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TITLE HOT DRY ROCK ENERGY ANNUAL REPORT FISCAL YEAR 1992

AUTHOR(S) David V. Duchane - Author
Willanne W. Winchester - Editor

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FISCAL YEAR 1992
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Program Manager: David V. Duchane

Contributors: HDR Program Staff

Editor: Willanne W. Winchester

Illustrator: Ruth Bigio

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EXECUTIVE SUMMARY

Hot Dry Rock technology took a giant leap forward this year as the long-awaited long-term flow test (LTFT) of the Phase II HDR reservoir at Fenton Hill got underway. Energy was produced on a twenty-four hour a day basis for a continuous period of nearly four months of steady-state testing. Hot water was brought to the surface at 90-100 gallons per minute (gpm) with temperatures of 180°C (356°F) and higher. During that time, the HDR plant achieved an on-line record of 98.8%. Surface temperature measurements and temperature logging deep within the wellbore confirmed that no decline in the average temperature of fluid produced from the reservoir occurred. Tracer experiments indicated that flow paths within the reservoir were undergoing continuous change during the test. Remarkably, it appeared that longer flow paths carried a larger proportion of the flow as the test proceeded, while more direct fluid pathways disappeared or carried a significantly reduced flow. In sum, access to hot rock appeared to improve over the span of the test.

Water losses during the test averaged 10-12% and showed a slow long-term decline. These results confirmed what had been previously discovered in static pressurization testing: Water consumption declines significantly during extended operation of an HDR reservoir. In combination with a recent demonstration by the Japanese that water losses can be greatly reduced by the proper placement of multiple production wells, the recent results at Fenton Hill have effectively demonstrated that excessive water consumption should not be an issue for a properly engineered HDR facility at a well chosen site.

Because it was operated under steady-state conditions, the LTFT provided the first opportunity to obtain information on the cost of operating a HDR facility in a production mode. Total costs of fuel oil to

power the injection pumps and electricity for all other parts of the site averaged \$10.73/hour. With thermal power produced at a rate of about 3.9 MW, this translated to an energy cost of about \$0.81/million BTUs. Since electricity was not generated, it is not possible to quantify these costs exactly, but rough estimates are in the range of 2-4¢/kWh.

Although the same water was continuously recirculated during the LTFT, suspended solids in the circulating fluid remained in the range of one to two parts per million (ppm). The amounts of dissolved solids also remained low and stable, never reaching as high as 4,000 ppm. The principle gas in the fluid was carbon dioxide at a level of about 2,000 ppm. Hydrogen sulfide levels were typically less than 1 ppm. The low level of contaminants in the fluid, even after several months of circulation, provided a solid indication that equipment scaling or fouling should not be a problem in HDR systems.

A major setback occurred with the failure of both primary injection pumps in late July 1992. Several months were required to overcome this problem and the LTFT had to be suspended until well into Fiscal Year 1993. During the interim, a modified flow testing program was implemented both to preserve the integrity of the HDR system and obtain limited data that could be generated from operations under less than optimum conditions. A second phase of the LTFT was begun in 1993 but budget limitations may lead to its premature termination.

From a technical standpoint, significant advances in understanding and implementing HDR technology were achieved during Fiscal Year 1992. The course for the future is clear. The test should be completed. Optimization experiments should then be conducted to demonstrate techniques for improving the productivity of HDR

reservoirs. Finally, a second domestic HDR site should be developed under the leadership of private industry to generate and market power at competitive costs. Completing these steps can lead to the rapid

commercialization of HDR as a fully competitive energy source. Unfortunately, it is not at all certain that the resources to accomplish this important work will be provided over the next few years.

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:

- 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.
- Improve the performance of drilling and completion technology under conditions typical of hot dry rock environments.

- Determine the environmental characteristics of HDR technology.
- 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 as follows:

Level III Objectives:

- Evaluate the large Phase II reservoir at Fenton Hill to determine its drawdown characteristics.
- Complete detailed reservoir analyses and confirm modeling of hydraulic and thermal performance of the Phase II system.
- Develop technology to monitor changes in reservoir volume and temperature and confirm monitoring data using tracers.
- Establish reservoir-mapping techniques to locate drilling targets for production wells.
- Conduct studies on water-rock interactions and their effects on flow through a hot dry rock reservoir.

- Verify that the environmental and social consequences of HDR development are acceptable.
- 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.
- Determine means to locate accurately the intersections of fractures with the wellbore.

BACKGROUND

The Resource

Hot springs, geysers, and erupting volcanoes provide clear evidence that the earth's interior is very hot. This heat is geothermal energy. It originates primarily in the lower crust and mantle and from the decay of unstable elements that occur naturally in the upper crust.

The earth's surface is cooled when its heat radiates into space. The outermost layers of the crust are almost the same temperature as the surface due to the cooling effects of ground water circulation. At increasing depth, the greater weight of the rock above reduces permeability and the rate of water circulation. Consequently, 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 accomplished 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.

Figure 1. A geothermal gradient map of the United States. Hot rock is generally found closer to the surface in the western part of the country.

The large earth movements that create earthquakes occur by the sliding of one part of the crust past another along a fracture called a fault. This movement is usually accompanied by considerable fracturing of rock on both sides of the fault. Where the fractures have not been sealed by mineral deposition, ground water 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 a hot spring, geyser, or steam vent. Or, the water 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 where temperatures are high enough to be potentially useful, the usual geologic environment is hot dry rock (HDR).

HDR exists everywhere, but at depths that vary with the local geology. Its heat content represents one of the largest supplies of energy available to man. Assuming 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 we can afford to drill geothermal wells to depths where there are temperatures high enough to generate electricity (depths of 6 kilometers or 19,700 ft are routinely reached in oil and gas drilling); 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 British Thermal Units - BTU's). In energy content, this is equivalent to about 1700×10^{12} (1700 trillion barrels of oil), or approximately 60,000 times the energy in the proven US reserves of crude oil.

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. HDR is also 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 fossil fuel resources are depleted.

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

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

Background studies and field investigations showed that useful hot rock is present at accessible drilling depths under most of the United States. 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.

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.

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.

Figure 2. Conceptual drawing of a hot dry rock geothermal heat mine. In operation, the same water is continually recirculated around the heat extraction loop.

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 Technology 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. In the US, high-grade HDR resources are estimated to occur over more than 60,000 square miles and medium-grade resources more than 300,000 square miles of the land surface of the US.

The work by Tester and Herzog also took into account the effect on costs of further advancements in HDR technology. As an example, the use of two or three production wells per injection well 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. Experimental multi-well HDR systems have been constructed in Japan but have not yet been evaluated from an economic standpoint.

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 BTUs currently and that with advanced development these costs could drop to less than \$5 per million BTUs. Direct thermal heat at \$5 or less per million BTUs is estimated to be obtainable from high-grade resources with today's technology, with the promise of future costs in the \$1-2 per million BTUs range.

International Aspects of HDR: The abundant HDR energy supply is, of course, not confined to the United States. It is a worldwide resource and is attracting increasing international interest. Under an International Energy Agency (IEA) agreement, agencies of the governments of 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.

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

The United Kingdom has been deeply involved in HDR research since 1978. Their experimental site in Cornwall has a relatively low thermal gradient of about 35°C/km. A conceptual design study concluded that the development of a commercial HDR system at that location would not be economically feasible with today's HDR technology. The British have thus decided to de-emphasize

underground work in Cornwall and take a more active role in other western European HDR projects with an eye toward future participation in a major HDR development effort under the auspices of the European Community.

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

All of these activities are leading to the selection of a single site for a major HDR Program to begin in 1994-1995 with financing by the European Community. A consortium of German, French, and British companies have proposed a \$300 million program to be conducted over 10 years. It would be designed to demonstrate the viability of HDR in the areas of low thermal gradient that are typical of northern Europe.

Significant HDR work was also conducted in Russia during the past few years. Drilling and fracturing operations were carried out at Tirniaus near Elbrus in the Caucasus Mountains. The experimental work followed the Fenton Hill model with drilling to 3.6 km followed by fracturing operations at

pressures up to 60 MPa (8700 psi). Mechanical problems led to abandonment of the deepest portion of the original wellbore, but sidetracking to another location at the same depth and further fracturing are planned. The Russian program could be greatly enhanced by some of the advanced technologies developed at Fenton Hill. Under the right conditions, joint US-Russian cooperation could lead to significant benefits for both parties.

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 related 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 surfaces within the rock; and the operation of a recirculating, pressurized-water loop to extract heat from the rock and transport it to the surface. At the surface, the useful heat is recovered through heat exchangers, and the cooled water is reinjected to recirculate through the fractured rock and recover more heat from it.

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

This "Phase I" or "Research" system extracted heat from hydraulically fractured granitic rock at a depth of about 3000 m (9850 ft), where the initial rock temperature was around 185°C (365°F), and brought it to the surface in pressurized water at 135° to 140°C (275° to 285°F) at rates up to 5 MWt (thermal megawatts, or about 17 million BTU/hr). Some of the heat was used to operate an experimental binary cycle power plant which produced 60 kW (kilowatts) of electricity that were used at the site. System

operation was essentially trouble-free, and there were 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 electricity-generating power plant in competition with fossil fuel or nuclear energy plants. Since higher temperature HDR systems had the potential to do so and a worldwide need existed for clean alternative energy supplies, the HDR Program was extended to attempt to meet those more demanding requirements.

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

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

The largest of the potential redrilling targets was the fractured volume produced in December 1983 by the Massive Hydraulic Fracture (MHF) Experiment during which 21,300 m³ (5.63 million gallons) of water were pumped at 48-MPa (7000 psi) pressure

into an isolated section of the deeper well, EE-2, in the depth interval 3529 to 3550 m (11,580 to 11,650 ft). The target volumes were based on the locations of microearthquakes determined from analyses of records of the seismicity that occurred during the MHF Experiment.

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

Figure 3. (a) Original conceptual design of the Phase II HDR reservoir.
(b) View of the actual Phase II HDR reservoir.

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 thirty 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 operation from temporary storage in the pressurized fracture system. Pumping rates were usually either 10.6 or 18.5 l/s (168 or 295 gpm) at surface pressures of about 26.9 MPa (3900 psi) and 30.3 MPa (4400 psi), respectively. To prevent boiling of the superheated water or evolution of carbon

dioxide gas entrained in the fluid, a back-pressure of about 3.5 MPa (500 psi) was maintained on the production well. Fluid production rates were 6.3 to 13.9 l/s (100 to 220 gpm). As illustrated in Figure 4, results of the ICFT were uniformly encouraging. Over the course of the thirty day test, the temperature of the produced fluid increased to about 200°C (390°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 during the test. The recovery rate of injected water increased with time under conditions of constant pressure and was continuing to improve at the close of the test.

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

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

In January 1987, the Geothermal Technology Division of the DOE convened a panel of drilling and well-completion experts to explore solutions to the problems at Fenton Hill. In accordance with their recommendations, the HDR Program opted to seal the casing leaks and add support to the upper part of the casing by cementing the annulus behind it. The well was also sidetracked and redrilled from a point above the region of casing collapse.

A drilling rig was mobilized over well EE-2 in early September 1987 to conduct 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 (2510 ft) in 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 Fiscal Year 1988, a whipstock was installed and the well was successfully sidetracked. The redrilled wellbore was 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 two and one half times faster than was achieved during the original drilling of the well in 1978-1979. 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 the overall costs to generate electricity.

A potential major obstacle to the long-term testing of the Phase II system was resolved by a long-term pressurization test of the Phase II reservoir during 1989-1991. The rate at which water is irrecoverably lost to the underground rock 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. At Fenton Hill, the rate of water loss, which had been measured during transient flow tests, including the ICFT noted above, would have been unacceptable for the long term operation of the Phase II system or others like it in the arid west. Subsequent measurements of water loss conducted under steady-state, conditions during long-term pressurization have shown that the water loss rate during operation of the reservoir should be much less than earlier estimates based on transient measurements.

As shown in Figure 5, the water required to keep the Phase II reservoir at Fenton Hill at a constant level of pressurization has been shown to decline linearly with the natural logarithm of time as microcracks in the reservoir rock become saturated. Eventually, water consumption reaches a very low rate, indicative primarily of water leakage from the periphery of the reservoir. This important finding provides strong evidence that excessive water consumption will not be a major problem during sustained operation of HDR plants.

Figure 5. The water required to maintain the HDR reservoir at a constant pressure of 15 MPa (2180 psi) declined linearly with the natural logarithm of time.

Construction of the surface plant required for continuous operation of the Fenton Hill HDR system was essentially completed in late 1991. Figure 6 is a flow diagram of the facility. The system was constructed to power plant standards and completely automated. The most important data

acquisition and control points in the surface loop are shown in Figure 7. With plant construction essentially complete, 1992 began with the Fenton Hill facility ready for plant commissioning and flow-test operations.

Figure 6. Flow diagram of the Fenton Hill HDR surface plant. The system is normally operated in a closed-loop mode with water constantly recirculated through the underground reservoir.

Figure 7. The Fenton Hill HDR plant is fully automated with numerous control and data acquisition points.

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. This mutually beneficial arrangement provided the opportunity for industrial and HDR program personnel to learn from and with each other in advancing the technology of drilling, well completion, and hydraulic fracturing in a new and challenging underground environment. Drilling and coring bits, downhole motors, open-hole packers, and other equipment developed for the HDR Program are now used throughout the drilling industry. Instruments developed for use in the Fenton Hill wells are now used in both 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. Innovations and developments from the HDR Program will significantly increase the efficiency and reduce the costs not only of future HDR systems but also of many other underground operations.

Possible applications of HDR technologies for the mitigation of the pressure decline at The Geysers (the world's most productive hydrothermal energy field) 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 assist in assessing the problem at The Geysers. LANL scientists applied their knowledge of the mechanical properties of fractured reservoirs (obtained through the years of research at Fenton Hill) to recommend solutions.

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. That study and the request for a further study were both funded by the city of Clearlake, CA under the auspices of the California Energy Commission. In the completed study, Los Alamos assembled and analyzed well log, geophysical, and geological data available for the Clearlake region with the goal of identifying potential hot dry rock locations for the siting of a power plant for the municipality. Scientific data were compiled in a portfolio at the scale of 1:62,500 comprised of topography, gravity, aeromagnetic, resistivity, geology, thermal gradient, and well location sheets. Subsurface predictions of the locations of hot dry rock environments were made by the simultaneous interpretation of information assembled together in the portfolio. Two areas for the potential siting of a hot dry rock power plant were identified.

