Hot Dry Rock Geothermal Energy Development Program

Annual Report
Fiscal Year 1990

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Photograph by Chris J. Lindberg

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**HDR-90-ANNUAL REPORT
JANUARY 1991**

**HOT DRY ROCK HEAT MINING
GEOTHERMAL ENERGY
DEVELOPMENT PROGRAM**

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Prepared by:

David Duchane

**Contributors
Hot Dry Rock Program Staff**

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 provide 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 the 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 FY1990.

The companion volume to this report is a compendium of scientific and technical publications of the project staff during Fiscal Year 1990. The publications are grouped into review articles and technical articles. The compendium is intended to provide the details of the technical information published in this program during Fiscal Year 1990.

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EXECUTIVE SUMMARY

This was a year of significant accomplishment in the HDR Program. Most importantly, the design, construction, and installation of the surface plant for the Phase II system neared completion by the end of the year. Basic process design work has been completed, and all major components of the system except the gas/particle separator have been procured. For this component, previous design problems have been resolved, and purchase during the first half of FY91 is anticipated. Installation of the surface plant is well underway. The system will be completed and ready for operation by the end of FY91 under the current funding scenario. The operational schedule to be followed will then depend upon the program funding level. Our goal is to start long-term flow testing as soon as possible.

Of equal importance, from the standpoint of the long-term viability of HDR technology, during this year, for the first time, it has been demonstrated in field testing that it should be possible to operate HDR reservoirs with water losses of 1-3%, or even less. Our experience in the deep, hot, Phase II reservoir at Fenton Hill is in sharp contrast to the significant water losses seen by Japanese and British scientists working in shallower, cooler, HDR reservoirs. Calculations and modeling based on field data have shown that water consumption declines with the log of time in a manner related to water storage in the reservoir. This work may be crucial in proving that HDR can be an economically viable means for producing energy, and that it is useful even in areas where water is in short supply.

In addition, an engineering model was developed to predict and explain water consumption in HDR reservoirs under pressure, the collection and processing of seismic information was more highly automated, and the detection limits for reactive tracers were lowered to less than 1 part per billion. All of these developments will add greatly to our ability to conduct, analyze, and understand the long-term flow test (LTFT).

Water-rights acquisition activities, site clean-up, and improvements in the 1 million gallon storage pond at Fenton Hill have assured that we will have adequate water to carry out a vigorous testing program in a safe and environmentally-sound manner. The 1 million gallon pond was recontoured, and lined with a sophisticated multi-layer plastic barrier. A large part of the work on the pond was paid for with funds from the Laboratory's Health, Safety and Environment Division.

Almost all the expected achievements set forth in the FY90 Annual Operating Plan were substantially accomplished this past year, in spite of a \$300,000 shortfall in funding. This funding shortfall did delay some work and result in some projects not being completed,

however. We have had to go more slowly than we would like on some aspects of the installation of the surface plant for the LTFT, purchase of non-critical equipment, such as a back-up electric generator for Fenton Hill, has been delayed, and some work has not been brought to an adequate conclusion. The fracture healing work, for example, was completed but not written up. We simply did not have the funds to pay for the effort needed to fully document this work.

As the program enters FY91, the completion of the surface plant at Fenton Hill is within sight. The long-awaited LTFT can then begin, and the large investment in science and technology represented by the HDR Program will begin to bear still greater dividends.

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 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). We don't really know this.

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

average annual ambient air temperature
(heat pumps!)

GEOTHERMAL GRADIENT MAP OF THE UNITED STATES

Figure 1. Geothermal Gradient Map of the United States.

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

Amended
Sentence

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.

The Heat Mining Concept: A concept for recovering useful heat from this tremendous natural resource originated at Los Alamos National Laboratory. As shown 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 transport it to the surface.

Geothermal Division

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 Security¹, 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 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. like up ^

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 U.S.

Figure 2. A Hot Dry Rock Geothermal Reservoir.

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.

Now cancelled
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 U.S. effort. The Japanese are conducting field work at two 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 1993. The United Kingdom has been doing extensive research on HDR since the late 1970's, and is presently conducting a conceptual design study for a deep, hot, reservoir in England.

A consortium of German, French and British companies has proposed a \$300 million, ten-year effort to demonstrate the viability of HDR in low-gradient areas such as are typical of northern Europe. The work would begin in 1992, with financing by the Commission of European Communities. The Soviets are interested in HDR and have drilled at least one HDR well. At present, however, they lack the advanced technology base required to build a complete two-well HDR system efficiently. Under the right conditions, this might be a fertile area for joint U.S.-Soviet technical cooperation.

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.

extraction
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 *continuously* for more than *nine months* 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 was 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. *goals*

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 3. The second well was then directionally drilled with its inclined section 380 m (1250 ft) vertically above that of the first well.

Contrary to theory,
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 unusual 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.

This isn't quite how it happened

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.

Figure 3. Conceptual Design of the Phase II Geothermal Reservoir.

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.

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 temporary storage in the pressurized fracture system. Pumping rates were usually either 10.6 or 18.5 l/s (168 or 294 gpm), at surface pressures around 26.9 MPa (3900 psi) and 30.3 MPa (4400 psi), respectively. To prevent boiling and CO₂ evolution downhole, a back-pressure of about 3.5 MPa (500 psi) was maintained on the production well, resulting in fluid-production rates of 6.3 to 13.9 l/s (100 to 220 gpm). As illustrated in Figure 4, results of the ICFT were uniformly encouraging. Temperature of the produced fluid increased throughout the 30 day test, to a maximum of 192°C (378°F), and the rate of energy production increased correspondingly, to nearly 10 MWt (34 million Btu/hr). Overall flow-impedance through the fractured reservoir decreased throughout the test. The rate of recovery of injected water increased with time under conditions of constant pressure, and was continuing to improve at the close of the test.

Indicates why the test was terminated with everything going so well.

Preparations for Long-Term Testing: As a result of fatigue failure of a flow-line connection to well EE-2, an uncontrolled vent had occurred that led to the termination of the MHF in 1983. The venting created leaks in the lower part of the 245-mm (9-5/8 in.) casing and an obstruction in the 178-mm (7-in.) transition liner below the casing. Removal of the upper sections of the liner, and caliper logs and impression block runs in November, 1986, showed that both the liner and the casing had partially collapsed at a depth of about 3200 m (10,500 ft).

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.

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

Too much history detail not appropriate for an annual report

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, 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."

However, a 1986 review of geothermal energy programs by the Solid Earth Sciences Panel of the Energy Research Advisory Board 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 FYs 88-91.

While agreement is not unanimous, the large majority of well-informed experts ~~who~~ ^{concluded} have evaluated it ^{with} 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 1990's.~~

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~~ ^{advanced} 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.

The Program Development Council (PDC)

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 ^{PDC} 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 Clear Lake 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.

Late in FY90 the City of Clearlake was close to securing 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 will concentrate 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 will be 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 will also be completed.

Good material, but excessive as
lead-in for annual report. In future,
limit to 2-3 pages.

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. Improve instrumentation and hardware to control, locate, and measure fracture propagation in hot dry rock reservoirs.**
- 5. Establish reservoir-mapping techniques to locate drilling targets for production wells.**
- 6. Complete studies on water-rock interactions and their effects on flow through a hot dry rock reservoir.**
- 7. Verify that the environmental and social consequences of HDR development are acceptable.**
- 8. 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.**
- 9. Determine means to locate accurately the intersections of fractures with the wellbore.**

The activities associated with this project during the FY1990 year 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 FY90 Annual Operating Plan, are listed below.

HDR Program Work Breakdown Structure

HDR Geothermal Energy Development Program

Fenton Hill Operations Task Area

Design Procurement and Installation

- Phase II Surface Plant
- Reservoir Pressurization Tests

Phase II Ancillary Activities

- Water Supply
- Environmental Safety and Health

Test Site Support

- Equipment Maintenance and Upgrade
- Safety and Emergency Activities
- 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.

FY90 Expected Accomplishments

- A. Procurement and Installation of LTFT system components with 90% or more of the installation of the system complete.
- B. Complete field pressurization tests for improved estimates of water reservoir performance.
- C. Complete acquisition of adequate make-up water supply and water handling capability for the LTFT.
- D. Complete Version 1.0 of the 2D and 3D thermal/fluid dynamic and mass transfer model using pressure and temperature-dependent continuum analysis.
- E. Complete automation of fracture mapping techniques and reanalysis of MHF seismic data stress and flow path determination.
- F. Complete adsorption tests in laboratory for chemically-reactive tracer work.
- G. Complete fracture healing laboratory experimental work.
- H. Conduct environmental water analysis and seismic monitoring.
- I. Technology transfer will include interface with industry on the LTFT and participation in technical meetings.

