE Geothermal Program Review IX, San Francisco, March 19-21, 1991.

Burns, K. L., "Orientation of Minimum Principal Stress in the Hot Dry Rock Geothermal Reservoir at Fenton Hill, New Mexico," submitted for presentation at the Geothermal Resources Council 1991 Annual Meeting, Reno, Nevada, October 6-9, 1991.

Burns, K. L., "Hot Dry Rock Research -- A Compendium of Publications, October 1989-September, 1990," Hot Dry Rock Geothermal Energy Development Program Annual Report for Fiscal Year 1990.

Duchane, D. V., "Hot Dry Rock Heat Mining: An Alternative Energy Progress Report," International Symposium on Energy and Environment, Espoo, Finland, August 25-28, 1991.

Duchane, D. V., "Commercialization of Hot Dry Rock Geothermal Energy Technology," submitted for presentation at the Geothermal Resources Council 1991 Annual Meeting, Reno, Nevada, October 6-9, 1991.

Duchane, D. V., "Moving HDR Technology Toward Commercialization," Proceedings of the DOE Geothermal Program Review IX, San Francisco, March 19-21, 1991.

Duchane, D. V., "Hot Dry Rock Heat Mining: An Advanced Geothermal Energy Technology," submitted for presentation at the Energy-sources Technology Conference and Exhibition, Houston, TX, January 26-30, 1992.

Ponden, R. F., "The Design and Construction of Hot Dry Rock Pilot Plant," Proceedings of the DOE Geothermal Program Review IX, San Francisco, March 19-21, 1991.

Ponden, R. F., "Performance Testing the Phase II HDR Reservoir," submitted for presentation at the Geothermal Resources Council 1991 Annual Meeting, Reno, Nevada, October 6-9, 1991.

Robinson, B. A., "Alternative Operating Strategies for Hot Dry Rock Geothermal Reservoirs," submitted for presentation at the Geothermal Resources Council 1991 Annual Meeting, Reno, Nevada, October 6-9, 1991.

Swenson, D., Brown, D., and Martineau, R., "A Coupled Model of Fluid Flow in Jointed Rock," 16th Annual Workshop on Geothermal Engineering, Stanford University, Stanford California, January 23-25, 1991.

Work Supported by the California Energy Commission through the Phase II Clearlake, CA, HDR Initiative.

Burns, K. L., "Three-Dimensional Modeling and Geothermal Process Simulation," Proceedings of Conference on 3-Dimensional Computer Graphics in Modeling Geologic Structures and Simulating Geologic Processes, Society of Mathematical Geology, Freiburg, West Germany, October 7-11, 1991.

Burns, K. L., "The Clearlake Hot Dry Rock Geothermal Project: Institutional Policies, Administrative Issues, and Technical Tasks," submitted for presentation at the Geothermal Resources 1991 Council Annual Meeting, Reno, Nevada, October 6-9, 1991.

Work Supported by the USDOE Division of Basic Energy Sciences.

Fehler, M., "Characterizing Hydraulically Fractured Reservoirs Using Induced Microearthquakes," Society of Exploration Geophysics Research Workshop, St. Louis, Missouri, July 28-August 1, 1991.

Fehler, M., House, L., Phillips, W. S., Block, L., and Cheng, C. H., "Imaging of Reservoirs and Fracture Systems Using Microearthquakes Induced by Fluid Injections," submitted for presentation at the Geothermal Resources Council 1991 Annual Meeting, Reno, Nevada, October 6-9, 1991.

Fehler, M. C. and Phillips, W. S., "Simultaneous Inversion for Q and Source Parameters of Microearthquakes Accompanying Hydraulic Fracturing in Granitic Rock," Bulletin of the Seismological Society of America, V81, pp. 553-575, 1991.

Ferrazzini, A., Chouet, Fehler, M. C., and Aki, K., "Quantitative Analysis of Long-Period Events Recorded During Hydraulic Fracturing Experiments at Fenton Hill, New Mexico," Journal of Geophysical Research, V95, 21844-21871, 1990.