Early in FY 91 the city of Clearlake secured additional funds from the California Energy Commission for a greatly expanded study, citing Los Alamos as the sole source for HDR technology in the country and requesting Los Alamos direction of the study. Work has concentrated on the development of a conceptual and computational model to explain the assembled data on the basis of thermal history, temperature and hydrologic gradients, rock structure, and the distribution of fracture permeability. Data from existing wells has been heavily relied upon in the development of the model. An analysis of the comparative merits of sites in the Clearlake area vis-a-vis current hot dry rock technology is also being completed. At the conclusion of this phase of the project, the stage should be set for site selection and initial drilling in connection with the development of the Clearlake HDR resource.

PROGRESS: FISCAL YEAR 1992

Overview: During this year, the construction and commissioning of the surface plant was completed and flow-testing was initiated. After a few short preliminary runs, the long-term flow test (LTFT) was begun on April 8, 1992. The plant operated around the clock for 112 days with a 98.8% on line record until a major failure of the injection pumps forced a shutdown of the system on July 31. Cold water injected during the test was returned to the surface at a rate of 90-110 gpm and at temperatures in excess of 180°C (360°F). This approximately four-month long flow test has been designated as the LTFT Phase I. An interim flow test, (IFT) program was carried out for the remainder of the year with the goal of maintaining the wellbores and reservoir in a stable condition and gathering the limited technical data that could be generated from less than optimal operations. The IFT was conducted with backup and rental pumps not suited for sustained operations at LTFT Phase I conditions. By the end of the fiscal year, arrangements had been made to lease a specially built pump designed for extended operation and capable of injecting fluid at the pressures and volumes required to resume flow testing at the conditions in effect during the LTFT Phase I.

Results of the four-month LTFT Phase I were extremely encouraging.

- There was no indication of thermal drawdown of the reservoir.
- There was evidence of increasing access to hot rock as the test proceeded.
- Suspended and dissolved solids and entrained gases remained at extremely

low levels throughout the entire period of closed-loop circulation.

- Water consumption was in the range of 10-12% of the injected volume.
- Measured pumping costs as reflected in the cost of fuel to power the injection pumps and electricity to run the other plant components were less than \$0.003 per thermal kilowatt of energy produced.

Progress in plant commissioning and operation, the details of flow-testing and all aspects of scientific and engineering support for the HDR Program this past year, are discussed in the following sections of this report.

Plant Commissioning: Figure 8 is an illustrative sketch of the Fenton Hill HDR Plant. The final details of construction of this plant were completed and shakedown operations were underway by early in Fiscal Year 1992. A minor problem with one of the injection pumps was corrected at the beginning of the year when an out-of-tolerance bearing was detected and replaced. During the related disassembly of the pump, scratches and peen marks were noted on the sealing surfaces of its valves. These were attributed to particulate material apparently carried into the pumps during start-up operations. The fluid contacting surfaces of the valves from both pumps were remachined and strainers were installed upstream from the pump to prevent a recurrence of the problem. Final pressure hydrotesting of the entire loop early in the year confirmed the pressure integrity of all the components.

Figure 8. The Fenton Hill HDR Surface plant (not to scale).

A major milestone was reached in early December when the full plant was operated to circulate fluid through the reservoir for a four-day period. About 370,000 gallons of hot water were produced during this time. All major components of the plant performed adequately, but a number of minor operational issues were identified and addressed. A second circulation flow test run was carried out in early February. Approximately 460,000 gallons of hot water were produced during that four-day run. At its close, a short experiment was conducted to evaluate the feasibility of using a low-level

production flow (10-20 gpm) to protect the surface equipment from freezing when the system was shut down for any reason during the winter. By the close of the fiscal year, this low-flow operating mode had been designed into the plant control system so that it could be programmed to go into operation automatically whenever a plant shut down occurred.

A third shakedown run near the end of February was designed to test the plant under a variety of realistic operating scenarios. Because power outages at the Fenton Hill site

can occur unexpectedly, part of this test simulated the loss of electric power in order to verify that specially designed control functions would act to assure an orderly shutdown of operations on these occasions. In fact, several power outages occurred during subsequent flow testing while the plant was running with no operating personnel on site. In all cases, the automatic shutdown controls performed flawlessly.

Surface Loop Expansion: By the first of March, all system components appeared to be functioning as designed. After inflation of the reservoir to the appropriate pressure, circulation was initiated on March 3, with personnel on duty at Fenton Hill on an around-the-clock basis for what was expected to be an extended flow test. Except for some minor problems such as a brief power loss, the surface facility performed satisfactorily throughout the start-up period. On Friday, March 13, however, it was necessary to cease operations due to a problem developing in the surface loop piping circuit.

Regular inspections of the surface loop components were established as part of the standard operating procedure at the site. Some growth of the production wellhead piping was noted, and the situation was monitored closely. When it appeared that continued thermal expansion could lead to excessive bending in some of the piping and put undue strain on some components, the decision was made to shut the system down and modify that section of the loop.

The remainder of March was spent in determining how much further expansion could be expected, designing an expansion section with minimal dislocation of the existing piping, procuring material, fabricating the new piping string, and inspecting the finished work both visually and radiographically. By early April, the system was ready for the resumption of extended flow testing.

The reworked piping was closely monitored throughout the month of April to assure that the expansion problem had been adequately addressed. The observed expansion was well within the limits of the redesigned section. In addition, an outside engineering firm was called in to look at the entire surface facility as part of a quality control plan to prevent further problems of this nature. Doug Brown of the Ben Holt Company visited the Fenton Hill HDR site on April 14 to review the design and construction of the surface plant. He found no obvious deficiencies requiring immediate attention. His follow-up report, issued several weeks later, contained several suggestions for minor changes in the design and operation of the plant. These were adapted to the extent they could be implemented on a practical basis.

Unmanned Plant Operations: The Fenton Hill HDR facility has been designed for automated operation with numerous fail-safe mechanisms. If boundary conditions of important operating parameters are exceeded, these mechanisms will trigger a controlled shutdown of the plant without human intervention. In mid-April, the plant was put on a schedule that included operation, without the presence of personnel, through the late night weekend hours. An automatic shutdown occurred on the second evening of unmanned-manned operation due to a momentary loss of electrical power supply to the site. This unplanned event provided a realistic test of the automatic shutdown controls. The shutdown occurred exactly as designed. Over the next few weeks, several other minor and major power failures triggered additional shutdowns which confirmed the reliability of the fail-safe system. Modification of electrical controls, so that relatively brief power glitches did not shut in the system, brought the plant to a point where cost-saving, unmanned operations could be implemented in a completely safe manner with minimal risk to the experimental program.

By mid-June, operating personnel were working only a limited shift schedule, making flow testing possible even in the face of an extremely limited program budget. As usual, the site was guarded on a round-the-clock basis to discourage vandalism. The guard also monitored the functioning of the plant but was neither trained nor authorized to intervene in the event of an operational incident.

Failure of the Primary Injection Pumps:

The sudden, unexpected, and dramatic failure of both primary injection pumps in late July was by far the major operational problem faced this year. The resulting loss of injection capability forced an unplanned suspension of the long-term flow test (LTFT), although an interim flow test (IFT) using first a lower capacity backup pump and then a used rental pump was instituted within a few weeks. By the end of the fiscal year, plans were underway to procure a specially built rental pump with the injection capabilities required to resume testing under LTFT operating conditions.

The plant had been running smoothly for nearly four months with the two injection pumps operating on an alternating basis in ten-day segments each. On July 29, leakage of circulating water into the pump lubricant shut down one of the injection pumps. While that pump was being dismantled for inspection, the other pump was put into operation. The leakage was rapidly traced to a crack in one of the pump's five working cylinder blocks (forged blocks of steel in which each of the pump's five pistons operate). A detailed examination of the other four cylinder blocks was underway when the second pump failed in the same manner on July 31. Upon further inspection, all the cylinder blocks from both pumps were found to have hairline cracks making them unusable. An intensive investigation was immediately begun to determine the cause of the cracking. A variety of hypotheses were advanced including unanticipated operating

stresses, fabrication defects, materials incompatibilities, and cavitation induced failure

The investigation into the working barrel failure involved several analytical reviews of their design and two metallurgical evaluations of the failed components. Stress analyses were conducted by the pump manufacturer (Ingersoll-Rand), the Mechanical Engineering Department of Kansas State University, and the Los Alamos Advanced Engineering Technology Group. All three studies concluded that the mechanical design of the working barrels was adequate for the stress conditions expected in operations at Fenton Hill.

The metallurgical examinations were carried out independently by Ingersoll-Rand and the Los Alamos Materials Technology Division. A review of the metallurgical finding was conducted by John Weeks, a metallurgist from the Brookhaven National Laboratory. All the metallurgical evaluations reached the same conclusion: the microstructure of the barrel material, a Nitronics 50 stainless steel alloy, was not homogeneous. Large amounts of a sigma phase were detected in all the samples examined. The sigma phase apparently separated as the alloy was cooled after the blocks from which the barrel was ultimately machined had been forged. The sigma phase is known to be both chemically reactive and brittle in comparison to the normal austenitic structure of the Nitronic 50 alloy.

The two reviews differed in assessing the mechanism of the component failure. Ingersoll-Rand concluded that the barrels fractured by brittle fatigue. As part of the Los Alamos study, material from the defective components was fatigue-tested. Two test specimens, one of which had been notched to induce fatigue cracking, were subjected to more than 25 million test cycles in air. Neither specimen showed any signs of fatigue cracking. At the time the failure

occurred, the injection pumps had been operated for a total of about 12 million cycles each. The Los Alamos metallurgists thus concluded that corrosion as well as fatigue must have played a part in the failure of the barrel material.

The presence of the deleterious sigma phase in the alloy was attributed to the method used to anneal the barrel forging. The annealing process for Nitronics 50 entails heating the material to a temperature of 1950-2050°F and then cooling. The technique used for these defective components entailed a slow cooling method. All the metallurgists involved in this investigation recommended a rapid cooling cycle (water quench, for example) be employed to inhibit the formation of sigma phase in the alloy material. To verify the effectiveness of rapid cooling, a heat treatment experiment was conducted by the Los Alamos Materials Technology Group. It involved heating one of the defective components to 2050°F and then rapidly cooling it by oil quenching. After this annealing procedure, the barrel was cut into sections and examined microscopically. The amount of sigma phase was found to be significantly reduced although it had not been completely eliminated. The residual sigma phase was attributed to the previous thermal history of the material.

The forging procedure used to produce the material for the barrels, including the annealing steps, had been the subject of numerous technical analyses. These included correspondence from the supplier of the material, the pump manufacturer, the forge shop, and Los Alamos as represented by its consultant on this aspect of the project. The records show that a variety of opinions were voiced as to the preferred method for annealing the forgings. What appears to have been the definitive memo was issued in May of 1990 by the consulting firm representing Los Alamos. It specifies a course in regard to the forging process which

includes air (slow) cooling as part of the annealing process.

The manufacturing document from the forging vendor stipulates fan cooling in which air is blown over the component. While no justification is given for opting for air cooling rather than a water quench, it can be surmised that the assumption was made that slow cooling would result in greater relief of residual stresses in these large, heavy (approximately 600 lbs each) blocks of metal. The completed components were accepted by Los Alamos as produced. The pumps themselves were formally accepted by the Laboratory in March of 1991 after considerable on-site operational testing at Fenton Hill. Performance of the pumps was guaranteed by the manufacturer for 1-year from the date of final acceptance. This guarantee period expired in March 1992, about five months before the massive pump failure.

In seeking remedies for the failure of the injection pumps, a number of courses of action were considered. A decision was immediately reached that no steps would be taken to repair the pumps until the reasons for the failure of the working barrels were understood and a viable solution had been proposed. In the meantime, backup pumping was installed to maintain the reservoir in a pressurized condition and permit a modicum of testing to continue. The backup pump employed was an old unit already on hand at Fenton Hill that had neither the capacity to inject at the levels established during the LTFT, or the quality of construction to function on a long-term basis. Other pump options were explored and a used oil field "mud pump" of reciprocal design was found to be immediately available. It was leased for a three-month period. This pump had the required capacity but in operation it proved to be highly unreliable and prone to frequent breakdowns requiring the replacement of minor components.

The REDA Pump Company of Bartlesville, Oklahoma, agreed to build a pump of their design specifically to meet the requirements of the Fenton Hill test program. As shown in Figure 9, the REDA pump is fundamentally different in design from the Ingersoll-Rand pumps. It is a centrifugal rather than a piston pump and is powered by electricity instead of diesel fuel. The REDA pump is constructed in stages, and over 200 stages are needed to achieve the required injection pressure of about 4,000 psi. Early in Fiscal Year 1993, the REDA pump was

procured on a three-month, renewable lease contract. The REDA pump has been delivered, installed, and put into satisfactory operation at Fenton Hill. Although the REDA centrifugal pump lacks the flexibility of operation of the failed reciprocating pumps and is somewhat less efficient, it is simpler to operate and maintain. As long as the LTFT continues to be conducted within a narrow range of operating parameters, the REDA pump may prove to be completely satisfactory for the requirements at Fenton Hill.

Figure 9. (a) A cut-away view of a diesel powered Ingersoll-Rand reciprocating pump. (b) The REDA centrifugal pump consists of over 200 stages in a long pipe driven by an electric motor.

a)

b)

OTHER PLANT MODIFICATIONS

Rotojets: A lingering problem noted during the commissioning and early flow-testing at the Fenton Hill plant involved spurious shutdowns of the Rotojet makeup water pumps. Because makeup water could be supplied by other available pumps, although only against a lower pressure head, this problem did not interfere with the operation of the loop. It did limit the pressure in the low pressure segment of the loop to a maximum of 200 psi. After a series of discussions with the Rotojet Co. engineering staff, the required modifications control system for Rotojet pumps was finally worked out and implemented. Since that time the Rotojet pumps have performed up to their original specifications. Using these pumps, it has generally been possible to maintain the low pressure portion of the piping at about 700 psi during closed-loop operations.

Wellheads: Platforms were designed and installed around both the injection and the production wellheads early in the year. These structures have greatly simplified access to valves, controls and other wellhead

components. Both routine operations and special procedures, such as logging runs and tracer experiments, have been expedited as a result. The platforms also provide a structure around which canvas tarps can be installed as part of a freeze protection procedure employed whenever necessary.

Water rights: A guaranteed water supply is essential to the operation of any HDR plant. Water at Fenton Hill is obtained from an on-site well in accordance with the stipulations of a permit issued by the Water Rights Division of the New Mexico State Engineer's Office. In January 1992, this permit was renewed with the provision for the withdrawal of 30 acre feet of water in 1992 and 15 acre feet in 1993. The conditions of the permit included a provision that these diversions be offset by the dedication or retirement of existing water rights in the area. The responsibility for addressing this requirement is administered by the Los Alamos Area Office of the U.S. Department of Energy which purchases water rights from statutory owners using funds allocated to the Los Alamos HDR Program.