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

Fenton Hill Site Operations Task Area

The activities in the Fenton Hill Site Operations Task Area are concerned with the preparations for the long-term flow test of the Phase II reservoir (level III objective #1), but are relevant to all the program objectives. During FY90, they have been directed toward the attainment of accomplishments A, B, and C.

Phase II Energy Extraction System

Under the Phase II Energy Extraction Project, the design, procurement, and installation of the surface facilities needed to carry out the LTFT are essential engineering steps to the actual conduct of the test. Our goal this year has been to complete more than 90% of the system.

Reservoir tests are being used to set the operational parameters of the LTFT, and to provide data for the study of the thermal and hydraulic characteristics of the reservoir (level III objectives # 2, and #3), with particular attention to water consumption this year as stated in accomplishment B. Reservoir testing also serves to improve mapping technology by pressurization to levels of seismic activity (level III objective #5), and provides an opportunity to test improved instrumentation and hardware (level III objective #4) in a real-world setting. Chemical analyses of the reservoir fluids provide data on which to evaluate water-rock interactions (level III objective #6).

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. This year, procurement of sufficient water to conduct the LTFT (accomplishment C) was an important goal of this activity area.

Environmental monitoring adds to the store of data needed to verify the environmental characteristics of HDR development (level III objective # 7). 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 (level III objective #8). Accomplishment H falls in this area.

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. This year, particular emphasis was placed on ES&H issues in concert with the increased level of attention being given to this area throughout the DOE.

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 development and operation of an HDR heat mine.

Reservoir Engineering: The work in reservoir engineering provides 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 #8, which relate to overall system performance, but it draws heavily upon and interactively contributes to the information generated in meeting level III objectives #5, #6, and #9. The reservoir engineering effort this year has been in part concerned with applying the results of extended pressurization testing at Fenton Hill to the attainment of a more complete understanding of water consumption in the Phase II HDR reservoir (as part of accomplishment B).

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, #6, and has an important role in reaching objectives #7 and #8. Accomplishment D was an important goal of modeling in FY90.

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 #4 and #5, and, since this activity includes monitoring for potential seismic environmental effects of HDR experiments, it also contributes to the attainment of level III objective #7. During FY90, accomplishments E and H were directly relevant to seismology efforts.

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 in providing a basis for modeling and predictive studies. Potential environmental effects of HDR technology can 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. FY90 accomplishments F, G, and H fell under the purview of this activity area.

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 and related developments 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 U.S. industry, and the objectives at all levels are directed toward this end. The goals of technology transfer are expressed in accomplishment I.

ACCOMPLISHMENTS

The preceding section of this report stated the objectives of the HDR Program, and described the relationship of the efforts carried out this past year (as delineated in the work breakdown structure) to these objectives. The work breakdown structure (Figure 5) also forms the basis for this summary of the accomplishments of the HDR Program during FY90.

Fenton Hill Site Operations Task Area

Phase II Energy Extraction System

Design Procurement and Installation: Major progress was made in the design, procurement, and construction of the surface plant being built for the long-term flow test of the Phase II HDR Reservoir. By the end of the fiscal year, design of the basic system was complete, most equipment had been purchased, and many components had been installed at Fenton Hill. Figure 6 is an illustrative sketch of the surface system as it will appear when completed in the summer of 1991. The design layout of the Fenton Hill Phase II Energy Extraction System surface plant has been entered into a CAD (computer aided design) program file to facilitate updating the drawings as changes are made in the future.

One important feature of the surface plant design is the incorporation of a bypass line which will allow the surface loop to be operated without pumping fluid through the reservoir. This will permit the testing of all components on the surface under a variety of operating conditions with no impact on the underground portion of the system.

By the end of FY90, the high pressure injection pumps, the most expensive and probably the most technically sophisticated elements of the surface plant, had been manufactured and were being fitted with auxiliary equipment but were not yet on site. Of the other major pieces of equipment required for operation of the system, only the separator, which removes gas and particles from the produced fluids, remained to be purchased. The process design for it had been finished, but the mechanical design was yet not yet complete. At the close of the year, the design of the LTFT surface plant was approximately 95% complete, procurement of components was more than 90% complete, and installation was about 60% complete. Evaluation of the critical components of the system was about 80% complete. Check out of the entire system will take place in 1991. An item-by-item summary of progress is as follows:

Figure 6. Fenton Hill Phase II Surface Plant.

Injection Pumps: Early in the year, Rust Enerpac, of Albuquerque, NM, was awarded the \$972,000 contract for the delivery of two identical high pressure pumping systems, each comprising a skid mounted assembly of a reciprocating pump, a diesel engine, an automatic transmission, a speed reducer, controls, instrumentation, and a sound-proof housing for the entire unit. An Ingersoll-Rand pump was specified with a Caterpillar engine and an Allison transmission.

Rust quoted an estimated delivery time of 38-42 weeks which would put the pumps on site at Fenton Hill by about mid-October, 1991. An eight-week strike took place at Ingersoll-Rand during the spring of 1990. This led to a delay in the delivery of the units to Rust-Enerpac, and slippage of the predicted delivery date to Fenton Hill. (In spite of this setback, the pumps were received at Fenton Hill before the end of the first quarter of FY91.)

Extensive review and testing of the pump packages was carried out during manufacture and assembly. As a result of multilateral discussions among Ingersoll-Rand, Rust, and Los Alamos representatives, a forging procedure was developed to assure that the materials used for those surfaces in contact with geothermal fluid would meet the special materials requirements imposed by such exposure.

A mathematical evaluation of the acoustic characteristics of the surface loop design was used to predict vibrations due to the flow pulsations produced by the reciprocating pumps. Vibration dampeners then were incorporated into each pump assembly, as required. By the close of the fiscal year, the pumps were at Rust-Enerpac and assembly of the packages was well underway.

During the final quarter of 1990, work began at Fenton Hill on the foundations for the pumps. Each of the support pads measures 10 ft x 28 ft, and is capable of supporting 70,000 lbs, the weight of a pump assembly. Completion of this work prior to the onset of cold weather at Fenton Hill has been extremely important, since it is difficult to pour concrete at the subfreezing temperatures typically prevalent at the site during the winter. The 10,000 gallon diesel fuel tank for the pumps was also installed during this time. It is elevated to provide a gravity assist in supplying fuel to the pumps. As part of the environmental design requirements, a secondary containment structure was built around the tank. It consists of a plastic-lined berm with the capacity to contain all the fuel in the tank should an inadvertent spill or leak occur.

Make-up Water Pumps: Certain operational advantages can be attained by operating the production portion of the surface loop at an elevated pressure. In order to do this, all

components of that portion of the system must be capable of operating under that pressure. The make-up water pumps, in particular, must have the ability to pump against a sufficient pressure head. Early in the year, we asked for bids on two pumps, each capable of delivering 25 gpm at a pressure of 1,000 psi. The Roto-Jet Pump Company was the sole bidder for this item and was awarded a contract to build the pumps in the spring of 1990.

The pumps were shipped by Roto-Jet on September 28, 1990. They will be interconnected and will be computer controlled to operate sequentially. In this mode, one pump is started to initiate pumping and the second unit comes on automatically when the system demand exceeds the capacity of the first pump. If demand then declines, the pump initially energized is the first to shut down. Thus, in cyclic pumping operations, the operation of the pumps will automatically alternate. These procedures equalize usage time and, thus, wear on the two units, and extend the life of seals and bearings.

The pumps will be installed in the make-up water pumphouse. Since this is a heated structure, work on this portion of the surface system can be carried out even in inclement weather.

Heat Exchanger: The heat exchanger, manufactured by Yuba Heat Transfer Corp., was installed at Fenton Hill in 1974. It has been used in all the flow tests of both the Phase I and Phase II reservoirs. In total, it has seen between 1 and 2 years of service over the period of the past 16 years. In the second quarter of FY90, Yuba inspected the heat exchanger tubes for scaling, erosion, and corrosion. A visual inspection revealed a buildup of scale and sludge on almost all the inner surfaces of the tubes. Sections of the tubing were removed to facilitate rigorous cleaning and accurate measurements of the wall thickness.