House, L., and Phillips, S. W., "Imaging of a Fractured Rock Volume Using Coda of Seismograms from Induced Microearthquakes," submitted for presentation at the 1991 Fall Annual Meeting of the American Geophysical Union, December, 1991.

Phillips, W. S. and House, L., " An Array Method to Estimate Seismic Velocities in a Cluster of Microearthquakes," EOS, Transactions of the American Geophysical Union, 71,1446-1447, 1990.

BUDGET

The budget for the Hot Dry Rock Program over the past four years (FY88-91) and as currently allocated for the next fiscal year (FY92) is summarized below:

HDR Program Budget (\$K)

<u>Task/Project</u>	<u>Fiscal Year</u>				
	<u>1988</u>	<u>1989</u>	<u>1990</u>	<u>1991</u>	<u>1992*</u>
Fenton Hill Site Operations	<u>3876</u>	<u>2465</u>	<u>2471</u>	<u>2483</u>	<u>2593</u>
Phase II Energy Extraction System	3099	1582	1588	1610	1710
Phase II Ancillary Activities	466	284	284	320	300
Test Site Support	311	599	599	553	583
Scientific & Engineering Support	<u>1344</u>	<u>1135</u>	<u>829</u>	<u>817</u>	<u>577</u>
Engineering Development Activities	1130	847	729	725	471
Technology Applications	214	288	100	92	106
<u>Reserve and Miscellaneous</u>	<u>600</u>	<u> </u>	<u> </u>	<u> </u>	<u> </u>
Total	5820	3600	3300	3300	3170

* Allocated as of 1/1/91

A continual decrease in the budget has occurred over the course of this 5-year period, seriously hampering our ability to meet program goals. While the surface plant required for the conduct of the long-term flow test has been completed within this budget framework, it will not be possible to run the test for an extended period of time without supplementary funds.

It is estimated that the FY92 funding level shown above will be sufficient to conduct only about 3 months of continuous flow testing. We are working with the US Department of Energy to obtain the additional funding to permit a full-scale flow test lasting a year or more to be carried out. If such funding is not forthcoming, we shall have to revert to an intermittent test schedule. While short tests can provide much technically valuable data, they cannot answer the fundamental question about HDR regarding the ability to extract energy from hot dry rock continuously over an extended time period.

During recent years, the major part of the funding has been applied to the Fenton Hill Operations Task Area. In FY91, about 78% of the money allocated was spent on Fenton Hill operations. In FY92, this figure is expected to exceed 80% of allotted funds. The effect is to

create a situation in which the scientific underpinning for the HDR facilities is being significantly eroded. In the short run, this means that less than the maximum scientific knowledge is gleaned from the work at Fenton Hill, while in the longer term the technology may founder due to the lack of advancement in the scientific state of the art required to develop it to its full potential.

The budget reduction in FY92, while amounting to only about 3% of total allocated funding, comes on the heels of a record of continual cuts and forces further belt tightening in a program which has already experienced serious staff reductions in the past several years.

FUTURE PLANS

With the surface plant essentially complete, the Fenton Hill facility is ready for a long-term flow test (LTFT) slated to begin early in 1992. In accordance with the advice of our industrial review panels, this test will be conducted at the highest fluid injection pressures which do not lead to reservoir growth. The continuous, steady state phase of this test can be sustained for only about 3 months at scheduled funding levels for FY92. If supplementary funding is not obtained, a low cost program of static testing and/or intermittent flow tests will be conducted until sufficient funds are obtained to resume the LTFT on a programmatically sound basis.

Industrial participation in all facets of the Los Alamos HDR Program will be actively pursued. In addition, cooperation will be extended to any American industrial effort to make use of any of the technological developments arising from this project. Realistically, however, the interest of industry in HDR appears to be very strongly tied to the successful completion of an LTFT of sufficient duration to provide evidence for the potential commercial viability of the technology.

In the longer run, development of a second domestic HDR site and the investigation of advanced operating techniques are essential. HDR can readily meet the Level 1 Objective of providing electric power at costs of 5-8¢/KWh but only if the resources are provided for the work needed to move the technology rapidly forward.

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