RESERVOIR TESTING

Overview: Extended pressurization testing came to a close early this year and the long-term flow testing program began. Figure 10 provides a synopsis of the state of the reservoir over the span of Fiscal Year 1992. Water was circulated through the reservoir for more than 160 days in a number of flow test segments. The longest of these, designated LTFT Phase I and lasting for 112 days, provided extremely important evidence in regard to the viability of operating HDR

reservoirs for extended periods of time. The flow tests prior to the LTFT Phase I were primarily designed to refine the operation of the surface plant and establish operating parameters. Post-LTFT Phase I testing, referred to as the Interim Flow Test, was of a stop-gap nature, conducted to maintain the thermal stability of the underground system and gather the limited data that could be obtained from circulation under less than optimum conditions.

Figure 10. Production flow (top) and pressurization history (bottom) of the Fenton Hill HDR system over the course of Fiscal Year 1992. Four preliminary flow tests, the long-term flow test (LTFT) and the interim flow test (IFT) were conducted during the year.

Reservoir Pressurization Testing:

The multi-year reservoir static pressurization experiment came to an end early in Fiscal Year 1992 when fluid was circulated through the reservoir on December 3, 1991. The reservoir pressure stood at 13.2 MPa at the beginning of Fiscal Year 1992 on October 1, 1991. It was allowed to decay through the months of October and November as work on the surface plant was completed. By November 22, it had declined to 9.2 MPa (1330 psi), the lowest level the reservoir pressure had been allowed to drop to since May 1989. On November 22, a sixty three hour injection run was initiated during which 400,000 gallons of water was pumped into the reservoir to raise the reservoir pressure to 21.5 MPa (3125 psi), the highest reservoir pressure attained in the course of the extended pressurization experiment. Near the end of this run, water was being pumped into the reservoir at a rate of 117 gpm at 28.9 MPa (4200 psi) injection pressure. There were no indications of reservoir growth

During the first 6 hours after the pumping was halted, the reservoir pressure declined by only 0.44 MPa (64 psi or an average of 10.7 psi/hr), indicating that the reservoir was extremely water tight. The reservoir subsequently declined to 15.7 MPa (2270 psi)

before injection was resumed on December 2 in preparation for flow testing.

Pre-LTFT Flow Testing: Prior to the inception of The LTFT Phase I, short flow tests were conducted in December 1991, February 1992, and March 1992. The December test marked the first significant period of circulation through the reservoir in about 4 years (although the system had been kept pressurized by injection of water into it over most of that time). It was conducted to evaluate the surface plant and look for any obvious changes in the reservoir which might have occurred during the long shut-in period. About 370,000 gallons of water were circulated through the reservoir during this three day test with production temperatures ultimately reaching 154°C (310°F). All major components of the plant performed adequately but, as expected, a number of minor problems interfering with smooth plant operations were revealed. Additional short flow tests were conducted during February-March 1992 as part of the continuing effort to check out the surface system, gain hands-on experience operating the facility, and determine the optimum operating parameters. Table 1 summarizes some of the important data from these short flow tests.

Table 1
Reservoir Performance During Pre-LTFT Flow Tests

<u>Test Date:</u>	<u>Dec. 4-7</u>	<u>Feb. 4-7</u>	<u>March 3-13</u>
<u>Injection Conditions</u>			
Flow Rate, l/s (gpm)	5.4 (85.8)	7.2 (114)	7.0 (111)
Pressure, MPa (psi)	25.5 (3700)	26.7 (3865)	25 (3760)
<u>Production Conditions</u>			
Flow Rate, l/s (gpm)	4.7 (74.1)	6.3 (101)	6.0 (95)
Backpressure, MPa (psi)	15.2 (2210)	10.6 (1510)	10.3 (1500)
Temperature, °C (°F)	154 (310)	177 (351)	180 (356)
<u>Water Loss</u>			
Rate, l/s (gpm)	0.61 (9.7)	0.72 (11.5)	0.46 (7.3)
Percent	11	10	6.9

Results of the Four-Month Steady-State Long-Term Flow Test: Between April 8 and July 31, 1992, water was circulated through the Fenton Hill HDR reservoir to produce thermal energy on a 24-hour-a-day basis under almost constant operating conditions. Over this 112 day period, energy production was maintained at an average level of about 4 thermal megawatts with only a few short interruptions due to electric power outages. The system operated for 2,716 hours and production was shut-in for 31.4 hours. The on-line availability factor was 98.84%. There was no evidence of thermal drawdown. In fact, it appeared that access to the reservoir rock increased as the test proceeded. Water consumption averaged about 11% during the test, but about 17% of this

water use could be directly attributed to increased storage in newly opening or enlarging rock joints within the reservoir.

Figure 11 shows that the injection pressure rapidly increased to the highest level that could be maintained without causing reservoir growth, as indicated by induced seismicity. No microearthquakes were detected by the deep seismic monitoring devices at Fenton Hill during the test period. At the same time, a backpressure of 9.7 MPa (1400 psi) was generally imposed on the production wellhead in order to dilate the joints in the normally low-pressure region of the reservoir near the production wellbore.

Figure 11. Wellhead pressures during the LTFT. The injection pressure was maintained at the highest possible aseismic level. A backpressure of about 9.7 MPa (1400 psi) was typically maintained on the production well.

Figure 12 gives production and injection temperature profiles over the course of the test. After rising rapidly to 184°C (363°F) the production temperature tapered off very slowly to 183°C (361°F) over the duration of

the test. This slight decline in temperature was definitely **not** due to thermal drawdown of the reservoir. A series of logging runs indicated that there had been no net cooling of the reservoir's production zone.

Figure 12. Production and injection fluid temperatures during the LTFT.

The cause of the drop in surface production temperature during the four-month flow test can be directly attributed to the observed decline in the production flow rate shown in Figure 13. Cooling of the circulating fluid during passage through the several-kilometer-long production wellbore has proven to be strongly related to the flow rate.

For example, at flow rates in excess of 200 gpm, production fluid surface temperatures of nearly 200°C have been reached. At flow rates of about 100 gpm and 60 gpm, surface production temperatures have been found to be in the range of 180°C and 160°C respectively.

Figure 13. Injection and production rates declined about 10% over the course of the LTFT. The bypass flow is due to a leak from the reservoir to the annulus of the injection wellbore.

Figure 13 indicates that both the injection and production flow rates decreased over the term of the test in spite of the fact that the injection pressure was maintained and even slightly increased throughout the test. The concomitant reduction in the production fluid

temperature is somewhat less than would have been anticipated based on the previous experience cited above.

The 10% decline in the production flow rate can best be explained by reference to tracer data collected during the four-month LTFT. Figure 14 shows the results of tracer tests conducted during May and July. During the May test, tracer was detected after only three and one half hours residence time in the

reservoir and the tracer return peaked at about eleven hours. In the July test, the first return of the tracer was not observed until about five hours after it entered the reservoir and the peak return point was reached after about sixteen hours.

Figure 14. A tracer injected in July took considerably longer to pass through the HDR reservoir than a similar tracer injected in May, indicating that the flow within the reservoir had become redistributed to more indirect pathways between the wellbores.

These two sets of tracer data provide a clear indication that a redistribution of flow within the reservoir occurred between May 18 and July 7. Quantitatively, about 6% of the fluid (6 gpm of the 100 gpm being produced) that travelled more or less directly between the wellbores in May was flowing through more circuitous, longer-residence flow paths by early July. The increased impedance to flow which developed during this period, as evidenced by lower production flow at a constant injection pressure, would be one expected result of such a flow redistribution. At the same time, the increased fluid access to more remote portions of the reservoir would be expected to enhance its thermal performance over time.

Another temporal change in the reservoir has also been quantified from the tracer data. The total volume of all flow paths

transmitting fluid from the injection to the production wells increased by 520 cubic meters (from 2246 cubic meters to 2766 cubic meters) between May and July. Much of this increase can be attributed to thermal contraction of the rock in the region of the inlets to the reservoir from the injection wellbore, but additional flow paths connecting the wellbores may also be making a contribution to the increased fluid volume.

Thermal power production during the continuous test phase is illustrated in Figure 15. After peaking at 4.67 MW on April 29, power production declined in concert with the declining flow rate. Near the termination of the test in late July, it was averaging about 3.86 MW. Over the 112 days of the test, a total of more than 10,800 MWh of thermal energy was produced.

Figure 15. Thermal power production during the LTFT.

The apparent rate of water loss from the reservoir is shown in Figure 16. As discussed in detail later in this report, tracer studies indicate that about 17% of this apparent water loss can be accounted for by

the 520 cubic meter increase in the fluid volume in the flow paths described above. The remaining water loss is due primarily to permeation from the boundaries of the reservoir.

Figure 16. Water losses during the LTFT varied greatly on a day-to-day basis but showed a long-term downward trend.

As illustrated in Figure 16, the rate of water loss gradually declined with time after an initial transient period when the reservoir was still filling up. This occurred in spite of gradually increasing injection pressure, the primary driving force for increasing water

losses in the very large, stagnant side of the reservoir away from the production wellbore. The data thus suggest that the reservoir is behaving in the same general manner as it did during static pressurization testing conducted during 1989-1991.

The small hump in the water loss curve beyond day 90 of the test is fallacious, being primarily a function of refill of the reservoir in response to a seventeen hour shut-in that occurred on July 11-12 when electric power to the site was interrupted. The July shut-in incident is clearly discernible in the daily average data of Figures 11-13 and 15-16. Although pressure, temperature, flow, and power output stabilized rapidly when operations were resumed, water losses were only approaching their long-term trend line when the test was suspended at the end of the month.

In summary, this LTFT segment produced no evidence of thermal drawdown, but system impedance increased with time,

Post-LTFT Phase I Testing: When the massive failure of the primary injection pumps forced suspension of LTFT flow testing, an interim flow test (IFT) program was initiated. The function of this test effort was both to maintain the thermal stability of the injection and production wellbores and to obtain any operational data that could be generated with a less-than-optimal injection pumping capability. During the six week period from August 20 to October 1, 1992, the IFT was conducted at an injection rate of about 4.3 l/s (68 gpm) using a limited-capacity, reserve pump on hand at Fenton Hill. This pump was not designed for continuous operation and it was necessary to shut the system in for a week part of the way through the test to repair the pump.

Figure 17 shows the injection and production pressure profiles over the course of the six

apparently due to a redistribution of flow within the reservoir as the test proceeded. This steady-state test provided a wealth of valuable data until mechanical problems, fundamentally unrelated to HDR technology, forced it to be suspended at the end of July. It is imperative that the conditions of this test be re-established. Several more months of testing under these conditions should be conducted to verify the validity of the data collected during April-July and to provide a more complete picture of the behavior of the Fenton Hill HDR reservoir under conditions of continuous circulation. Within the limitations of the available budget, the Los Alamos HDR staff is attempting to do just that.

week IFT. The reservoir shut-in period during mid-September is readily apparent. After steady-state flow conditions were established at the beginning of the test, the injection pressure gradually leveled out at about 22.2 MPa (3220 psi). The production wellhead pressure was maintained at 9.7 MPa (1400 psi) during flow periods. It rose rapidly to about 19 MPa (2750 psi) when the system was shut in and stayed at that general level until circulation was resumed. Of particular note is the fact that upon shut in of the system, the pressure at the production wellbore increased much more than the pressure at the injection wellbore as the two wells approached a common pressure level. This phenomenon provides a strong indication that the bulk of the reservoir impedance to flow is found in the region of the production wellbore.

Figure 17. Injection and production pressures during the IFT. The injection pressure remained well below the threshold of seismic activity.

The injection and production flow rates during the IFT are shown in Figure 18. Again, the shut-in period is evident. Throughout the test, only a small difference between the injection and production flow

rates was observed indicating a very low level of water loss. Comparison of this data with that from the LTFT Phase I highlights the importance of injection pressure in determining water loss.

Figure 18. Injection and Production flow rate during the IFT. The test was interrupted by a several-day shut-in during early September. A small bypass flow through the injection well annulus is not shown.

The wellhead temperatures during the IFT are given in Figure 19. The rapid rise in the production temperature to a steady-state level of about 165° C (329°F) indicates that the three week shutin between the end of the LTFT Phase I and the beginning of the IFT

did not significantly perturb the temperature field in the region surrounding the production wellbore between the reservoir and the surface. No doubt this was because the rock in that region had been considerably heated

during the previous four months by the continuous flow of superheated water.

Figure 19. Production and injection fluid temperatures during IFT.

Table 2 is a comparison of performance data of the LTFT Phase I and the IFT.

Table 2 Reservoir Performance During the LTFT and the IFT		
Test:	LTFT	IFT
Measured Performance Dates:	July 21-29	Sept. 29
<u>Injection Conditions:</u>		
Flow Rate, l/s (gpm)	6.76 (107.1)	4.34 (68.8)
Pressure, MPa (psi)	27.29 (3958)	22.36 (3243)
<u>Production Conditions:</u>		
Flow Rate, l/s (gpm)	5.66 (89.7)	3.85 (61.1)
Backpressure, MPa (psi)	9.66 (1401)	9.65 (1399)
Temperature, °C	183	165
<u>Water Loss:</u>		
Rate, l/s (gpm)	0.79 (12.5)	0.23 (3.6)
Percent	11.7	5.2

The lower steady-state production temperature attained during the IFT is a direct result of the reduced production flow rate and the

resultant increased thermal loss to the surrounding rock as the hot water traveled from the reservoir to the surfaces.

Two additional observations can be made from the data of Table 2. First, although the difference in injection pressure between the two tests was only 22%, the flow rate difference was 56%. These data thus demonstrate the strong nonlinear relationship between pressure in the body of the reservoir and joint flow. Second, as mentioned earlier, the rate of water consumption was much lower at the reduced injection pressure, indicating the large nonlinear dependency of

permeation outflow on the mean pressure level difference between the reservoir boundary and the far-field, as opposed to simply the driving pressure pushing water through the reservoir.

Figure 20 further illustrates that the temperature decline as the fluid travels from the outlet of the reservoir to the surface is very significant and highly dependent on the flow rate.

Figure 20. Logging data shows the effect of flow rate on the surface temperature of the produced fluid.

SUPPORTING SCIENCE AND ENGINEERING WORK

Almost all of the scientific and engineering work on HDR during Fiscal Year 1992 was conducted in support of the reservoir testing effort at the Fenton Hill HDR plant. Reservoir engineering, seismic monitoring, tracer studies, geochemical analyses and modeling work contributed substantially to

understanding the performance of the HDR reservoir at Fenton Hill during the tests and to providing a basis for predicting the behavior of HDR reservoirs in general. Specific activities and results are summarized below.

Reservoir Engineering

Reservoir engineering work this past year was concentrated on the design and conduct of the LTFT. Reservoir engineering decisions based on the preliminary flow tests were used to set the conditions for the four-month LTFT. Reservoir engineering considerations, as well as the limitations of the surface plant, formed the basis for the IFT conducted toward the end of Fiscal Year 1992. Many of the activities in the reservoir engineering support category are thus embedded in the descriptions of the reservoir testing program elsewhere in this report. Reservoir engineering support for the Fenton Hill flow testing program is critical to maintaining a rational test effort.