Yuba reported that despite the scale buildup, there appeared to be no severe deterioration of the tubing walls, no significant pitting, and no significant reduction in the life expectancy of the heat exchanger. The heat exchanger was originally built to allow working pressures of 2,500 psi, and we plan to operate at no more than 1,000 psi, so there will be a very large margin of safety.

The scale was found to be primarily iron carbonate. Yuba has suggested that it can be removed by either chemical or mechanical cleaning. We will determine if this is necessary on the basis of preliminary flow experiments. The heat exchanger has excess capacity so we may find that it is more than adequate for our cooling requirements even without removal of the scale.

New electrical controls were purchased for the heat exchanger this year to bring it into compliance with the latest codes. New manually operated control valves were also installed.

Separator: The most significant problem in the construction of the Phase II Energy Extraction System this past year involved attempts to procure the gas/particle separator. Specifications for the separator were finalized and released for bidding in November, 1989. Three bids were received in early January, 1990, but all of them were much higher than anticipated. The bidders had problems with the requirements placed on the materials of construction, especially with regard to materials availability, ability to meet code requirements, and lack of fabrication experience.

After discussions with several potential suppliers, it was decided to redesign the separator along simpler, more standard lines, and rebid this item. As reconfigured, effective gas separation will be possible under all operating conditions, but a smaller, conventional cyclone separator will be used for preliminary solids removal at high flow rates, if necessary. This should enable us to purchase a separator at much lower cost and simplify the procurement process considerably. Procurement of the separator is now anticipated in the second quarter of FY91.

Data Acquisition and Control System: A new data acquisition system was procured this year to replace the outdated equipment at Fenton Hill. The hardware consists of an IBM PS-2, Model 80 computer. It will be interfaced with an IBM-AT located in the chemical analysis trailer to allow the geochemists to utilize its capabilities in their work. The software was supplied by Intellution, Inc. Key members of the HDR staff were trained in its use this past summer.

The system will be capable of both data acquisition and control functions. All analog-to-digital conversion will be done in the field rather than at the data acquisition trailer. This will speed the rate of data collection. The process of installing, debugging, and testing the system was well along by the close of FY90.

1 Million Gallon Storage Pond Upgrade: A major upgrade of the 1 million gallon storage pond was completed during this fiscal year. A plan for excavating, grading, and lining the pond was completed and approved by the Oil Conservation Division of the New Mexico Department of Energy in the early part of the year. Excavation and grading continued throughout the spring months, along with the installation of various collection tanks, auxiliary piping, and miscellaneous hardware.

After application and compaction of a base sand layer, a layer of felt was put down, followed by the first plastic layer of 30 mil thick PVC. A drainage trench was built into the pond on top of the PVC to prevent accumulation of water that might leak through the top plastic liner. This trench was lined with a perforated pipe and filled with gravel. The final layer of plastic was then applied. It is made of XR-5, a Hypalon-like material which has superior resistance to degradation by ultraviolet light. The final stage of the installation entailed packing of the edging around the rim of the pond to hold everything in place. By the end of FY90, work on the pond was 100% complete.

The 1 million gallon pond now exists as an environmentally-sound storage reservoir for the Fenton Hill site and represents a substantial asset. This work was largely financed by an appropriation of \$65K from Laboratory environmental safety and health funds.

Wellhead Trees and Valves: The EE-2A and EE-3A wellhead trees were largely rebuilt at or above the master valve this past year. A total of 16 valves of various types was purchased to accomplish this. All had API service ratings of 5,000 psi or greater. Figures 7a and 7b show the current configurations of the EE-2A and EE-3A wellheads, respectively. The newly installed valves are illustrated in each case. While normal maximum operating pressure at the wellheads is 5,000 psi, the design is such that the wellheads can be reconfigured for pressures as high as 10,000 psi, if required for special operations.

Miscellaneous Valves: A total of 23 valves of various types was purchased for installation in the surface loop at various points other than the wellhead trees. These valves serve a number of control, bypass, and safety functions. As but one example, 4 new valves were installed on the heat exchanger this year. The approximate value of all the valves purchased and remanufactured during this past year was \$165,000.

Piping and Fittings: Over 170 ft of stainless steel pipe and about 300 ft of carbon steel pipe were purchased for the surface plant during the past year, as well as numerous flanges, ells, tees, reducers and other fittings. Some of the carbon steel pipe was installed and welded during FY90. The balance of the pipe installation work will be completed during the first half of FY91. Total piping and fitting purchases in the fiscal year amounted to about \$40,000. All piping is being designed and constructed to meet power plant piping standards.

New EE-2A Wellhead Components (Production Well)

New EE-3A Wellhead Components (Injection Well)

Legend		
1. Lower Master Valve	3. Wing Valves	5. Logging Valve
2. Upper Master Valve	4. Operator Valve (Hydraulically Actuated)	6. Bypass Control Valve
		New Components

Figure 7. Wellhead Trees as Rebuilt in 1990.

Miscellaneous: Ultrasonic test equipment has been purchased for the inspection of various components of the surface plant. This equipment has been used to evaluate the condition of key components of the loop already in place. It will also be employed as part of a monitoring program to check for corrosion during the progress of the LTFT.

Reservoir Pressurization Tests: The long term pressurization study of the Fenton Hill Phase II reservoir (Experiment 2077) continued throughout FY90. This test has clearly demonstrated that water consumption can be very low in extended operation of a deep hot reservoir. It has also shown that the Fenton Hill HDR reservoir is aseismic (non-extending) at pressures up to 19 MPa, and provided a new basis for calculating the effective storage volume of the reservoir under specific pressurization conditions.

Design of Experiment 2077: This test has been implemented simply by maintaining a cyclic pumping schedule at the injection wellhead to maintain the reservoir pressure, as measured at the shutin production wellhead, at a sequence of predetermined values. As in any extended experiment, equipment problems and the need to carry out other activities at the site, have forced modifications in the pressurization schedule. By the nature of this experiment, however, such perturbances can be accommodated, although generally at the cost of continuity in the sequence of planned pressure stages.

Figure 8 is a pressure profile of the reservoir over the entire course of the experiment as measured at the shutin production wellhead. The most important phases of the experiment during FY90 were the three 15 MPa pressure plateau stages in October-November, March-April and September, and the 19 MPa pressure plateau during the month of May.

There were two significant shutin periods during FY90. The first, in the early part of the year was due to mechanical problems and the Laboratory closure for the holiday season. The second, during the summer, was to permit important work on the system wellheads to be accomplished as part of the construction of the surface plant for the LTFT. A long, slow repressurization schedule was followed in restoring the reservoir to 15 MPa pressure after the first shutin, but rapid repressurization with a temporary pressure overshoot was used to reestablish the 15 MPa plateau after the summer shutin period. Our experience this year has demonstrated that a variety of operational techniques can be employed to bring the reservoir to a specific operational state.

15 MPa Pressure Plateau Studies: Data from the three 15 MPa pressure plateau stages in FY90 can be integrated with information collected earlier in this experiment to provide a long-term picture of the performance of the Phase II reservoir at this pressure. After about 17 months of pressurization, water consumption at 15 MPa dropped to less than 3 gpm.

Figure 8. Phase II Reservoir Pressure Profile during Experiment 2077.

Thus, this experiment has demonstrated that a pressurized reservoir many millions of cubic meters in size can be maintained by an amount of water that could easily be delivered by a household garden hose. Figure 9 shows that the rate of water loss at the periphery of the reservoir declines with the log of time over about the first year of the test, and then slowly begins to level off. These results imply two dimensional diffusion from the plane of the reservoir to the far field over the course of more than a year of pressurization. Since seismic data show that the reservoir has the shape of a somewhat flattened ellipsoid, this pattern of diffusion is not surprising. The leveling-off in the decline of the rate of water loss seen in the most recent observations indicate that the water consumption rate is approaching a constant value more indicative of a point source, perhaps because the effective water-loss periphery has by now been extended far from the source.

19 MPa Pressure Plateau Study: The pressure on the reservoir was raised from 15 MPa to 19 MPa over a thirteen day period beginning in late April of 1990. This process required about 1,127 cubic meters (297,900 gal) of water. This volume includes additional stored water in the pressurized joints, internal and external permeation into the rock matrix, and flow losses from the reservoir boundary. Calculations based on this measurement have allowed us to determine the pressure-affected volume of the reservoir as discussed elsewhere in this report.