Logging: Wellbore logging operations are an important part of the reservoir engineering effort. Production well logs were conducted on June 25, July 16, September 1, and September 29, 1992. In each case, Los Alamos personnel worked with a commercial logging company to conduct the operation and obtain the data. All the logs were carried out under conditions of high

temperature and pressure and with fluid production maintained throughout the course of the logging operation. For this reason, special measures had to be taken to cool the logging wire as it was retrieved from the hot production wellhead.

The June and early-September logs were of the simple Kuster type in which temperatures were measured only to the end of the wellbore casing at a depth of about 10,500 ft. The logs indicated a linear rise in the wellbore pressure with depth, from a surface value of 9.7 MPa (1,400 psi) to about 36.8 MPa (5,330 psi) at 10,500 ft. During the July log, temperature, gamma and collar data were collected to a depth of 12,200 ft, well into the open-hole section of the production wellbore.

Figure 21 shows the results of logs conducted over the past year and clearly indicates that there was no decline in the production temperature of fluid from the reservoir over the course of the flow testing program.

Figure 21. A number of production well logs conducted during flow testing in 1992 confirmed that the temperature of fluid being produced from the reservoir did not show a significant decline.

The temperature profile of the wirelong line log through the fluid production interval during the July 16 log is shown in Figure 22.

Figure 22. Temperature profile through the production interval of the production wellbore from a wireline log moving out of the wellbore on July 16, 1992. Points A-C are located near major producing fractures. The temperature at point D, at the top of the production zone, is representative of the sum of all the produced fluid.

The irregularities in the temperature profile indicate points at which fluid-producing fractures occur. As fluid flows from these fractures into the production wellbore and mixes with the fluid already present there, it produces a sharp perturbation in the temperature. It is obvious that there are a number of such fractures over the length of the production interval. Points A-C of

Figure 22 are located near major producing fractures. The temperature at point D, at the top of the production zone, is representative of the sum of all the produced fluid. Table 3 compares temperature data taken during July and September logging runs, respectively, at depths indicated by the letters A-D on Figure 22.

TABLE 3
Fluid Temperatures at Points within the Production Interval

	<u>July 16 Log</u>	<u>Sept. 29 Log</u>
<u>Point A</u> (11,840 ft)	234.5°C (454.1°F)	233.9°C (453.0°F)
<u>Point B</u> (11,320 ft)	233.4°C (452.1°F)	232.9°C (451.2°F)
<u>Point C</u> (10,990 ft)	232.0°C (449.6°F)	231.7°C (449.1°F)
<u>Point D</u> (10,750 ft)	228.2°C (442.8°F)	228.1°C (442.6°F)

Although the temperatures of the fluid entering the wellbore at points A-C showed declines of 0.3-0.6°C over the two and one half months between the logs, the mixed-mean production temperature just above the highest fracture entrance (point D) declined

by only 0.1°C. These data suggest that the relative amount of flow from the various fractures is changing with time, a hypothesis which is supported by the results of tracer testing discussed elsewhere in this report.

Reservoir Volume Calculations:

Estimates of the Fenton Hill reservoir rock volume are extremely important in calculating the useful thermal lifetime of this resource. The estimates are applied in heat transfer calculations and for that reason must be representative, to the greatest extent possible, of the effective volume from which heat can be extracted. The size estimates

typically take into account the fact that not all the rock that is stimulated during a hydraulic fracturing experiment becomes a part of the swept volume when a steady-state flow field is established between the injection and production wells. Several methods that have been used to estimate rock volume are described below:

- Geometric: Simply based on the positions of the wellbores.
- Microseismic: Based on the locations of microseismic events detected during hydraulic fracturing.
- Tracer: Derived by relating the tracer-determined reservoir fluid volume to an estimate of fracture porosity.
- Hydraulic: Based on hydraulic and mechanical information.

The most recent estimates of reservoir volume by each of these methods are shown in Table 3 below:

Table 4 Estimates of Reservoir Volume	
<u>Estimation Technique</u>	<u>Estimated Volume (millions of cubic meters)</u>
Geometric	5
Microseismic	28
Tracer	22
Hydraulic	20

These estimates, along with the reasons why they differ, are discussed in detail in an internal Laboratory memo (Appendix A of this report). The choice of which estimate to use in any particular modeling effort will depend upon the details of the model employed. Comparisons of modeling results

should allow us to provide estimates of reservoir heat transfer capacity, to test our ability to make a priori predictions, and to develop a measure of the uncertainty associated with each of the various modeling approaches.

Tracer Studies

Three tracer experiments and a fresh-water flush of the HDR reservoir at Fenton Hill were conducted during the past year. These provided a wealth of information about the state of the reservoir at various times during the flow test effort.

A Benchmark Tracer Test: Figure 23 compares the results of a tracer test in March 1992 with those of a similar test carried out in 1987 just after the production wellbore had

been repaired and sidetracked. The similarities in the tracer return as a function of produced volume after injection confirm that the flow characteristics of the reservoir did not change significantly during nearly five years of pressurization without circulation. The two curves have been normalized to adjust for differences between the two tests in the production flow rates and in the amounts of tracer injected.

Figure 23. Tracer recovery data indicated that flow paths within the HDR reservoir had not changed significantly during about five years of pressurization without circulation.

There were also a number of other differences between the two tracer tests. In the 1987 test, a radioactive bromine tracer was employed while in 1992 the tracer was a fluorescein dye. The 1987 tracer test was performed prior to casing of the sidetracked production wellbore so the volume of the wellbore was somewhat larger than during the 1992 test. Since dispersion of the tracer increases with volume, this may have been part of the reason for the earlier first-appearance of the tracer in 1987 and its more gradual increase toward the peak concentration value. The flow test in 1987 was carried out with a backpressure on the production well just sufficient to prevent vaporization of the circulating fluid (a few hundred pounds per square inch-psi) while during the 1992 test, a backpressure of 1500 psi was maintained on the production wellhead.

Although high-backpressure operations have been shown to reduce impedance to flow

within the reservoir, they appear to have had little or no effect, adverse or beneficial on the fluid sweep through the fracture system and no significant new fluid pathways seem to have opened. These data lend credence to the hypothesis that the effects of high backpressure are primarily related to the dilation of joints in the otherwise relatively low-pressure region near the production wellbore. In spite of all these experimental differences, the two tracer curves agree quite closely.

Figure 24 is a plot of the total fraction of tracer returned versus time during the March test. Even though (as shown in Figure 1) the peak of the tracer response curve had already been reached, only about 8% of the injected tracer had been detected when the test was terminated due to a system shutdown. From these data, it appears there are numerous pathways in the reservoir with no significant short-circuiting.

Figure 24. Only about 8% of the tracer was recovered more than ten hours after it entered the reservoir. These data imply that most of the circulating fluid has a very long contact time within the hot reservoir rock.

Most earlier tracer tests had been carried out while the reservoir was still filling with water and it therefore might be expected that much of the tracer would be lost in the rock matrix or in filling dead-end fluid paths. The low level of water consumption during the March test, however, indicated that the reservoir was in a relatively stable state and that the eventual recovery of a high proportion of the tracer could be anticipated.

Unfortunately, the shutdown of the system less than a day after the experiment began, precluded the collection of any more data. Long-term tradeoffs in the tracer recovery curves were observed in subsequent tracer testing presented below. These provided convincing evidence for the existence of multiple fluid pathways in the reservoir, some of which may be extremely convoluted.

The First LTFT Tracer Test: The second tracer test of the year, in May, involved the use of three different tracer materials injected concurrently into the circulating fluid. As indicated in Figure 25, a fluorescein tracer

gave almost exactly the same results in May as it had in March when the system operating parameters were very similar. An organic tracer, para-toluene sulfonic acid (p-TSA) was also used in this test.

Figure 25. Tracer recovery data indicated that flow paths within the HDR reservoir did not change significantly during the first month of long-term flow testing.

Figure 26 shows that the shapes of the response curves for the fluorescein dye and the p-TSA were very similar but that the normalized concentration of the p-TSA was uniformly higher. This data indicates that the p-TSA is significantly more conservative (non-reactive) as it passes through the system. About 20% of the fluorescein dye

appears to have been lost, probably as a result of reaction with the circulating fluid at the high temperatures prevailing in the Fenton Hill reservoir. On this basis, it may be possible to utilize fluorescein as a temperature-sensitive tracer if its reaction rate in the reservoir as a function of temperature can be sufficiently well documented.

Figure 26. The tracer recovery curves for p-TSA and fluorescein show similar shapes, but the lower level of recovery for the fluorescein indicates that it may be undergoing partial degradation as it passes through the hot reservoir.

The third tracer compound employed in the May experiment was, in fact, specifically selected to act as a temperature-sensitive tracer. The material, para-bromonitrobenzene (p-BNB) had been shown in laboratory tests to react rapidly to an easily detectable product at temperatures similar to those of the HDR reservoir, but to decay much more

slowly at the lower temperatures expected to be typical of the cooled reservoir regions. Neither the BNB or its reaction product were found in the production fluid, however, due to analytical problems. Thus, while it has shown promise in the laboratory, BNB has not yet been successfully employed as a temperature-sensitive tracer in actual practice.

The Second LTFT Tracer Test: A tracer test, initiated on July 7, entailed a direct repetition of the May experiment using fluorescein and p-TSA tracers. Because the reservoir had been operating under steady-state conditions since early April, a comparison of the May and July tracer data provides a realistic picture of the temporal changes in an HDR reservoir that might be expected during routine energy production operations. A number of surprising results were noted.

First, a smaller proportion of the fluid was found to be flowing in relatively direct paths from the injection to the production well. Apparently, either entirely new flow paths were established or pathways which had carried only an insignificant proportion of the fluid began to play a more significant role as the LTFT proceeded. Thus, it appears that the heat extraction efficiency of the reservoir increased between May and July.

Second, calculations based on the tracer data indicate that some of the water consumption during the LTFT, typically attributed to water loss at the boundary of the reservoir, may

have actually been reflecting the increased *storage* of water in newly established or enlarged flow paths within the reservoir. These findings are consistent with the increased system impedance and changes in flow rate/temperature relationships observed during the interval between the two tracer experiments.

Figure 27 shows the recovery curves for the P-TSA tracer for both the May and July tracer tests. Note that the initial recovery of the tracer occurred at a significantly greater production volume after tracer injection during the July test and that the total amount of tracer recovery (as indicated by the area under the curve) was always less after any specific production volume in July than in May. The two curves appear to converge and follow a similar path after a production volume of about 500 cubic meters. At production flow rates of 90-100 gpm this represents an operating period of about 22-25 hours after tracer injection. A comparison of the curves to the 500 cubic meter volume point indicates that 6% less of the total flow reached the production well by that point in July (16 % in July vs 22 % in May).

Figure 27. Tracer recovery data indicated a significant change in reservoir flow paths during two months of flow testing between May and July. These results contrast markedly with those shown in Figures 23 and 25.

The tracer data further indicate that the modal volume of the reservoir increased significantly over the period between the May and July tests, implying an increased surface area in contact with the hot rock in the main flow paths. The integral mean volume of the reservoir, a measure of the total volume of all fractures, increased by 520 cubic meters during the period between the two tests. Approximately 3,140 cubic meters of water was consumed in the forty-eight day inter-test period. Based on the tracer results, about 17% of this water (520/3140) was actually stored in the increased joint volume. This means that a significant fraction of the reported water loss was actually going into reservoir flow paths and contributing to the heat extraction process. Calculations of rock contraction due to the cooling effects of the circulating fluid can account for a fracture volume increase of about 190 cubic meters, leaving 330 cubic

meters to be assigned to additional fracture opening.

The recovery curves for fluorescein showed similar results to those for p-TSA. The fluorescein dye also degraded to a greater extent in July than it had in the May test. The increased degradation could be a result of an increase in the average temperature experienced by the tracer as it traversed the reservoir or it could be due to subtle changes in the geochemical nature of the circulating fluid (although geochemical analyses show no obvious composition changes). The former explanation would fit a model of reservoir behavior that predicts an ever increasing downward flow of injected fluid into hotter flow paths as circulation continues, but any such interpretation must be supported by additional information including geothermometer data which is not yet available.

The Freshwater Flush: A fresh water flush of the Fenton Hill HDR reservoir was carried out commencing on September 2 and lasting until the system was shut in on September 8. During this time, the reservoir fluid, which had been recirculated through the system repeatedly for a number of months, was replaced with relatively clean ground water from a well on the Fenton Hill site. A fresh water flush washes out residual amounts of tracer compounds from previous tracer experiments and is in itself a tracer test involving a variety of naturally occurring species such as chloride, sodium, dissolved silica, and others. By comparing these data to a p-TSA tracer test carried out simultaneously, we can determine whether these species are being actively produced via mechanisms such as dissolution or the displacement of *in situ* pore fluid.

The concentrations of a variety of chemical species were monitored as the fresh water flush proceeded. Both boron and chlorine showed an increased concentration in the production fluid as compared to the behavior of the p-TSA tracer. Because mineralogical analyses indicate that these elements are essentially absent in the reservoir rock, it must be assumed that they originate in pore fluid. On this basis, it appears that, even after several years of pressurization and more than 4 months of circulation, about 5% of the fluid being produced arises from the small amount of natural fluids already present in the rock at the time the reservoir was created.

The concentration of fluorine in the produced fluid was also found to be much greater than in the fresh water. In this case, however, the dissolution of a fluorine-containing mineral such as mica or fluorapatite might be taking place at the temperatures and pressures prevailing in the reservoir, although ion-exchange in which the fluoride ion in the intact rock is simply replaced with another anion cannot be ruled out.

A number of elements such as calcium and magnesium were found at significantly lower concentrations in the production fluid than in the injected water, probably because they had precipitated on the surface of reservoir rock. Previous geochemical data had shown much higher levels of silicon in typical production fluid than in the fresh water injectate. The concentration of silicon in the production fluid declined only very slowly as the fresh water flush proceeded indicating that the residence time in the reservoir during one pass is long enough for the fluid to reach a quasi-equilibrium state with regard to quartz dissolution.

At ninety-two hours into the fresh water flush experiment, an injection pump failure occurred. In response to this failure, the automatic control system throttled back the flow at the production wellhead, thereby effectively increasing the backpressure in the production wellbore. Several hours later, the conductivity of the production fluid (one measure of the total amount of dissolved solids) showed a distinct drop. The time was equivalent to the time required for fluid to travel up the length of the production wellbore and reach the surface. This phenomenon is illustrated in Figure 28 which plots both the backpressure at the production wellhead and the produced fluid conductivity over the time period of interest. Each change in backpressure is reflected several hours later in a change in the conductivity. The observed initial drop in conductivity indicates that fresher water entered the wellbore almost immediately when the pressure was increased. This in turn implies that some of the more direct pathways began to transport a larger fraction of the fluid. These results lend increased credence to the hypothesis that the backpressure imposed on the production well has a highly significant effect on the flow characteristics of the reservoir.

Figure 28. The conductivity of the production fluid showed a sharp decline about six hours after an increased back-pressure was imposed on the production wellbore during a freshwater flush. This corresponds to the time required for fluid to travel up the wellbore from the outlet of the reservoir and indicates that fresher water began to be produced coincidentally with the increase in pressurization.

The fresh water flush obviously produced a vast amount of information about the HDR system at Fenton Hill. The manifold results of the fresh water flush experiment were

reported in detail as one part of a paper by Rodrigues, Robinson, and Counce, presented at the Eighteenth Stanford Workshop on Reservoir Engineering.

Geochemistry

Literally hundreds of geochemical analyses have been conducted over the past year. Table 5 compares geochemical data from two dates during the four-month LTFT. It is apparent that the level of dissolved solids remained at a remarkably low level throughout the test period in spite of the fact

that the same fluid was being continually recirculated through the reservoir. Suspended solids were consistently in the range of 1-2 parts per million, with no particles large enough to be seen by the naked eye being detected.

TABLE 5
Geochemical Analysis of Water from the Fenton Hill
HDR Plant During April and July, 1992

Component:	Concentration in Production Fluid (parts per million by weight)	
	<u>April 15</u>	<u>July 27</u>
Chloride	1220	953
Sodium	1100	900
Bicarbonate	552	588
Silicate (as Si O ₂)	458	424
Sulfate	285	378
Potassium	95	89
Boron	47	35
Calcium	19	18
Lithium	19	16
Fluoride	14	17
Bromide	6.5	5
Arsenic	3.8	7.2
Iron	1.0	0.8
Aluminum	0.9	1.2
Ammonium	0.8	1.1
Strontium	0.8	0.8
Barium	0.2	0.2
Magnesium	0.2	0.1
Sulfide	0.2	0.1
Bisulfate	<0.03	0.2
Total Dissolved Solids	3845	3434

Dissolved gas concentrations also remained low as shown in Table 6. Carbon Dioxide at a concentration of 0.2-0.3% by weight was

by far the most significant gas in the circulating fluid. Hydrogen sulfide levels were typically less than one part per million.

TABLE 6
Geochemical Analysis of Water from the Fenton Hill HDR
Plant During the April, July and September, 1992

Component	Concentration in Production Fluid (parts per million by weight)		
	<u>April 15</u>	<u>July 27</u>	<u>Sept. 28</u>
<u>Gases</u>			
Carbon Dioxide	2747	2370	1440
Nitrogen	58	71	16.76
Oxygen	0.25	0.35	0.3
Hydrogen Sulfide	0.45	0.33	0.55

Table 7 presents geochemical analyses for the well water used in the fresh water flush experiment and for produced fluid as of late September. The differences in the composition of the fresh well water and the water produced from the reservoir (discussed in the section on tracer testing, above) are apparent. In addition, it is clear that the composition of the production fluid on September 28, during the interim flow testing period, was very similar to that

observed while Phase I of the LTFT was being conducted (see Table) in spite of an intervening period consisting of a relatively long shut in, a fresh water flush, and a few days of circulation. This provides further evidence that the concentration of dissolved species in the circulating fluid at Fenton Hill reaches an equilibrium level within a short time and does not vary significantly thereafter.

TABLE 7
Geochemical Analysis of Water from the Fenton Hill
HDR Plant During September, 1992

Component:	Concentration in Production Fluid (parts per million by weight)	
	<u>Sept. 2</u>	<u>Sept. 28</u>
Chloride	101	1109
Sodium	54	935
Bicarbonate	259	419
Silicate (as Si O ₂)	81	451
Sulfate	21.3	361
Potassium	9.7	94
Boron	1.9	39.8
Calcium	88.8	18.3
Lithium	0.72	15.8
Fluoride	0.48	13.5
Bromide	0.57	5.61
Arsenic	0.1	3.4
Iron	0.46	0.5
Aluminum	0.2	0.6
Ammonium	0.08	1.32
Strontium	0.32	0.72
Barium	0.12	0.16
Magnesium	8.55	0.12
Total Dissolved Solids	633	3471

Seismology

Seismic activities this past year were severely constrained by budget limitations. Early in the flow test program, seismic monitoring from a triaxial station located very close to the reservoir in a wellbore which formed part of an earlier, shallower, HDR system (the EE-1 station) produced wave forms showing peculiar characteristics. Two classes of

events were observed. The first type consisted of extremely large events occurring at twelve hour intervals with many events in a brief period followed by total cessation of activity. Because they were so large and yet not recorded on the more distant Precambrian seismic network, it appeared that they must have arisen from instrumental

sources and therefore not be seismic at all, or that they occurred very close to the EE-1 station. After the large events ceased, a series of small events occurred at a rate that diminished over time. In some cases, a few small events preceded the onset of a series of large events. The wave forms from all these events were unusual and no clear interpretation of their cause was arrived at this year.

In work funded by the DOE Office of Basic Energy Sciences (BES), a method was developed this year to analyze the arrival times of microearthquakes located in a tight cluster using data from the massive hydraulic fracturing event that created the present HDR reservoir at Fenton Hill and from a subsequent thirty day flow test run at seismic condition in 1986. This technique can provide reliable data about the relative locations of the events and a measure of the ratios of elastic velocities, V_p/V_s , in the

region containing the clusters. This ratio is a good measure of the presence of fluid-filled fractures in the cluster region. The method has been tested on a cluster of microearthquakes located near the top of the seismically active region of the reservoir. Surprisingly, the ratio of the velocities in this zone has been found to be smaller during the flow test than prior to it. This result was not expected since it indicates the possible presence of gas-filled rather than liquid-filled fractures. This unanticipated result is being further investigated under the auspices of DOE-BES.

No microearthquakes were detected in Fiscal Year 1992 during any of the flow test periods, including the four-month LTFT. This evidence, together with water consumption data, provided the basis for asserting that, as planned, the flow testing effort proceeded in the non-expansion mode.

Modeling

Modeling efforts have concentrated on the development of information about the potential thermal lifetime of the reservoir. The Finite Element Heat and Mass (FEHM) Model and the HDR-HEAT Model were used to predict drawdown of the Fenton Hill reservoir. In the FEHM model, the code computes the flow field and heat transport behavior (including the production temperature) as a function of the operational time. In contrast, HDR-HEAT is a tracer-based heat transfer model which simulates flow channeling using the results of tracer experiments to set the degree of short-circuiting between the injection and production wells. The HDR-HEAT model also assumes fractures of a given spacing and this assumption can result in less than

perfect heat extraction under conditions of high flow, because some heat is left in the rock between the fractures. The details of each model and what it predicts with regard to the lifetime of the Fenton Hill HDR reservoir are discussed below.

The FEHM Model: This model requires that the user set the system geometry, the flow, and the transport properties. The code then computes the flow field and heat transport behavior (including the production temperature) as a function of operational time. The fundamental assumption relative to heat transfer is that the circulating fluid extracting heat from the porous medium is in intimate contact with the rock at all locations.

In the FEHM model, the nature of the fluid flow pattern is governed by the positions of the injection and production wellbores, and the shape of the reservoir. Our calculations were based on a two-dimensional idealization of the reservoir, with injection and production regions modeled as small areas spaced 110 meters apart within a domain with gross dimensions of 140 x 427 x 267 meters.

Figure 29 shows the results of an FEHM Model simulation for produced fluid temperature versus time at a flow rate of 126

gpm. note that at this flow rate, the model predicts an extremely long period of constant temperature production before any thermal drawdown is observed. Under aseismic operating conditions, it is unlikely that we will exceed an injection rate of 126 gpm during our LTFT. This model would thus predict that we will see no significant thermal drawdown during a one to two year aseismic LTFT. Of course, the FEHM Model provides the most optimistic picture of reservoir thermal behavior since it assumes intimate contact between the fluid and the entire flow-connected rock volume.

Figure 29. FEHM Model prediction of production fluid temperature with time at a flow rate of 126 gpm. No noticeable temperature decline sets in until more than three years. The reservoir is still producing fluid at useful temperatures after almost five and one half years of continuous operation.

The HDR-HEAT Model: In contrast to the FEHM Model, this tracer-based heat transfer model simulates flow channeling using the results of tracer experiments to set the degree of short-circuiting between the injection and production wells. The model also assumes fractures of a given spacing which can result in less than perfect heat extraction under

conditions of high flow, as some heat is left in the rock between the fractures.

The input parameters to the HDR-HEAT Model are the total rock volume and the mean fracture spacing. A total rock volume of 16 million cubic meters is equivalent to the volume of the flow domain used in the FEHM Model calculations described above.

Figure 30 shows the results of thermal drawdown predictions based on the HDR-HEAT Model for a number of mean fracture spacings and, again, a flow rate of 126 gpm. At the larger fracture spacings, the onset of temperature decline occurs earlier in time. The rate of thermal decline, however, is predicted to be slow enough in all the cases so that production fluid temperatures

(downhole) are still in excess of 200°C after five years of operation. Since, for practical purposes, the elapsed time for a given amount of thermal drawdown is inversely proportional to the flow rate in this model, doubling the flow rate to about 250 gpm would simply result in producing the thermal drawdown profiles shown in Figure 30 in about half the time.

Figure 30. HDR-HEAT Model prediction of production fluid temperature with time at a flow rate of 126 gpm. Relatively rapid temperature decline occurs only at joint spacings in the range of 20 meters. In all cases, the production fluid temperature is greater than 210°C (410°F) even after almost five and one half years of continuous operation.

FEHM and HDR-HEAT Model Comparison: The principal differences in the models are the modes of heat extraction (which converge as the fracture spacings in the HDR-HEAT Model are made smaller) and the representation of the flow field. The FEHM Model attempts to describe the flow field by means of geometric considerations and the first principles of fluid flow, while the HDR-HEAT Model forgoes this approach in favor of using experimental tracer data to set the flow behavior of greatest importance -- the degree of flow channeling between the wells.

The approximate agreement between the two models at small values of mean fracture spacing indicates that the FEHM Model calculations, in which flow channeling

behavior arises in the computation rather than from input data, result in flow patterns similar to those implied by the HDR-HEAT Model on the basis of tracer measurements. Indeed, when the FEHM Model has been used to predict tracer response, the results have been quantitatively similar to measured tracer behavior. The model results are thus converging in an understandable manner.

The key heat transfer parameter in both models is the rock volume. The model predictions can only be as accurate as the rock volume estimate, so the LTFT is an important experiment in validating or refuting the estimations of the Fenton Hill Phase II reservoir rock volume that have been used in this work.

Fracture spacing also impacts the predictions for cases in which the spacing is large enough for thermal gradients to be set up within the rock blocks. Short-circuiting is the extreme of one or two joints dominating the flow between the wells, and is simulated with very large fracture spacings in the HDR-HEAT model. In addition to

providing an estimate of the rock volume, the LTFT heat extraction data will be used to assess the degree of short-circuiting in the reservoir. Our current conception, based on tracer data, is that the degree of short-circuiting is minimal, and the absence of early thermal cooldown would confirm this prediction.

The GEOCRACK Model: Work by Kansas State University on the development of the GEOCRACK model continued this year. GEOCRACK is a fully-coupled model of fluid flow in jointed rock. It was applied this year to simulate shut-in and cyclic operations of an HDR system. The shut-in mode was evaluated in order to compare the model results to actual experience at Fenton Hill. GEOCRACK data matched the real results qualitatively, but more detailed calculations will be necessary to provide a comparison to specific experimental measurements.

Cyclic simulations involved an imposed pressure of 15 MPa (2200 psi) for five and a half hours followed by zero pressure for eight hours. Joint opening and fluid storage proceeded as expected during the injection part of the cycle, but an important effect, not previously noted, was seen during the production phase. The simulation showed the joint nearest the wellbore closing after a few minutes of production with the result that most of the fluid was trapped in the body of the reservoir. This result, which is intuitively obvious after its demonstration by the model, leads to the conclusion that any cyclic operation scheme must employ a production pressure boundary that is lower than the injection pressure but still sufficiently high so that joint closure never occurs. Reservoir engineering studies indicate that at Fenton Hill, such a lower boundary pressure would be between 10-15 MPa (1450-2200 psi).

As the year progressed, the problem size that could be solved in a reasonable amount of time was increased by incorporating more advanced solver codes into the GEOCRACK computer program. When the fully implicit solution algorithm was completely implemented and debugged, we were finally in a position to start comparing model predictions with experimental results from the Long-Term Flow Test (LTFT). In addition, upon implementation of the fully implicit solution, appropriately-sized reservoir geometries could finally be modeled in reasonable computational times.

The first consequence of these comparisons was that, for a suitable range of reservoir sizes and joint patterns, the predicted reservoir throughflows were excessive (several orders of magnitude too high) when compared to the actual experience at Fenton Hill. However, these calculations had been performed with a preconceived notion of the appropriate pair of controlling reservoir joint closure stresses as boundary conditions.

Three joint closure stresses (and therefore joint orientations) have been experimentally observed in the reservoir flow and pressurization data for the present HDR reservoir at Fenton Hill. These are 12, 22.5 and about 27 MPa (1740, 3260, and 3910 psi). However, what could not be determined from the data was which two joint sets (which pair of these three closure stresses) were actually controlling the interconnected joint flow through the Phase II reservoir.

From the inception of the modeling studies, the lower pair of closure stresses had been specified as boundary conditions.

In an effort to resolve the very significant flow rate discrepancy, three different ad hoc approaches were taken to reduce the computed flow rate:

1. Introduction of an out-of-plane restraining shear stress to limit the amount of joint opening as a function of fluid pressure,
2. Imposition of a pseudo-friction factor into the joint flow relationship, to account for the divergence from true laminar flow in individual joints due to the tortuosity caused by the presence of asperities,
3. Imposition of an upper limit on the allowable joint opening specified by the Gangi equation as the difference between the closure stress and the internal fluid pressure approaches zero.

In the final analysis, none of these three approaches turned out to be reasonable. To match the measured flow rates, both an unrealistically high level of out-of-plane shear and a friction factor in the range of 100 were required, combined with a restrictively low cutoff value for the joint opening law.

The upshot of these studies was the conclusion that the wrong pair of controlling joint closure stresses for the Phase II reservoir had been specified from the beginning. When these two boundary stresses in the GEOCRACK model were changed to the upper pair of measured stresses, 22.5 and 27 MPa, close agreement with measured LTFT flow rates resulted. This was achieved without the need for any of the ad hoc remedies discussed above. This is an excellent example of the ability of a model to help the experimentalist rethink arbitrarily imposed constraints.