The reservoir was maintained at 19 ± 0.5 MPa for 21 days. Figure 10 shows that the water loss rate over the short period of this test declined to about 8.3 gpm. The solid curve shows the residual storage term, which rapidly decreases and appears to saturate after about 6 days at 19 MPa. The remaining water consumption, due to permeation losses through the microcracked rock at the periphery of the reservoir, fits the logarithmic decay function shown as the dotted line in the figure. On the basis of this brief experiment, the decrease in water loss at 19 MPa reservoir pressure appears to be analogous to that observed in the more extensive test at 15 MPa.

An important point to note is that the reservoir remained aseismic during this phase of Experiment 2077, even though injection pressures as high as 24.8 MPa were employed to maintain the 19 MPa reservoir pressure. It is apparent that 19 MPa is still below the threshold pressure for fracture extension at the reservoir periphery.

Figure 9. Phase II Reservoir Water Loss vs. Time at 15 MPa Pressure.

Figure 10. Phase II Reservoir Water Loss vs. Time at 19 MPa Reservoir Pressure.

EE-3A Annulus Leak: It has been known for several years now that a leak of a few gallons per minute exists in the EE-3A wellbore. The leak manifests itself as fluid returning to the surface in the annulus between the wellbore and the outermost casing. Analysis of water samples collected from the annulus flow early this year have indicated that it is probably reservoir fluid. It appears that a connection of the reservoir to the EE-3A wellbore exists at some point above the cemented-in section.

During this past year, automated monitoring of this bypass flow has convinced us that the leak is not getting worse. The flow rate does change in response to changes in pumping schedules and reservoir pressures, but in a manner which is somewhat predictable. During the past year it has averaged in the range of 2-3 gpm. While the leak complicates some of our work, it does not seem practical or expedient to repair it at this time since considerable cost would be involved as well as some risk to the system. We intend to continue to monitor this situation closely.

Phase II Ancillary Activities

The ancillary activities at Fenton Hill in FY90 were directed toward procuring water for current and projected needs, assuring that environmental requirements are met, and addressing long-term aspects of health and safety at the site. These ongoing tasks, while often mundane, are sometimes protracted and complex. They are essential to the continued success of the HDR program.

Water Supply: During this past year, the water rights at the site were maintained and the lease for 2.4 acre-ft of irrigation water was renewed. The current available supply of water amounts to 15 acre-ft per year which may be used over a period of several years. In combination with the total storage capacity of 6 million gallons of water in our two ponds, this should provide us with adequate water for the LTFT and any other activities at Fenton Hill in the foreseeable future. Work on upgrading the 1 million gallon pond has been described earlier in this report.

Environmental Safety and Health: Environmental surveillance including seismic and water chemistry monitoring continued throughout the year. It was clearly demonstrated that the continuing pressurization experiment in the Phase II reservoir did not induce any seismic activity, since no seismic events of any nature originating at Fenton Hill were detected. A number of small seismic events from distant locations were recorded, however.

During a routine inspection in late November, 1989, Fenton Hill personnel discovered the wellhead of well GT-2 had been lifted 3 ft above its normal position. The master valve

had struck the tower encasing the wellhead causing structural damage to the decking. An investigation showed that the 7 5/8 inch casing had extended through the pack-off flange. The probable cause of this incident was failure of the casing which extends over 8,500 feet below ground level, and was installed with a preload of 417,000 pounds. When the casing failed, the elastic energy of the preload was released imparting the upward force that caused the casing to move out of the ground. An optical televiewer confirmed that the failure occurred at a depth of 1020 ft.

An Unusual Occurrence Report and a Report on Property Damage and Loss regarding this incident were submitted to the Laboratory Health Safety and Environment Division for submittal to the DOE. Specific Corrective actions included disassembly and disposal of damaged materials, and construction of structural supports at GT-2 to prevent further movement at the wellhead. In addition, a review of the wellhead designs of all other Fenton Hill wells was conducted, and modifications were completed as required to prevent a recurrence of this type of incident at another well. A program of monthly inspections of inactive wells at Fenton Hill has been initiated.

A risk assessment and mitigation plan for Fenton Hill operations was completed in March, 1990. It included a review of all environmental, safety, and health (ES&H) records, and updating as required. Fifty three (53) recommendations for ES&H improvements with regard to facilities and equipment were implemented as a result of this assessment.

Documented monthly operational checks mandated either by the Laboratory or OSHA regulations were made of the Fenton Hill communications equipment, cranes, forklifts, wellheads, emergency airpicks, vehicles, eyewash stations, and fire extinguishers. Training required by previously existing or new Laboratory and OSHA regulations was completed in the areas of hazards communications, waste generation, pressurized systems, water discharge, equipment operations, environmental awareness, and substance abuse. In addition, a number of people from the Los Alamos HDR Program attended a day-long training session on hydrogen sulfide in July, 1990. The course was presented by the Oil Field Training Center of Eastern New Mexico University. It covered hazards associated with hydrogen sulfide exposure at various concentrations, safety procedures, detection equipment and procedures, and other relevant topics. It is not unusual to encounter hydrogen sulfide in geothermal operations, and small amounts have been detected at Fenton Hill in the past. The equipment for detection of hydrogen sulfide at Fenton Hill is being upgraded to provide the maximum protection against this hazard.

Site Support Activities

Site support includes the myriad of day to day activities required to keep the site running, maintain equipment and facilities in good operating condition, install modern equipment of general value to the site, and carry out day-to-day ES&H activities. During FY90, a concerted effort was made to clean up the site generally and dispose of all outdated and unnecessary equipment in concordance with the effort to conform strictly to the increasing emphasis on ES&H by the Laboratory and the DOE. More than 20 truckloads of scrap and obsolete materials were disposed of. This operation was essentially 100% completed for all the active work areas at Fenton Hill by the close of FY90, although some cleanup of storage and peripheral areas remains to be done.

The site work related to construction of the Phase II Energy Extraction System and ancillary site activities, such as the installation of the liner on the EE-1 pond, have been discussed in detail in other parts of this report. A few examples of the broad range of work in this project are discussed below.

Equipment Maintenance and Upgrade: The two Kobe pumps used for pressurizing the reservoir were rebuilt by the manufacturer during this past fiscal year. In spite of this fact, numerous incidents of minor pump problems were encountered throughout the year. These additional repairs were normally made on the spot with a minimal impact on our experimental program.

Measurement of the annulus flow from the EE-3A well was upgraded to a continuous monitoring system. Collection of information regarding this leak is now a standard part of Fenton Hill operations. Our observations over this past year have indicated that the leak is very steady under conditions of constant pressure. Chemical analysis conducted early in FY90 showed much higher concentrations of dissolved solids in water from this leak than in water from the large pond. This leads us to conclude that the annulus water is flowing through the reservoir and mixing with more concentrated deep reservoir pore fluid prior to returning to the surface rather than coming back via a direct leakage path within the wellbore.

A leak in the EE-3A wellhead was discovered and repaired in December, 1989. It involved a faulty flange. Later in the year, the external weld between the surface casing and the lower casing was found to be defective during pressure testing. The weld section was removed, replaced, and successfully pressure tested. As part of the replacement process, backing plates were installed to provide additional weld area between the casing head and the surface casing. All welding work in preparation for the LTFT will undergo stringent

quality assurance procedures, and welds in existing section of the surface system which will become part of the LTFT loop will be carefully reevaluated by qualified personnel.

Safety & Emergency Activities: Safety inspections by Laboratory EES and HSE Division personnel were conducted on several occasions during this year. We have been working throughout the year to prepare for an inspection by the DOE Tiger Team. A visit to Los Alamos by the DOE Tiger Team is expected sometime in FY91.

General Site Work: A new guard house was installed at Fenton Hill this year. It provides a central point for the communications equipment needed at the site.

The appearance of the site has been drastically altered by the massive clean-up effort and the removal of the towers over wellheads EE-2A and EE-3A. The towers were removed and the wellheads were cleaned, stripped, and repainted as the initial step in rebuilding the wellhead trees for the LTFT. Conduit was laid across various parts of the site to carry the numerous installation and control lines being installed for the LTFT.

A leak in the supply line supplying domestic water to the site was repaired in June, 1990. Water losses from this leak had been amounting to about 40,000 gallons per month.

An in-ground vent tank was installed for well EE-2A.

Scientific and Engineering Support Task Area

Engineering and Development Activities

Reservoir Engineering: Reservoir Engineering at Los Alamos entails developing an improved understanding of the fracturing geometry and thermal flow characteristics of the Fenton Hill reservoir, and the engineering activities directed toward controlling all aspects of reservoir operation and performance. The diagnostic and modeling techniques developed, however, are applicable to HDR reservoirs in general. While modeling, seismic, and geochemical studies all contribute to the accomplishment of reservoir engineering work, they are discussed separately in this report. During this fiscal year, much of the reservoir engineering activity has been concerned with the planning and conduct of the long-term pressurization experiment (Experiment 2077). The details of that test are described separately under the Fenton Hill Site Operations category of this section of this report. Other reservoir engineering work this year has involved continued participation in the development of a fractured reservoir discrete flow model and

determination of the volume of the reservoir based on the results of Experiment 2077, as well as a continued effort to build on and extend the FRACNET model.

Seismic Basis For Calculation of Reservoir Volume: Further calculations of the volume of the Phase II HDR were made this year using seismic results from the most appropriate pressurization and/or flow experiments, taking into consideration current reservoir connectivity. The best-fit ellipsoidal volume of 2,430 seismic events was calculated from the locations of these events. Statistical methods based on the spatial scatter of the events were used to determine the certainty with which the volume could be specified. By this technique, the reservoir seismic volume was calculated to be in the range of 16 to 130 million cubic meters. This wide deviation simply indicates that the density of seismic events falls off rapidly with distance from the stimulation points.

The designation of the effective reservoir boundaries is somewhat arbitrary, but by using standard deviation statistics, some semblance of mathematical reasoning can be applied to the problem. The lower value above represents the limits of the reservoir at 1 sigma, and the upper limit at 2 sigma, distribution levels of the data.

As described below, related calculations of the "effective pressurized volume" during Experiment 2077 have indicated a reservoir volume closer to the smaller than the larger seismic volume. However, Experiment 2077 has been run primarily at reservoir pressures in the range of 15-19 MPa, while many of the data points used to calculate the seismic estimates of reservoir volume resulted from stimulations at significantly higher pressures. Work is continuing on the extremely complex problem of determining a realistic measure of reservoir volume.

Fluid Storage Basis for Calculation of Reservoir Volume: In mid-FY90, as one part of Experiment 2077, the pressure of the Phase II HDR reservoir was increased from 15 MPa to 19 MPa. Since the primary objective of this part of the experiment was to determine the water permeation at 19 MPa, the rate at which the pressure increased was not carefully controlled, and reservoir equilibrium was not rigidly established prior to the pressurization process. In spite of these facts, an estimate of the pressure-affected volume of the reservoir has been obtained from measurements of the amount of water required to increase the reservoir pressure by 4 MPa in this pressure range.

During the 14 day pressurization effort, 298,000 gallons of water were pumped into the system. Calculations which take into account extraneous water losses and changes in fluid density, can establish that this resulted in a net increase in the volume of the reservoir of about 620 cubic meters. This increase in volume can, in turn, be used to calculate the

pressure-affected volume of the reservoir in the pressure range of 15-19 MPa, if uniaxial joint opening, such as has been observed indirectly in pumping fluid into the reservoir, is assumed.

The calculation of reservoir volume relies on a simple set of equations, and the Young's Modulus value for the hard basement rock at Fenton Hill, which has been previously determined from seismic data. Further, it is based on the following assumptions: 1. The effective matrix compression in the maximum and intermediate stress directions is small compared to that in the minimum stress direction, and can therefore be neglected. 2. The pressure affected region is similar in shape to the seismically determined reservoir. Neither of these assumptions is scientifically unreasonable based on our current knowledge of the HDR system at Fenton Hill.

With the above considerations taken into account, the pressure-affected volume of the reservoir in the pressure range of 15-19 MPa is calculated to be about 16.8 million cubic meters. As a point of comparison the volume of the reservoir determined by means of seismic observations during fracturing operations, as has been previously reported, ranges from 16.3 million cubic meters to 130 million cubic meters depending on whether the spread of the microearthquake locations is considered to within one standard deviation (67% of the microearthquakes accounted for) or two standard deviations (95% of the microearthquakes accounted for).

Modeling: Modeling work this year has involved progress on a number of important and interrelated models of reservoir performance.

Extension of the FRACNET model: The FRACNET computer code simulates fluid flow and solute transport in fractured media. While previously this code was strictly useful for steady state conditions, this year it has been extended to simulate transient fluid flow and transport. This makes it possible to test recently collected transient data as well as the transient data available from the Initial Closed-Loop Flow test (ICFT) conducted several years ago. Our understanding of HDR reservoirs will be enhanced by requiring that our models match existing and planned pressure interference data. Initial code development work, including a pressure-dependent aperture submodel to simulate behavior often seen in fractured systems was completed early in this fiscal year.

The model has been used to simulate data from the Fenton Hill Phase II reservoir. Both low pressure/low flow rate and high pressure/high flow rate transient data have been adequately simulated. Model parameters obtained from the simulations have suggested ways in which the model can be refined to achieve better fits to the data, and a more

realistic representation of fluid storage and flow in the reservoir. The model has also been used to explore alternatives to the two well circulating mode of operation normally considered for HDR reservoirs. Simulations using it have shown high backpressure and cyclic operations to be promising alternative operational schemes which may enhance reservoir productivity.

Indications are that ten days to two weeks would be required to reach a quasi-steady state in the Fenton Hill Phase II reservoir under high backpressure conditions, assuming an initial reservoir condition similar to that created by our long-term pressurization experiment. This model has also been used to estimate the boundary pressure at which the onset of microseismicity will occur under conditions of high backpressure operations. Preliminary calculations predict a value equivalent to 22 MPa at the surface, but correction factors must be applied to further refine the results.

The Finite Difference Model: Early in the summer of FY90, John Pendergrass, a summer student under the tutelage of Bruce Robinson, wrote a finite difference model for transient fluid flow in homogeneous media. It simulates two-dimensional flow, with the ability to model pressure dependent permeabilities and porosities. Hari Viswanathan, another summer student working under Bruce Robinson, performed fluid diffusion calculations to demonstrate the importance of matrix storage during Experiment 2077. His calculations show that, using parameter values similar to those measured in the laboratory, fluid storage in the matrix blocks between fractures occurs at a rate sufficient to explain a significant fraction of the fluid storage observed in the experiment. This modeling has thus identified storage in the matrix blocks within the fractured region as another mechanism for fluid storage and apparent "water loss". This loss would be expected to diminish to a very low value during long-term operation of the reservoir.

The Dual Porosity Model: Working with Bruce, John combined the finite difference code with the FRACNET code described above. The two media (fractured and porous) may be thought of as overlapping, with a fluid transfer term to couple them. Thus, the condition of fluid flow in the fractures with diffusion into or out of the rock matrix can now be simulated.

This combined code differs from other dual porosity models in two important respects. First, the model allows the network to be generated stochastically to capture the random nature of the joint systems. Second, the homogeneous medium is itself divided into a series of discrete, finite difference grid sections in which fluid flow can occur, rather than simply a series of storage volumes connected to each fracture, with no permeability between the individual storage volumes. Both of these improvements are needed in order

to conduct modeling studies to better understand flow in HDR reservoirs, particularly in experiments such as the sustained pressurization study currently underway (Experiment 2077), in which matrix storage is important. Furthermore, the code can be used simply as a homogeneous continuum model with no fractures, for applications in which this is appropriate.

This model will be tested against known analytical and semi-analytical solutions, although a rigorous test for the important case of a fracture-matrix interactions is difficult to develop. To date, the code has compared favorably when tested against several solutions. The testing procedure has now been automated so that when future code changes are made, the reliability of the modified code can be tested automatically. Code development in this area is about 90% complete with the primary remaining task being the updating of a subroutine which computes tracer transport in the reservoir.

The model will be used to reexamine some results of Experiment 2077. Our original work on modeling this experiment alerted us to the importance of including a matrix parameter in our simulations, and the new code will allow us to perform these simulations more rigorously. Ultimately, we hope to apply the dual porosity model to perform calculations which specify the relative fractions of storage in the fractures and in the matrix.

The Fractured Reservoir Discrete Flow Model: Again, during the summer of FY90, Rick Martineau, a graduate student under Professor Daniel Swenson of Kansas State University worked with Don Brown on further development and application of the "fractured reservoir discrete flow" model, which can be used to understand and predict pressure-dependent flow in a jointed rock mass. Development of this model began in 1987. It couples fluid flow to rock and joint-deformation, but does not yet incorporate heat transfer effects. The model is designed to analyze steady-state and transient responses of fluid flow in jointed rock to injection and production flow rates or pressures.