MANAGEMENT

Organization: As shown in Figure 31 the HDR Program continues to be field-managed jointly by the Los Alamos National Laboratory (LANL) and the DOE Albuquerque Operations Office (DOE/ALO) under the overall purview of the Geothermal Technology Division of the DOE (DOE/GTD). Gladys Hooper is the DOE/GTD Program Manager, George Tennyson is the DOE/ALO Field Manager,

and David Duchane is the Los Alamos Program Manager. The Technology Commercialization Board is an industrial advisory group being set up to succeed the Program Development Council as a point of private sector input to the HDR Program. It will provide guidance on developing increased participation in HDR technology by private industry.

Figure 31. HDR Program management structure.

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

Alamos management entails both direct program management and management support and services.

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

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

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

the California Energy Commission are particularly noteworthy in this regard.

Attendance at professional meetings, the presentation of papers and talks, program reviews, and meetings of advisory groups such as the Technology Commercialization

Board 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.

CONTACT SUMMARY FISCAL YEAR 1992

INTERNATIONAL

Guests from the following countries visited the HDR Program and toured Fenton Hill:

JAPAN	six visitors
AUSTRALIA	one visitor
EUROPEAN ECONOMIC COMMUNITY	two visitors
UNITED KINGDOM	four visitors
SWITZERLAND	one visitor

Papers were presented at three international conferences.

INDUSTRIAL

The HDR Program Staff was in contact with the following companies during FY 1992:

Ellicotville Energy	Pacific Gas & Electric
EBASCO	RE/SPEC Inc.
Iowa Power	UNOCAL Geothermal
Texas Ohio Power Company	Copar Pumice Company
Texas-Ohio Gas	Aggieland Saltwater Disposal

GOVERNMENTAL

The following people/organizations were in touch with the HDR Program during FY 1992:

Offices of Senators: Domenici, Hatfield, Reid, Burdick and Inouye
Offices of Representatives: Kostmayer, Ovens and Riggs
California Energy Commission
City of Clearlake, CA
Ellsworth Air Force Base
N.M. Public Service Commission
Secretary of the Interior-Stewart Udall
Government Committees/Organizations:
House Mining & Natural Resources Committee

House Energy and Water Subcommittee
National Renewable Energy Laboratory
U.S. Bureau of Mines
U.S. Forest Service

NON-PROFIT ORGANIZATIONS AND PROFESSIONAL SOCIETIES

The following organizations were in touch with the HDR Program staff:

Center for Resource Management (CRM)
American Bar Association Coordinating Group on Energy Law
American Institute of Mining, Metallurgical and Mechanical Engineering (AIME)

ACADEMIC

Faculty and students from the following educational institutions visited the HDR Program:

five high schools in the Las Cruces, NM area
Colorado College
College of Santa Fe
University of Nebraska, Lincoln
Kansas State University
Turabo University, Puerto Rico
North Carolina State A & T University
NM Tech Dept. of Geosciences, Dept. of Mechanical Engineering
University of New Mexico, Advanced Vulcanology

In addition, Dr. Paul Kruger of Stanford University and Professor Daniel Swenson of Kansas State University visited the HDR program as consultants to the Laboratory.

MEDIA

The following print media were in contact with the HDR Program:

<i>Reader's Digest</i>	<i>Science Magazine</i>
<i>Santa Fe New Mexican</i>	<i>Scientific Drilling</i>
<i>ABOARD</i>	<i>International Solar Energy Report</i>
<i>Arizona Daily Reporter</i>	<i>Solar Energy Intelligence Report</i>
<i>Scientific American Magazine</i>	<i>Albuquerque Journal</i>
<i>American Way</i>	<i>Familia Christiani</i>
<i>Environment Magazine</i>	<i>Washington Post</i>
<i>Power Line</i>	<i>Earth News</i>
<i>California Energy Markets</i>	

Television and radio contacts included:

KGGM-TV	KOAT-TV
KOB-TV	KRSN-RADIO
UNITED STATES INFORMATION AGENCY	

ARTICLES

Articles about HDR were carried in the following publications:

New York Times
Scientific Driller
The Southampton Press
East Hampton Star
Albuquerque Journal
Los Alamos Newsbulletin
Los Alamos Monitor
Santa Rosa Press Democrat
Standpunkt
Geotimes
EOS
Washington Post
Geothermal Resources Council Bulletin

Santa Fe New Mexican
Superscience
Kansas State Collegian
Geothermal Hot Line
Reader's Digest
Denver Post
ABOARD
Inside Energy
Field Notes
American Way
Geothermische Energie
Concerned Citizens of Montauk

MEETINGS

Members of the HDR staff attended 18 professional and technical meetings.

DETAILS OF THE HDR PROGRAM CONTACTS

INTERNATIONAL

On October 22, Dave Duchane presented a paper on HDR at an international conference on "Global Climate Change: Its Mitigation Through Improved Production and Use of Energy". The meeting, held at Los Alamos, brought together approximately 150 participants from more than a dozen countries to discuss the known and projected impacts of growing energy usage on worldwide climate.

Dr. Takeji Kokusho, Manager of the Siting Technology Department at The Abiko Research Laboratory of the Central Research Institute of Electric Power Industry (CRIEPI), visited the Laboratory on November 6, to discuss the current state of HDR technology and tour the Fenton Hill Test Site. Dr. Kokusho is the manager of the Japanese HDR efforts funded by CRIEPI.

On the same day, Professor Hilary J. Harrington of the Bureau of Mineral

Resources, Canberra, Australia, also visited the Laboratory for HDR briefings and a tour of Fenton Hill. Dr. Harrington is exploring the possibility of initiating an HDR program in Australia.

On November 14, Dr. Konosuke Sugiura, General Manager of the Washington Office of the Tokyo Electric Power Company, was briefed on HDR technology and its potential, the status of the Los Alamos HDR effort, and the state of HDR work in Japan. Dr. Sugiura visited the Laboratory in the company of William F. Martin. Mr. Martin is a partner in the consulting firm, Washington Policy and Analysis.

Isao Matsunaga of Japan, John Garnish of the European Community, Tony Batchelor of Geosciences Limited in the United Kingdom, Paul MacDonald of the Energy Technology Support Unit of the United Kingdom Department of Energy, and Andy

Green of the Camborne HDR Project in the United Kingdom visited the Laboratory to take part in the Conference on Renewable Energy Technologies held in early December.

Paul MacDonald from the Energy Technology Support Unit of the United Kingdom Department of Energy visited the Laboratory on February 4-5. He is responsible for overseeing the UK HDR Program.

Dr. Peter Wiederkehr of the Environment Directorate of the Organization of Economic Community Development (O.E.C.D.) based in Paris France was given a briefing on HDR as part of a visit to the Laboratory on February 7.

Mr. Masakatsu Ueno, Chief Research Metallurgist, Nippon Steel Corporation, Japan, visited Los Alamos on February 20. Accompanying him was Mr. William C. Turner, President, Tiger Fabrications. As part of their visit, they were given an update on the status of the HDR effort and a tour of Fenton Hill. Nippon Steel proved to be the sole source of some of the tubular materials used at Fenton Hill during the development of the underground portion of the Phase II HDR system.

Dr. Tsutomu Yamaguchi of the Geothermal Energy Technology Department, New Energy and Industrial Technology Development Organization (NEDO), Tokyo, Japan, visited the Laboratory on March 27-28. He discussed the Japanese HDR Program at NEDO with staff scientists, reviewed our HDR efforts, and was given a tour of the Fenton Hill HDR site.

Dr. Francois D. Vuataz received an update on HDR and toured the Fenton Hill plant as part of a visit to the Laboratory on July 23. Dr. Vuataz had been involved in the HDR project during the early 1980's when he worked as a post-doctoral fellow at Los Alamos. He currently is a project leader in the area of geohydrology, including work on geothermal energy, at the University of Neuchatel in Switzerland.

Formal approval was received from the US Department of Energy in August for an extended visit by Nelson Rodrigues, a scientist associated with the United Kingdom HDR Program. While at Los Alamos, Mr. Rodrigues will participate in tracer studies with members of our HDR staff.

Mr. Nobuo Nagata, a Japanese official with NEDO, toured the Fenton Hill HDR site and discussed the state of HDR research and development with Laboratory personnel on August 28. Mr. Nagata was responsible for the assignment of the 27 Japanese scientists and technicians who worked at Los Alamos during the years when Japan was an active participant in the HDR Program.

In mid-August, Anne Tellier of the Laboratory's International Programs Office presented a paper on Hot Dry Rock and other geothermal energy technologies at the High Temperature Geothermal Resources Workshop in Lhasa, Tibet.

On September 4, Dr. John E. (Ted) Mock presented a paper discussing the potential industrial applications for HDR at the International Conference on Industrial Applications of Geothermal Energy in Reykjavik, Iceland.

INDUSTRIAL

Information about HDR technology was sent to Mr. Bill Northrup of Ellicottville Energy

Co., an independent power producer in upstate New York. Mr. Northrup and Ann

Widger of Ellicottville Energy Company were later given a tour of the Fenton Hill HDR site on April 2. They are particularly interested in coupling unique energy sources such as HDR to small power plants.

Kerry Burns, Dave Duchane, Bob Potter, and Alan Jager met in Sacramento, CA, with a number of parties interested in the Clearlake HDR initiative. Kelly Birkenshaw and Roger Peake of the California Energy Commission (CEC), Dan Obermeyer of the City of Clearlake, Pete McCluer of Pacific Gas & Electric, and Gary Murath of EBASCO, a consultant to the CEC, were present at the meeting. Dave Duchane summarized the Conference on Renewable Energy Technologies and gave a brief report on his view of the status of the HDR work being jointly sponsored by the DOE and the state of Arizona. Alan Jager presented a rough draft of his report on water sources for HDR at Clearlake. Kerry Burns and Bob Potter discussed the overall magnitude of the HDR resource in the Clearlake area.

Thomas McGuinness and Richard Franks visited Los Alamos on December 6 for overviews of several advanced technologies being developed at the Laboratory. Mr. McGuinness is an engineer with many years experience in the oil and gas services industry, while Mr. Franks has a background in project finance. They are forming a company to engage in design, development, and implementation of innovative engineered products. Their interests include various applications of HDR technology including desalination.

RE/SPEC Inc. representatives Tim Webster, Associate Vice President, and Angus Robb, Manager of Mine and Field Services, visited the HDR Program on February 27. RE/SPEC is involved in field studies and technical support for a variety of geological, environmental, and energy projects.

Stan Bright, Chief Executive Officer of Iowa Power, and Gerry Geist, former President and Chief Executive Officer of Public Service Company of New Mexico, visited the Laboratory on February 29 to review current energy programs.

Bill Cumming of Unocal Geothermal contacted the HDR Program Office on April 8 to receive an update on the progress of the LTFT. Mr. Cumming is a geophysical supervisor in Unocal's Santa Rosa, CA office.

On April 22, Mr. John Thomas of Texas Ohio Power Company contacted the HDR Program Office for information on HDR technology. Then, on August 25, John Thomas, Chief Executive Officer of Texas-Ohio Gas, and J. Patrick LaStrapes, President of Texas-Ohio Power, visited Los Alamos to discuss a proprietary process they had developed to utilize HDR resources. The discussions were carried out according to the terms of a proprietary information agreement executed between the Laboratory and Texas-Ohio. The visitors were given a tour of the Fenton Hill HDR site to provide them with a first-hand view of the current status of HDR technology. By the end of the day, both parties seemed to agree that the process as presented lacked some important elements needed to make it practical.

Wayne Brown of the Copar Pumice Company visited the Laboratory on August 6 to discuss the possibility of using heat from the HDR facility at Fenton Hill to dry pumice being produced in the Jemez Mountains. On August 20, Mr. Brown toured the Fenton Hill HDR site along with Richard Cook, the president of Copar Pumice, and several members of the Laboratory staff from the Director's Office and Community Relations.

Jay D. Hughes, President of Aggieland Saltwater Disposal of Austin, Texas, visited the Fenton Hill HDR site in early September along with two local residents, Jim Johnson and Tom Cook. Aggieland provides

saltwater disposal services to the oil industry and pumps fluid into underground reservoirs

as part of their operation.

GOVERNMENTAL

On December 4, Governor George S. Mickelson of South Dakota, several members of his staff, and the South Dakota Secretary of Environment and Natural Resources, Robert Roberts, visited Los Alamos. Officials from Ellsworth Air Force Base near Rapid City, South Dakota were also present at the meeting. South Dakota is in a region of moderate geothermal gradient, but does have a significant high gradient area in the southeastern part of the state.

Several members of Senator Pete Domenici's staff visited Los Alamos on January 10. Charles Gentry, Administrative Assistant, Alex Flint, Legislative Assistant, and Tina Kaarsberg, Congressional Fellow, met with management staff, from the Energy Technology Directorate to discuss a number of issues, including the status of HDR technology.

Lawrence B. Ingrham, Chairman of the New Mexico Public Service Commission, visited the Laboratory on January 15 along with two commission members and six of his staff. They discussed areas for potential collaborations in energy technology development.

Jerry M. Rivera, Director of the Guam Energy Office, visited the Laboratory on February 10, to discuss alternative energy opportunities for this island possession of the United States.

On February 3, a request by the office of Representative Peter H. Kostmayer for information on the potential for HDR in the state of Pennsylvania was referred to the Los Alamos HDR Program Office by David Anderson of the Geothermal Resources Council. Relevant documentation was

forwarded to Representative Kostmayer's staff.

At the request of Gary Shulman of Geothermal Power Company, a Geothermal Gradient Map of the United States, with specific well locations delineated, was sent to Lynn Miller of the Energy and Water Subcommittee of the U. S. House of Representatives on March 30.

Frank Monestero from the Geothermal Program Office of the China Lake Naval Weapons Laboratory was given an overview of HDR and a tour of Fenton Hill on April 14. The Coso Geothermal Plant operated by the California Energy Company is on land under the jurisdiction of the China Lake Facility.

On April 3, Kenley Burnsdale of the Office of Congressman Wayne Owens contacted the HDR Program Office with questions about the potential for HDR.

Ms. Brett Bates of the Mining and Natural Resources committee also contacted the HDR Program Office on April 3 for background information on HDR and its potential.

Former Secretary of Interior, Stewart Udall, contacted the HDR Program Office on April 22 to check on the progress of the LTFT.

Jim Jones, a science writer at the National Renewable Energy Laboratory, visited Los Alamos on May 11 to collect information for a booklet on facilities operated by the Conservation and Renewable Energy Office of the DOE.

On May 14, Mark Kerrigan of SAIC, Steve Swan of the U.S. Bureau of Mines, and Hank Kreis and Al Raihl of ASARCO visited the Laboratory to discuss a joint project they have underway in leach mining of copper, and to explore the common aspects that may exist between their technology and HDR.