This year, the model was tested against the experimental results obtained during experiment 2070, a non-circulating experiment but one in which fluid flow was the result of reservoir inflation. It was also used as means for analyzing the effects of high and low backpressure on fluid flow, and the pressure response to increased impedance near the injection well.

Developmental work has involved adapting this large, complex model to run on the SUN work stations currently used at Los Alamos, improving the solution of the coupled equations to alleviate instability problems encountered under certain conditions, and

making modifications to speed up the program. As presently written, the model can take several days to converge to a transient solution of large problems.

Work on this model will continue in an effort to advance our understanding of the behavior of fluid flow in jointed rocks under a variety of conditions. Developments in this area could have important implications for both HDR and conventional geothermal technology.

Seismology: Seismology efforts this year included upgrading and maintenance of seismographic equipment and facilities, monitoring at Fenton Hill, and studies directed toward improving the understanding of the vast amount of data collected in the HDR Program over the years.

Early in the year, it was necessary to repair one of the downhole microearthquake monitors, the GT-1 instrument. A tool already on hand was refurbished to serve as a replacement for the defective monitor. The digital data recorder used to record data from the Precambrian network suffered from intermittent problems during the winter. It was sent to the manufacturer for repairs in December. It operated properly after reinstallation in January, but increasing noise levels forced us to desensitize it to avoid false triggering and the accompanying excessive use of recorder memory. Efforts to isolate and remove the noise led to the conclusion that it was sporadic with different characteristics from station to station. A plan has been developed to upgrade the weatherproofing of the electronics at the permanent Precambrian network stations as the first step in improving their performance.

Additional microearthquake plotting software was written this year in preparation for the LTFT. It allows for automated plotting of microearthquake waveforms as soon as they are acquired. The plotting process takes several minutes per event, so rates greater than one or two events every few minutes will require suspension of this real time capability. A relatively low event rate is anticipated, however, during most of the LTFT, since the reservoir generally will be operated in the nonextensional mode during the test. Work also began to prepare computer hardware and software for preliminary LTFT experiments which will attempt to carefully define the reservoir pressure at which the onset of microseismic response takes place.

Spectral analysis of seismic waveforms accompanying the massive hydraulic fracturing experiment (Experiment 2032) was completed. The analysis yielded measurements of the seismic Q in the reservoir, the seismic energies excited by the microearthquakes analyzed, and the physical sizes of the rock faces along which slip occurred during the microearthquakes. From these data, we estimated the number of events that occurred as a

function of earthquake size. We found that the seismic energy released during the experiment was dominated by the large number of small events that occurred. For naturally occurring earthquakes, the seismic energy released is dominated by the small number of very large events, contrary to our results for induced events. These results indicate that seismic risks associated with the creation of large HDR reservoirs are smaller than would be predicted by extrapolating data collected from natural earthquakes. A paper describing our method of data analysis and the results obtained has been accepted for publication.

Velocity tomographic modeling of the microseismic data from the massive hydraulic fracturing effort (Experiment 2032) of 1983, is providing a considerable improvement in the imaging of the Phase II HDR Reservoir. Inversion techniques developed by Lisa Block, a graduate student at MIT, have been employed to improve the precision with which the locations of seismically induced microearthquakes can be identified, and to determine the elastic properties of the reservoir in 3 dimensions. Data input to the model are a specifically chosen subset of the more than 10,000 event times obtained as a result of Experiment 2032. While this work has not been funded by HDR, the information generated is proving to be of great value to the HDR Program.

Monitoring for seismic events associated with the long-term pressurization test (Experiment 2077) has indicated no events associated with Fenton Hill activities, but a number of signals have been recorded from events occurring at other locations, all of which were some distance from Fenton Hill.

Toward the close of the year an optical disk package for the SUN computer network was procured, and work was begun to transfer the waveform data collected during HDR fracturing experiments to it from magnetic tape. Access to the data will be much more rapid on the disk than it has been on the tape.

Mike Fehler, a Los Alamos seismologist who has played a key role in the HDR Program, spent the first half of the year on a six month assignment at the National Research Center for Disaster Prevention in Tsukuba-shi, Ibaraki-ken, Japan, where he collaborated in research on the propagation of seismic waves. While in Japan, Mike had the opportunity to present talks on the U.S. HDR Program to a number of audiences. He was also able to participate in extended discussions with Japanese scientists working on HDR, and he visited the Japanese HDR site at Hijiori. Mike returned with valuable information and insight about the Japanese HDR initiative.

Geochemistry and Tracer Work: Detection limits in the range of 1.0 pph for the reactive tracer p-bromonitrobenzene, and the product of its reaction with geothermal fluid, p-nitrophenol, were achieved in the laboratory this year. Initial trials with new, microbore chromatographic columns indicate that further improvements in detection limits by as much as a factor of 5 may be possible. Tests continued to demonstrate that adsorption of the tracer compounds should not be a major problem during the LTFT. Unfortunately, the opportunity to evaluate this unique tracer during a flow test of the reservoir did not arise this past year.

The standard operating procedure (SOP) for handling radioactive tracers was updated this year. Procedures for injecting the tracer have been modified so that it can be directly injected into the system at pressures up to 35 MPa. Modifications in the equipment used to transport and handle the tracer have also been made to allow their use at these pressures.

Probes for online measurement of pH, redox potential, electrical conductivity, and oxygen were procured this year. They will be installed in the small, side stream line going to the Fenton Hill chemistry trailer, and used for automatic monitoring during the LTFT. New equipment and software for gas separation and analysis have also been obtained. A dedicated PC will be used for geochemical analyses during the LTFT, with an optical fiber interface to the new data acquisition system being installed at Fenton Hill.

Technology Applications

Technology Transfer Activities: Technology transfer efforts during FY90 included hosting a variety of visitors to the Laboratory, tours of the Fenton Hill HDR site, visits by members of the HDR staff to other organizations, attendance and presentations at meetings, telephone contacts, mailings of written material and related activities.

A total of 38 official visitors were briefed on the HDR Program during 26 separate visits during this year, not including meetings of the Program Development Council (PDC), intralaboratory visits, and other established forums. In most cases, the visitors were also given a tour of Fenton Hill. Visitors included 13 from U.S. private industry, 5 from educational institutions, 3 from news organizations, 3 from the DOE, 3 from other U.S. government organizations, and a congressional staffer. Visitors from the DOE included Deputy Secretary Henson Moore, and Assistant Secretary for Conservation and Renewables J. Michael Davis. There were also 9 visits from foreign nationals involving 11 individuals - 8 from Japan, and 1 each from the United Kingdom, Germany, and the Soviet Union.

Los Alamos personnel visited 7 private industrial organizations during the year, as well as a number of educational and non-federal government organizations specifically to discuss the transfer of HDR technology to the private sector. They attended a number of technical, business, and political meetings at which more than 20 formal presentations on HDR technology and potential were made. In addition, the HDR Program was a key element of general presentations on the topic of energy by Laboratory professionals. For example, a keynote speech on the topic of clean energy was presented by a member of the Los Alamos staff at a Rotary International meeting as a result of contacts arising out of the HDR Program, thus providing an opportunity for inclusion of HDR in broad energy discussions.

Eight (8) review articles and 17 scientific papers were published by the Los Alamos HDR staff during FY90.

A booth at the International Symposium on Geothermal Energy, staffed by Los Alamos personnel, provided interested parties with information on all aspects of geothermal work at the Laboratory. Numerous inquiries were received about Hot Dry Rock. Many people were interested in the application of the logging tools developed in the HDR Program to more conventional geothermal wells, and a number of queries were received regarding the development of HDR systems in dry holes drilled in search of conventional geothermal resources. Numerous requests for general information on HDR were answered.

Clearlake, CA, HDR Initiative: The Clearlake, CA, area was identified as a promising site for HDR development during the period when intensive resource evaluation was a significant component of the HDR Program. During 1987-1988, a preliminary study of the potential for development of HDR in the area of Clearlake was carried out. The results of this work led to the preparation of a proposal for a more in-depth study. A proposal to carry out such an evaluation, known as Clearlake Phase II, was submitted in September, 1988. The study will entail an intensive investigation of the Geysers/Clearlake region including thermal gradients, geologic structures, geohydrology, seismology, surface hydrology, and comparative geothermal regimes.