Barbara Crowley, Vice Chair, and Sally Rakow, Commissioner, of the California Energy Commission visited Los Alamos on May 18 to review Laboratory energy programs, particularly Hot Dry Rock.

Dr. Carel Otte, retired president of UNOCAL Geothermal and a consultant to the DOE, visited Los Alamos on May 28. Dr. Otte discussed HDR technology and its potential role in mitigating the steam decline at The Geysers geothermal field in California.

On May 29, a group of about 20 people involved in the Yucca Mountain Nuclear Waste Repository Program toured the Fenton Hill HDR facility.

Bill Fite, from the Laboratory Director's Office at Los Alamos, and Dave Duchane met with Jay Contis, Legislative Correspondent for Congressman Frank Riggs of California, in Washington on May 5. They discussed the potential development of an HDR facility in the Clearlake, CA, which is in Congressman Riggs' district.

Maryrose Szoka, a Senior Planner for the National Renewable Energy Laboratory from the DOE office in Washington, and Graham Hagey, a consultant, were briefed on the HDR program and given a tour of the Fenton Hill HDR site on June 11.

Dr. John E. (Ted) Mock, Director of the Geothermal Technology Division of the USDOE, visited Los Alamos on June 23.

Dave Duchane served as part of a geothermal delegation calling at the offices of several

senators on July 16-17. They visited with staff members from the offices of Senators Hatfield, Reid, Burdick, and Inouye. The other members of the delegation also met with a representative of Senator Domenici.

Roger Peake, Geothermal Program Manager for the California Energy Commission (CEC), visited Los Alamos on July 15-16.

A group of ten supervisors from various U.S. Forest Service regions was briefed on HDR as part of a visit to the Laboratory. The Fenton Hill HDR site is on Forest Service land and many high-grade HDR resources are found within the boundaries of National Forests.

Larry Kline of the U.S. Army Corp of Engineers toured the HDR facility on July 23.

Dave Duchane met with Gladys Hooper, DOE Program Manager for HDR on July 16 in Washington to discuss the current issues in the HDR Program.

Reid Detchon, Principle Deputy Assistant Secretary for Conservation and Renewable Energy at the United States Department of Energy, visited the Laboratory on August 18 to review a number of programs including HDR.

At the invitation of Dr. Paul Miller, Dave Duchane, along with professor Daniel Swenson and Bob DuTeau of KSU visited the National Renewable Energy Laboratory (NREL) on August 3. Dr. Miller is a professor from KSU currently doing work at NREL.

Gladys Hooper, the DOE HDR Program Manager visited Los Alamos on September 9.

John Weeks of Brookhaven National Laboratory visited LANL on September 9 as a DOE representative to take part in an

investigation of the injection pump failure problem.

NON-PROFIT ORGANIZATIONS AND PROFESSIONAL SOCIETIES

Dave Duchane, HDR Program Manager, and Sue Fenimore of the Laboratory Industrial Relations Office, met with Paul Parker and Nancy Nelson, of the Center for Resource Management (CRM), on November 21 to finalize plans for the Forum on Renewable Energies, subsequently held on the weekend of December 7-8, 1991.

Eighteen (18) visitors from the American Bar Association Coordinating Group on Energy Law visited Los Alamos and toured the Fenton Hill HDR site on May 9.

The Board of Directors of the American Institute of Mining, Metallurgical and Mechanical Engineering (AIME) visited Los Alamos on August 13.

ACADEMIC

A review of HDR technology and the Los Alamos HDR Program was presented to 32 DOE SERS (Science & Engineering Research Semester) students at Los Alamos by Dave Duchane on October 15.

On January 27, Don Brown presented an overview of HDR to a group of about 25 students from 5 high schools in the Las Cruces, NM area. The students were visiting the Laboratory as part of an "Upward Bound" Program sponsored by New Mexico State University.

Dr. Paul Kruger of Stanford University visited Los Alamos on March 26-27 to confer on collaborative projects and work on a joint publication.

A group of 23 students spending a semester in work/study at Los Alamos were given a briefing on HDR by Jim Albright and a tour of the Fenton Hill site by Ray Ponden on April 28. The students were part of the DOE Science and Engineering Research Semester (SERS) program.

A group of 22 students from Colorado College and their instructor, Dr. Thomas McGlinn, toured the Fenton Hill site and received an overview of HDR on April 29.

The visit was part of a field trip for a class on energy technology developments.

In early April, Jim Albright presented an overview of HDR to a group of about a half dozen high school students involved in the Los Alamos Science Student Program.

Zachary Anderson of the College of Santa Fe visited Los Alamos on July 28 and was briefed on all aspects of HDR technology.

On July 16, Professor Ned Hedges, Past Vice Chancellor of the University of Nebraska at Lincoln, visited the Lab.

Professor Daniel Swenson of Kansas State University (KSU) visited the Laboratory on August 4-5 to confer with Los Alamos staff and several KSU students who were at the Laboratory working on HDR problems for the summer.

Professor Eileen Chant of the Turabo University in Puerto Rico visited the Laboratory on August 13. Dr. Chant is a member of the Science and Technology Alliance formed to promote interactions of Los Alamos, Sandia, and Oak Ridge

National Laboratories with predominantly minority universities.

On September 10, Clinton Lee, an electrical engineer from North Carolina State A & T University, visited the laboratory to discuss potential joint projects under the HBCU Program.

On September 25, a group of 10 graduate students and their professor from the New Mexico Tech Department of Geosciences visited the Fenton Hill HDR site and were briefed on HDR technology by Don Brown and Bob DuTeau.

As part of a field trip in the Jemez Mountains, Fraser Goff conducted a tour of the Fenton Hill HDR site for the instructor and 13 students in a University of New Mexico class on Advanced Vulcanology on September 26.

On September 16, Bob Potter presented a seminar to the Mechanical Engineering Department at New Mexico Tech on the Fenton Hill HDR site and geological considerations related to the development of HDR systems there.

MEDIA

Information about HDR technology was forwarded to Mr. Lowell Ponti of *Reader's Digest* magazine.

While at the Global Climate Change Conference, Robert Morris of the United States Information Agency (USIA), collected video footage and conducted an interview for a program segment he is preparing on HDR technology.

Hiro Enterprises, a Japanese company with offices in New York City, contacted the HDR program for materials to include in a planned television segment dealing with HDR.

Elliot Marshall of *Science Magazine* visited Los Alamos on November 7-8 to gather material for a story about the future of the National Laboratories.

Keith Easthouse, a reporter for the *Santa Fe New Mexican* and Jeff Kline, a photographer, visited Fenton Hill on November 21, to gather information for an article on HDR.

James Ruhle, editor of *Scientific Drilling*, contacted the Laboratory early in December

to inquire about the current state of HDR research and development.

Bob Martin, a reporter for **KGGM-TV**, visited the Fenton Hill HDR site on December 4. He did extensive filming and conducted interviews in preparation for a feature on HDR. The segment aired on December 5.

Material was sent to **ABOARD** magazine for preparation of a story on HDR to be included in a future issue.

In mid-December, Mr. Alton Marsh of the *International Solar Energy Report* conducted an extensive phone interview on the state of HDR technology development for a story he was preparing.

In mid-January, Edward Cook of the *Arizona Daily Reporter* conducted a telephone interview with Dave Duchane on the status of the HDR effort at Los Alamos.

At the request of Representative Kostmayer of Pennsylvania, Ms. Kimberly Moore of the State News Service contacted the Laboratory on January 23. She conducted a telephone interview to find out how HDR technology works.

On February 5, Dave Lillard of the *Solar Energy Intelligence Report* conducted a short phone interview with Dave Duchane regarding the recent House hearing on HDR, the status of the LTFT, and the funding history of the program.

Sherri Lassiter of the Public Broadcast Service (PBS) in Boston, MA, conducted telephone interviews about HDR technology. Ms. Lassiter is considering proposing HDR as a subject for a future segment of the television series "Scientific American Frontiers" which is produced by PBS in cooperation with *Scientific American Magazine*.

As part of a visit to Los Alamos on February 18, John Fleck of the *Albuquerque Journal* interviewed Dave Duchane regarding the HDR Program and the status of the long-term flow test effort.

Allen Scott and John Bass from **KOAT-TV** (Channel 7) in Albuquerque, NM visited the Fenton Hill HDR site on February 26 to conduct interviews and make video recordings for a story on the initiation of the long-term flow test. The segment was broadcast on the Channel 7 News on February 27.

Steve Michaud, a writer for *American Way* magazine, conducted a lengthy phone interview with Dave Duchane in preparation for an article he is planning on HDR. American Way Magazine is distributed on American Airlines flights.

Ida Molinari, a science journalist, visited the Laboratory and was given a briefing on HDR on April 1. Ms Molinari resides in the

United States but writes for *Familia Christiani*, a large Italian publication.

Bill Eisenhood of the Albuquerque NBC Television affiliate, **KOB**, visited the Fenton Hill site on April 8 along with cameraman Hank Gonzales. Bill is preparing a story on HDR for broadcast during the week of April 13.

Julia Andrews, Associate Editor of *Environment Magazine*, contacted the HDR Program Office on June 4 for an update on the status of the long-term flow test.

As part of a visit to the Laboratory on June 11, Tom Lippman, a reporter for the *Washington Post*, toured the Fenton Hill HDR site and received briefings on HDR technology.

Joel Davis, a free-lance writer, contacted the HDR Program Office on July 7. Mr. Davis was preparing an article for *Power Line*, a publication of Environmental Action.

Tom Trowbridge of Los Alamos Radio Station **KRSN** conducted an interview with the HDR Program Office on August 31. A story on the subject was broadcast on KRSN on September 1.

On September 1, Kevin Graham of *Earth News* conducted an extensive phone interview with the HDR Program Office in preparation for an article he was writing on Hot Dry Rock.

Ms. Lea Beth Ward, a freelance journalist, working on a story for California Energy Markets, interviewed the HDR Program Office on September 10 for an article she was preparing for the publication, *California Energy Markets*.

ARTICLES

HDR Geothermal Energy was featured in a half-page article entitled "Mining Deep

Underground Energy," by Matthew L. Wald, which appeared in the technology section of

the *New York Times* on Sunday, November 2.

The December 5 issue of the *Santa Fe New Mexican* carried an editorial strongly endorsing the timely development of HDR technology.

An article on HDR appeared in the October, 1991 issue of *US Water News*.

The January, 1992 issue of *Scientific Driller*, a monthly newsletter on the subject of continental scientific drilling was devoted entirely to HDR.

An article on HDR was included in the January, 1992 issue of *Superscience*, a magazine for elementary school students published by Scholastic, Inc.

The January 30, 1992 edition of *The Southampton Press* carried a story discussing HDR and the efforts of a local environmentalist and attorney, Mr. Russell Stein, in trying to bring wider attention to this vast energy resource.

An article on HDR appeared in the February 5, 1992 issue of the *Kansas State Collegian*. It described HDR technology and the role of Kansas State University in helping to support the program at Los Alamos.

The "Suffolk Closeup" column in the *East Hampton Star*, a newspaper published on Long Island, featured a story on HDR and the recent congressional hearing. It called for letters to congress in support of the technology.

The January-February, 1992 issue of the *Concerned Citizens of Montauk Newsletter* carried a long article by Russel Stein describing HDR and extolling its virtues.

The *Geothermal Hot Line* published by the State of California Division of Oil and Gas

ran two short articles on HDR in its December, 1991 issue.

An article on the beginning of the LTFT appeared on the science page of the February 24 edition of the *Albuquerque Journal*.

A story about volcanoes in the March, 1992 issue of *Reader's Digest* entitled "Fires of Destruction and Creation" discusses geothermal energy, including Hot Dry Rock.

The start of the continuous phase of the LTFT was featured in an article in the March 6 issue of the *Los Alamos Newsbulletin*, the Laboratory's weekly newspaper, and in a press release issued by the Laboratory on March 3.

The March 4 edition of the *Denver Post* carried an article on the beginning of the LTFT.

On March 9, an article about HDR and the start of the LTFT appeared in the *Los Alamos Monitor*, the local newspaper in the Los Alamos area.

A story entitled "Harnessing Energy From HOT ROCKS" appeared as a feature article in the March/April issue of *Aboard* magazine. The article was 6 pages long and included several color photos of the HDR site at Fenton Hill.

A story on HDR and the Clearlake HDR Initiative appeared in the March 23 issue of the *Santa Rosa Press Democrat*.

A report on the start of the LTFT was carried in the March 23 issue of *Inside Energy*.

An article in the March, 1992 issue of *Standpunkt*, a magazine published in German by Siemens, discussed the European HDR Program.

The March, 1992 issue of *Field Notes* published by the Energy & Minerals Field

Institute of the Colorado School of Mines carried a long article on their summer field program of 1991. It included an extended discussion of HDR and their visit to the Fenton Hill site.

A story in the May, 1992 issue of *Geotimes*, a publication of the American Geological Institute, described the start of the LTFT and summarized the history and status of HDR work at Fenton Hill.

An article on Hot Dry Rock entitled "Rocky XXII" appeared in the May 15, 1992 edition of *American Way*, the inflight magazine of American Airlines

An article, in the June 9, 1992 issue of *EOS*, discussed the future of the DOE's geothermal program, including HDR.

The June, 1992 issue of *Geothermische Energie* carried a lead article on the framework and objectives of the European HDR Program.

The May, 1992 issue of the *Geothermal Resources Council Bulletin*, was devoted entirely to the subject of Hot Dry Rock.

A story on HDR technology appeared in the September 4 edition of the *Washington Post*. It was written by reporter, Thomas W. Lippman, who visited Los Alamos earlier in the year.

MEETINGS

On September 30-October 1, Dave Duchane attended a course entitled "Project Finance: The Tutorial". The course, conducted by Infocast under the auspices of several organizations including the Geothermal Resources Council, specifically addressed all aspects of financing private power projects and featured speakers from lending firms, contracting and operating companies, and other relevant organizations.

Six (6) papers on various aspects of the HDR Program were presented by Los Alamos authors at the Geothermal Resources Council Annual Meeting in Reno, Nevada, October, 1991.

The Los Alamos presentations were as follows:

Burns, K.L., "Orientation of Minimum Principal Stress in the Hot Dry Rock Geothermal Reservoir at Fenton Hill, New Mexico,"

Burns, K.L., "The Clearlake Hot Dry Rock Geothermal Project: Institutional Policies, Administrative Issues, and Technical Tasks,"

Duchane, D.V., "Commercialization of Hot Dry Rock Geothermal Energy Technology,"

Fehler, M., House, L., Phillips, W.S., Block, L., Cheng, C.H., "Imaging of Reservoirs and Fracture Systems Using Microearthquakes Induced by Fluid Injections,"

- Ponden, R.F., "Performance Testing the Phase II HDR Reservoir,"

Robinson, B.A., "Alternative Operating Strategies for Hot Dry Rock Geothermal Reservoirs,"

On November 21, Dave Duchane presented an overview of HDR technology and potential to the Casper, Wyoming section of the International Association of Drilling Contractors.