Funds in the amount of \$225K were allocated for this work by the California State Legislature in the summer of 1989. The funding is provided to the City of Clearlake, CA, by the California Energy Commission (CEC). The work will be carried out at Los Alamos under a "work for others" contract between the City of Clearlake and the USDOE. By the end of FY90, even though well over a year had passed since appropriation of the funds, no final contract had been signed. In early FY91, it appeared that all parties had reached agreement and work would begin during the second quarter of the fiscal year.

Extensive contacts have taken place among the City of Clearlake, the CEC, and Los Alamos HDR personnel during FY90. The administration of the City of Clearlake is strongly in favor of investigating the development of HDR resources, both for potential use in electric power generation and as a source of thermal energy for the community. The CEC likewise has consistently demonstrated a commitment to exploring the potential for HDR at Clearlake. The support of these parties, and the intrinsic quality of the potential resources, provide strong motivation for moving forward aggressively with the program at Clearlake.

MANAGEMENT

Organization

As shown in Figure 11, 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). Allan Jelacic is the acting DOE/GTD HDR Program Manager, George Tennyson is the DOE/ALO Field Manager, and David Duchane is the Los Alamos HDR 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.

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 of functional personnel.
- Carrying out technical and fiscal planning including preparation of the Annual Operating Plan (AOP), plans for the LTFT installation 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.

Figure 11. HDR Program Management Structure.

- Maintaining liaison with other HDR-related programs and relevant industrial organizations.
- Fostering the transfer of HDR technology to industry.
- Providing information and tours as appropriate to governmental, industrial, and institutional visitors.
- 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; other federal agencies including the USGS, US Forest Service, Environmental Protection Agency, and 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 PDC 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

Industrial: During October, Don Brown and Kerry Burns attended The Geysers Research Project Meeting.

Phil Bauman of Texas Electric Utilities visited Los Alamos in October to discuss the potential of HDR for electric power generation.

Wes Meyers, Don Dreesen, Don Brown, and Kerry Burns met with a number of management and technical personnel from UNOCAL in December to discuss the application of HDR technology to the problem of production declines at The Geysers.

Kerry Burns visited the Electric Power Research Institute in Palo Alto, CA, and Pacific Gas and Electric in San Francisco during February to discuss collaborative work at Clearlake, CA. He was accompanied by a representative of the City of Clearlake. Kerry also visited UNOCAL and Geysers Geothermal regarding joint work at The Geysers.

Jack Andresen, CEO of Energy Transformation Systems, Inc. and a member of the Energy Policy Board of the IEEE, was given a review of the HDR Program and a tour of Fenton Hill during May, 1990.

Kirk Hansen, a petroleum engineer from Shell Development, visited Los Alamos during June, 1990, to become familiar with the FEHM coupled process computer code originally developed for HDR.

A group of ten oil industry people, including seven from Exxon, two from Royal Wire Line, and one from Schlumberger, visited the Laboratory on June 18-19, 1990, to investigate the application of tools developed in the HDR program to their deep gas drilling effort in Oklahoma. After discussions with Laboratory personnel, they were given a tour of Fenton Hill.

Kerry Burns presented information on HDR assessment methods which he has been developing as part of the Clearlake effort to General Atomics computer graphics specialists at the Air Force Weapons Laboratory in Albuquerque, NM, on August 30, 1990.

Academic: Don Brown visited Kansas State University in October to present an HDR seminar and meet with Professor Dan Swenson and Rick Martineau, his graduate student in the Department of Mechanical Engineering. Swenson and Martineau visited Los Alamos in

January to present the results of their modeling work on the Fenton Hill Phase II reservoir performance during Experiment 2070.

Dr. Paul Kruger of Stanford University, a member of the HDR Program Development Council and a Laboratory Consultant, visited the Laboratory on June 13, and June 28, 1990, to confer with the HDR staff on reservoir engineering and seismology issues and to discuss potential Laboratory interests in HDR programs in the Soviet Union.

Lisa Block, of the Earth Resources Laboratory at MIT, visited the Laboratory on June 27-28, to present a seminar and discuss seismic modeling using HDR data.

Media: During May, 1990, Mr. Tom Jenkins, U.S. correspondent for the Portuguese newspaper, Expresso, was briefed on the HDR Program for a story about the Laboratory which he was preparing.

Ms. Jo Campbell of Ecotopics International News Service was given an overview of the HDR Program on June 12, 1990. She was at the Laboratory as part of an assignment for the U.S. Information Agency.

Non-Profit Organizations: Wes Meyers and Dave Duchane from Los Alamos, and Charles Cannon from Cannon Associates, met with Carol Werner of the Environmental and Energy Study Institute to discuss the potential of HDR as an environmentally benign energy source.

Dave Duchane presented a summary of the Los Alamos HDR Program to an audience of about 40 people at the Los Alamos Geological Society monthly meeting on September 16, 1990.

Governmental: Wes Meyers, Mike Berger, Jim Albright, Kerry Burns, and Ray Ponden reviewed all aspects of the HDR Program at DOE headquarters in October.

In December, Mr. Milton A. Eaton, Senior USDOE representative at the U.S. Embassy in Tokyo, visited Los Alamos for an update on the HDR Program and collaborative efforts with Japan.

Ray Waller, then Laboratory Coordinator for Alternative Energy Programs, visited Washington in February for discussions of HDR with DOE/GTD management.

James Rannels, then DOE Program Manager for HDR, visited Los Alamos on March 6-7, 1990.

Dave Duchane and Don Brown met with DOE/GTD management personnel in Washington in late March to discuss the status and future of HDR.

Dave Duchane and Kerry Burns attended a hearing in Lakeport, CA, on April 17, 1990, to discuss potential geothermal developments in Lake County, CA.

J. Michael Davis, DOE Assistant Secretary for Conservation and Renewables, visited Los Alamos on May 31-June 1, 1990. He was given an overview of HDR and participated in discussions on future energy technologies.

Alan Campoli of the U.S. Bureau of Mines visited the Laboratory in May, 1990, and was briefed on the HDR Program.

Kerry Burns, Bob Potter and Dave Duchane visited the California Energy Commission at Sacramento, CA, on June 5, to present overviews of HDR in general and the Clearlake work in particular to members of the commission staff and staff of the Oil and Gas Division of the California Department of Conservation.

Kathy Barco, a consultant for the Guam Energy Office, was given a briefing on the Los Alamos HDR Program and a tour of Fenton Hill on July 18, 1990.

Henson Moore, Deputy Secretary of the DOE, visited the Laboratory on July 13, 1990. He reviewed a number of Laboratory programs and was given a briefing on HDR.

Mike Nelson, a congressional staff person for the Senate Committee on Commerce, Science, and Transportation, visited Los Alamos on August 20th. He was briefed on the HDR program and other EES Division programs by Wes Myers, EES Division Leader.

Dave Duchane visited with Mike Kim, Al Jelacic, and Dr. Ted Mock at the DOE in Washington on August 7, 1990, to discuss a variety of HDR issues.

Dave Duchane attended an informational meeting of the Office of Competitive Technology of the California Department of Commerce on August 30, 1990.

Bob Schmidt of the Twin Cities Office of the U. S. Bureau of Mines visited Los Alamos on September 20, 1990, to discuss work on in-situ leaching of minerals being done by his

organization. Several members of the HDR staff were involved in the meeting with Boh, and it is clear that there are a number of important similarities between these two technologies.

Dave Duchane and Ray Ponden attended a meeting of the Industrial Consortium for the Utilization of the Geopressed-Geothermal Resource in Austin, Texas, on Sept. 11, 1990.

Dave Duchane and Kerry Burns made presentations to the Clearlake, CA, City Council on September 24. Dave presented an overview of HDR technology and our plans for the LTFT, while Kerry discussed the Clearlake work specifically.

International: Mike Fehler, a staff seismologist, spent the first half of FY91 in Japan on assignment to the National Research Center for Disaster Prevention at Tsukuba-shi, Ibaraki-ken.

Dr. Rob Jones of the Camborne School of Mines in the United Kingdom visited Los Alamos during November to discuss the U.S. and U.K. HDR Programs.

Yukiko Yagasaki and Isao Matsunaga of the Japan New Energy Development Organization (NEDO), visited Los Alamos on February 23-24, 1990, to discuss HDR issues.

Yasuto Takeda of the Tokyo Electric Power Services Company and Isao Matsushita of NEDO visited on February 27, 1990.

Professor Motoyuki Sato of the Department of Resources Engineering, Tohoku University, Japan, visited Los Alamos during May, 1990. He presented a seminar on HDR and related seismic research, and took part in discussions of our seismic work.

Dr. Toshiyuki Hashida of the Research Institute for Fracture Technology, Tohoku University, Sendai, Japan, visited the Laboratory on June 11-12, 1990, to discuss fracture mechanics with seismologists in EES Division. He was given a tour of Fenton Hill on June 12.

Dr. Hans Georg Munch of the German Company, Deutsche Schachtbau- und Tiefbohrergesellschaft (DST), visited the Laboratory during June, 1990, to learn about all aspects of our HDR Program and to discuss the plans for a European HDR Program being developed by European Hot Dry Rock Industries. In July, 1990, Dr. Munch visited with management personnel at the DOE/GTD in Washington on the same topic.

Hideshi Kaieda from the Central Research Institute of the Electric Power Industry at Chiba, Japan, visited the Laboratory on August 27-29, 1990, as a guest of our seismology team to confer with our HDR staff. During his visit, he presented an update on Japanese HDR activities carried out by the Central Research Institute of the Electric Power Industry (CRIEPI) of Japan at Akjnomiya, an HDR site on Honshu located somewhat to the north of Hijiori.

Takashi Narita of the Japanese National Institute for Pollution and Resources (NRIPR), Tsukuba, Japan, also visited Los Alamos on August 27-28. He conferred with our HDR staff and presented an update on HDR activities at Hijiori.

Iouri Diadkine, Chairman of the Department of Mining Thermophysics of the Leningrad Mining Institute, visited the Laboratory on September 27-28, along with Paul Kruger of Stanford University. They discussed a number of hot dry rock and hydrothermal energy projects in the Soviet Union which may form a basis for joint efforts between the United States and the USSR.

Intralaboratory: An overview of the HDR program was presented to the National Security Advisory Board on June 13.

Eleven members of the staff of the Laboratory Institutional Relations Office were given a briefing on the HDR Program on June 15. This was followed-up with a tour of Fenton Hill on June 20.

Meetings

Don Brown and Kerry Burns attended the Geothermal Resources Council Meeting at Santa Rosa, CA, in October.

Bruce Robinson attended the Fifteenth Workshop on Geothermal Reservoir Engineering at Stanford University during January 23-25, and presented a paper entitled "Pressure Transient Modeling of a Hot Dry Rock Geothermal Reservoir".

The Program Development Council (PDC) meeting was held in Albuquerque, NM, on March 8. Approximately 17 members from industry attended.

Wes Meyers, Dave Duchane, and Don Brown attended the "Energy and the Environment in the 21st Century" symposium at the Massachusetts Institute of Technology during the week of March 26, 1990. Wes presented a paper entitled "Hot Dry Rock Geothermal Energy - A Renewable Energy Resource that is Ready for Development Now".

Dave Duchane, Kerry Burns, and Don Brown presented papers entitled "Status of the Hot Dry Rock Geothermal Energy Program at Los Alamos," "HDR Technology Transfer Activities in the Clearlake Area, California," and "Using HDR Technology to Recharge The Geysers," respectively, at the Geothermal Program Review VIII meeting in San Francisco in April, 1990.

Don Brown attended the International Society of Rock Mechanics Conference on Rock Joints and the subsequent Workshop on Scale Effects in Rock Masses at Loen, Norway, during the week of June 4, 1990. He presented a paper entitled "The Pressure Dilation of a Deep Jointed Region of the Earth," at the conference.

Dave Duchane and Bruce Robinson attended the 1990 International Symposium on Geothermal Energy sponsored by the Geothermal Resources Council in Kailua-Kona Hawaii, and presented papers entitled "Progress in Hot Dry Rock Geothermal Technology Development," and "Modeling the Hydraulic Characteristics of the Fenton Hill, New Mexico Hot Dry Rock Reservoir," respectively. Paul Kruger of Stanford University also presented a paper entitled "Heat Extraction from Microseismic Estimated Geothermal Reservoir Volume," which summarized some of the work he has done in estimating the "effective" volume of the Phase II HDR reservoir at Fenton Hill. A booth at the symposium, staffed by Los Alamos personnel, provided interested parties with information on all aspects of geothermal work at the Laboratory. Numerous inquiries were received about Hot Dry Rock.

Mike Fehler presented a paper entitled "Inversion of Microearthquake Arrival Time Data at the Los Alamos Hot Dry Rock Reservoir" at the Sixtieth Annual Meeting and Exposition of the Society of Exploration Geophysicists held at San Francisco, CA, during the period September 23-September 27, 1990.

Publications

Review Articles:

Brown, D.W., 1990, "Hot Dry Rock Engineering." Geothermal Resources Council Bulletin 19, 3, 89-93.

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Dennis, B., 1990, "High-Temperature Borehole Instrumentation Developed for the DOE Hot Dry Rock Geothermal Energy Program," Geothermal Resources Council Bulletin 19, 3, 71-81.

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BUDGET

The budget for the Hot Dry Rock Program over the past four years (FY87-90) and as currently allocated for the next fiscal year (FY91) is summarized below:

HDR Program Budget (\$K)

<u>Task/Project</u>	<u>Fiscal Year</u>				
	<u>1987</u>	<u>1988</u>	<u>1989</u>	<u>1990</u>	<u>1991*</u>
Fenton Hill Site Operations	<u>3916</u>	<u>3876</u>	<u>2465</u>	<u>2471</u>	<u>2483</u>
Phase II Energy Extraction System	<u>2539</u>	<u>3099</u>	<u>1582</u>	<u>1588</u>	<u>1610</u>
Phase II Ancillary Activities	<u>710</u>	<u>466</u>	<u>284</u>	<u>284</u>	<u>320</u>
Test Site Support	<u>667</u>	<u>311</u>	<u>599</u>	<u>599</u>	<u>553</u>
Scientific & Engineering Support	<u>2959</u>	<u>1344</u>	<u>1135</u>	<u>829</u>	<u>817</u>
Engineering Development Activities	<u>2602</u>	<u>1130</u>	<u>847</u>	<u>729</u>	<u>725</u>
Technology Applications	<u>357</u>	<u>214</u>	<u>288</u>	<u>100</u>	<u>92</u>
<u>Reserve and Miscellaneous</u>	<u>1125</u>	<u>600</u>	<u>-----</u>	<u>-----</u>	<u>-----</u>
Total	8000	5820	3600	3300	3300

* Allocated as of 1/1/91

A continual decrease in the overall budget has occurred during the course of this 5-year period, seriously hampering our ability to meet program goals. The physical plant required to conduct the LTFT will be completed by the end of FY91 at the current funding levels. Without an increase in annual funding above the \$3.3 million level, however, it is doubtful that a long-term continuous flow testing can be conducted, although shorter, though still technically valuable, flow tests are certainly feasible. We are continuing to try to obtain the additional funding required to conduct the LTFT as a full-scale, extended test of the system.

During recent years, the majority of the funding has been applied to the Fenton Hill Operations Task Area in order to complete development of the Phase II reservoir and design, procure, and construct the surface plant. In FY90, 75% of the funding was spent on Fenton Hill operations. In fact, however, more than 90% of the project work was

The continued budget reduction in FY90 forced further belt tightening in the program, which had already experienced a 50% staff reduction in the previous two years.

FUTURE PLANS

By the end of FY91, the surface plant will be completed, and the Fenton Hill Phase II system will be ready for extended testing. The LTFT will begin as soon as funding levels permit. Every opportunity will be explored to involve industry in this experiment. Industry advice will be sought in developing the final plan for the conduct of the LTFT, and industry participation in the test, as observers or active participants, will be encouraged.

If sufficient funding to conduct a continuous flow test cannot be obtained, transient circulation tests will be carried out. These tests will be directed toward meeting level II and III program objectives with the newly installed plant. These operations may entail intermittent power production, and evaluation of strategies to enhance production including high backpressure, cyclic, and impedance reduction tests, among others.

The long-term goal of this program, as stated in the level I objective, is to improve the technology to the point where electric power can be produced commercially for 5-8¢/kWh. In order to accomplish this goal it is necessary to first convincingly demonstrate the technical viability of HDR. This will most readily be accomplished by a LTFT, which provides experimental answers to the important questions about reservoir lifetime, water consumption, environmental characteristics, power production, and operational parameters. Development of future HDR sites must be accompanied by transfer of the technology to industry for optimization and commercialization.

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