On November 4-5, Dave Duchane attended a seminar on "Power Needs for the Nineties" sponsored by Infocast in conjunction with a number of organizations including the Geothermal Resources Council. Speakers included representatives from a half dozen major utilities located in the Pacific Coast Region.

The semi-annual review of the HDR Program was held at DOE offices in Washington, D.C. on November 13.

On November 26, Los Alamos HDR personnel and DOE staff from the Los Alamos and Albuquerque offices met with John Peterson and Bob Crostic of the U.S. Forest Service. The purpose was to update the Forest Service on the status of the HDR project and address issues of mutual interest.

A conference on HDR and Other Renewable Technologies was convened on December 7-8 to bring together business, government, academic representatives, and concerned citizens, for relevant discussions. The meeting, conceived by former U.S. Secretary of the Interior Stewart Udall, was co-sponsored by the Center for Resource Management, Los Alamos National Laboratory, the Electric Power Research Institute, Southern California Edison Company, and the Bechtel Group, Inc.

A paper entitled "Hot Dry Rock Heat Mining: An Advanced Geothermal Energy Technology" was presented by Dave Duchane at the Emerging Energy Technologies Symposium of the Energy-sources Technology Conference and Exhibition at Dallas, Texas, on January 28.

The Stanford Geothermal Conference held at Stanford University on January 29-31

featured a session on HDR and included an update of the British HDR Program.

On March 22-23, Dave Duchane attended the course, "An Introduction to Geothermal Resources", in San Francisco. The Geothermal Resource Council sponsored the course.

A number of HDR personnel attended the DOE Geothermal Program Review X in San Francisco, CA on March 24-26. Dave Duchane, Ray Ponden, and Don Brown presented papers.

Russel Stein, an attorney from Montauk, New York, contacted the Laboratory on April 23 for an update on the status of the LTFT. He was preparing to serve as a panelist representing Hot Dry Rock at the Long Island Energy Conference being held at the Suffolk Community College in Selden, NY on April 24-25.

On April 28, Schon Levy and Don Brown presented summaries of some of their recent work to a panel appointed to review DOE research projects in the geothermal energy area. The review was held in Albuquerque, NM.

On May 12-13, Dave Duchane attended the Annual Technical Conference of the Institute of Shaft Drilling Technology in Las Vegas, NV.

The Hot Dry Rock Program Development Council met on the evening of June 2 and the morning of June 3 to review the recent progress of the HDR program and discuss pathways to commercialization of the technology.

A tour of the Fenton Hill HDR site was arranged in conjunction with the 33rd U.S. Symposium on Rock Mechanics held in Santa Fe, NM on June 8-10.

On September 15, Dave Duchane presented a paper entitled "The Prospects for the Commercial Development of Hot Dry Rock

Geothermal Energy in New Mexico" by D. V. Duchane and F. Goff at the New Mexico Conference on the Environment.

BUDGET

HDR Program Budget (\$K)

<u>Task/Project</u>	<u>Fiscal Year</u>				
	<u>1989</u>	<u>1990</u>	<u>1991</u>	<u>1992</u>	<u>1993*</u>
Fenton Hill Site Operations	<u>2465</u>	<u>2471</u>	<u>2483</u>	<u>3193</u>	<u>1973</u>
Phase II Energy Extraction System	1582	1588	1610	2210	1113
Phase II Ancillary Activities	284	284	320	400	280
Test Site Support	599	599	553	583	580
Scientific & Engineering Support	<u>1135</u>	<u>829</u>	<u>817</u>	<u>677</u>	<u>495</u>
Engineering Development Activities	847	729	725	571	330
Technology Applications	288	100	92	106	165
<u>Reserve and Miscellaneous</u>	<u>000</u>	<u>000</u>	<u>000</u>	<u>000</u>	<u>000</u>
Total	3600	3300	3300	3870	2468
* Allocated as of 4/1/93					

With the exception of Fiscal Year 1992, the budget for the HDR Program has declined steadily over the past several years. In addition, the budgets shown above already reflect a considerable drop from the \$5-20 million annual level of support for HDR during 1980-1988. The increase shown for 1992 was achieved only by borrowing from the 1993 budget to support the LTFT. As a result, it is estimated that the Fiscal Year 1993 funding level of \$2.5 million will only be sufficient to support a total of about three months of flow testing.

While we are working with the US Department of Energy to obtain supplemental funding to permit flow testing to continue through the balance of the fiscal year, the prospects that such funds will be forthcoming are uncertain at best. When the available funds are exhausted, it will be necessary to put the Fenton Hill plant on a

stand-by status, thus forfeiting the opportunity to complete the long-term flow test of the Fenton Hill reservoir in an expedient manner. The budget reduction this year has seriously hampered efforts to move HDR technology toward commercialization.

During recent years the proportion of the HDR funding applied toward Fenton Hill operations grew to about 80% of the total allocation. As a result, the scientific support which has provided the underpinning for many of the advances in HDR technology has been significantly eroded. In the short run, this means that we are no longer able to extract the maximum amount of available scientific information from the test program. In the longer term, progress in the development of the technology may be seriously hampered by the inattention to the scientific base on which HDR development rests.

FUTURE PLANS

Long-term testing is now underway and the stage is being set for the development of a second HDR site. The severe constraint imposed on the program by repeated budget cuts during the past few years is now the major obstacle to accomplishment of the goals of this program.

Industrial interest in HDR technology continues to grow. An industrial partnership to further demonstrate the technology by the development of a second HDR plant at a geographically different location will be vigorously pursued. That facility will be designed and built to generate and market power at competitive production costs. The results of flow testing to date have provided strong encouragement that the HDR objective of producing electric power at 5-8¢/kWh is well within reach. This can only be achieved if the resources needed to keep this technology moving solidly forward are provided.

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

memorandum

TO: Distribution
FROM: Bruce Robinson and Mike Fehler, EES-4
SYMBOL: EES-4-91-208
SUBJECT: ESTIMATES OF ROCK VOLUME SUITABLE FOR HEAT TRANSFER CALCULATIONS

DATE: September 30, 1991
MAIL STOP/TELEPHONE: D443, 7-4318

The purpose of this memo is to document our current best estimates of reservoir rock volume on the basis of microseismic, tracer, and hydraulic data. It is understood that this estimate is to be used in a heat transfer calculation, and thus must represent the effective volume from which heat will be extracted. The size estimates will attempt to account for the fact that not all rock stimulated during a hydraulic fracturing experiment is necessarily part of the swept volume when a steady state flow field is established between the wells.

Several methods will be used to estimate the rock volume. The methods are:

- rock volume estimate from simple geometric arguments related to the positions of wellbores (swept volume);
- determination of the volume of rock in which microseismic events occurred during the hydraulic stimulation experiments that created the reservoir (microseismic rock volume);
- computation of the rock volume by dividing the tracer-determined fluid volume by an appropriate estimate of fracture porosity (tracer-determined rock volume);
- estimation based on hydraulic and mechanical considerations (hydro-mechanical rock volume).

After presenting the estimates, we discuss which value we believe to be the most appropriate to use in a heat transfer model.

Swept Volume

- The most conservative estimate of the effective rock volume swept by fluid is obtained from geometric arguments related to the spacing of the wells. This model assumes that when a flow field is set up between two wells, most of the circulating fluid travels directly between the wells, thus contacting only the rock in the vicinity of the two wellbores. Figure 1 illustrates the geometry used for this estimate of the rock volume. The assumed geometry is a right-circular cylinder with diameter equal to the well separation distance. The height is taken to be the

depth along the wellbores in which fluid is entering or leaving the well. The distance between the wells in the depth intervals where fluid is entering and exiting the wells is approximately 110m. From temperature log information, the reservoir height is approximately 300m. These dimensions yield a swept rock volume of $2.9 \times 10^6 \text{m}^3$.

Figure 1. Geometry used to estimate the swept rock volume.

This calculation probably underestimates the accessible rock volume when a flow field is set up between two wells. In reality, fluid is probably forced to sweep through a somewhat larger volume of rock than is shown in Figure 1. For example, in the classical dipole flow model, some fluid circulates in paths behind each well before reaching the production well. A more appropriate equivalent diameter for such a situation would be on the order of 150m, resulting in a swept volume of $5.3 \times 10^6 \text{m}^3$.

Microseismic Rock Volume

The ensemble of microseismic event locations determined during hydraulic stimulation experiments effectively outlines the region of rock in which the joints were stimulated. For this estimate of rock volume, it is assumed that shear stimulation has resulted in an enhancement of the permeability of pre-existing joints. Although there exist some theories that postulate the movement of fluid in the absence of seismicity, we will assume that this estimate is an absolute upper bound on the accessible rock volume.

For the volume estimate, the microseismic event locations obtained from three experiments were considered: 1) Experiment 2032, the massive hydraulic fracturing experiment during which the reservoir was initially created; 2) Experiment 2062, the first circulation experiment in which a large amount of microseismicity was observed; and 3) Experiment 2067, (the ICFT), during which a significant volume of new rock was stimulated during the circulation experiment. Other experiments during which microseismic events were located but no circulation occurred between the wells were omitted from the analysis, since this rock volume is probably not part of the volume that will be accessed during circulation and heat extraction.

An estimate of the stimulated rock volume is obtained by assuming an ellipsoidal reservoir, and determining the dimensions of the ellipsoid such that a given percentage of the events fall within it. For an ellipsoid encompassing 95% of the events (the so-called 2σ estimate), the semi-major axes of the ellipse are 174, 334, and 534m, yielding a stimulated rock volume of $130 \times 10^6 \text{ m}^3$. By contrast, the 1σ estimate, corresponding to approximately 68% of the events, results in semi-major axes of 87, 167, and 267m, for a total rock volume of $16 \times 10^6 \text{ m}^3$. The large difference in these two estimates highlights the fact that the microseismic rock volume estimate depends greatly on the method used to reduce the data.

A related method for estimating rock volume is to compute the volume over which physical properties have been changed by the fluid injections. This provides a direct measure of the volume of rock that has been altered by fluid flow. We calculated the total reservoir volume with S wave velocity below some value. The S wave velocity was used because it is most sensitive to the presence of fluid filled porosity. We use the velocities determined by Lisa Block using the microearthquakes during the first 19 hours of experiment 2032. We will use the velocities in Lisa's preferred model, which was obtained using a smoothing parameter of 4 and with a constraint imposed on the V_p/V_s ratio to keep Poisson's Ratio physical. The initial, unperturbed, velocity was 3.52 km/s. In the horizontal slice near the injection zone depth, 3500 m, the velocity dropped as low as 3.10 km/s. If we calculate the volume of the reservoir by choosing a velocity of 3.42 km/s to be the maximum velocity of the altered region, we get a volume of $71 \times 10^6 \text{ m}^3$. The velocity of 3.42 is 75% of the way from 3.10, the minimum velocity, to 3.52, the maximum velocity. If we choose a velocity of 3.32 km/s, halfway between the minimum and maximum velocities, we get a volume of $28 \times 10^6 \text{ m}^3$. The zone enclosed by the velocity of 3.32 km/s appears to be simply connected. Since a constraint was imposed on the inversion to give preference to smoother models, there is some smearing of low velocity regions into unperturbed zones. For this reason, the halfway point between the minimum and maximum velocities, 3.32 km/s, probably defines a better velocity to use for selecting a truly altered portion of the reservoir. Thus, our best estimate of the rock volume from this related geophysical technique based on microseismic data is $28 \times 10^6 \text{ m}^3$.

Tracer-Determined Rock Volume

Assuming steady state fluid flow and a tracer that follows the same flowpaths as the fluid, the total fluid volume V_f can be estimated from the first moment of the tracer-determined residence time distribution. Then, assuming an appropriate value for the porosity of the rock mass ϕ , the rock volume V_r is computed using $V_r = V_f / \phi$.

A tracer test conducted during the ICFT at conditions similar to those anticipated for the LTFT yielded a fluid volume of 2200m^3 . The value of porosity is far more difficult to estimate and more subjective. Clearly, it is the fracture porosity that is of interest, since fluid flow during circulation testing is predominantly through fractures. A rough estimate of porosity is obtained by assuming joints of aperture 1mm with an average spacing of 10m. The resulting porosity is 10^{-4} , which yields a tracer-determined rock volume of $22 \times 10^6\text{m}^3$.

Hydro-Mechanical Rock Volume

In the pressure transient experiments of the past several years, fluid has been injected into the rock mass while monitoring the reservoir pressure at the shut-in production well. This controlled experiment has allowed us to measure the volume change (as given by the fluid volume injected) associated with a change in the overall reservoir pressure. Assuming the duration of the experiment is sufficient for the fluid to diffuse throughout each of the rock blocks, the volume change is accommodated by compression of the mineral constituents of the rock matrix, predominantly quartz and feldspars. An estimate of the rock volume affected is thus given by $V_r = K\Delta V / \Delta P$, where K is the bulk modulus of the minerals, ΔV is the volume change, and ΔP is the corresponding pressure change. During the initial stages of this experiment, a change in reservoir pressure of 7.5 MPa resulted from the injection of 2715m^3 of fluid. Assuming a bulk modulus of 55 GPa, the relation above results in a hydro-mechanical rock volume estimate of $20 \times 10^6\text{m}^3$.

Discussion and Recommendations for Heat Transfer Modeling

The wide range of rock volumes obtained using these various estimation techniques illustrates that we currently do not have a proven technique for estimating the rock volume accessible for heat transfer. Actually, the nature of the discrepancies are probably due in large part to the method of estimation, and are reasonable given our understanding of the physical processes involved. For example, the microseismic rock volume (2σ estimate) should yield the largest volume estimate because the volume of rock stimulated in a high-pressure stimulation experiment is likely to be much greater than the swept volume during circulation at lower pressures. Note that the 1σ volume obtained in the microseismic estimate agrees with the tracer-determined and hydromechanical rock volume esti-

mates, but at present we have no physically based explanation for this agreement, and thus it must at this stage be considered to be fortuitous agreement. Furthermore, the related technique of determining the volume of rock with altered S wave velocity also gives a result similar to the other measurement techniques.

It seems likely that the volume appropriate for heat transfer should take into account the geometry of the two wellbores and the depth intervals at which fluid enters and leaves the system. The 2σ microseismic estimate should represent the maximum rock volume connected to the wellbores, but the close spacing of the wells makes it unlikely that the entire volume can be accessed during circulation. If heat extraction experiments show that the effective heat transfer volume is much smaller than the 2σ estimate, then operating strategies that more effectively force fluid into this larger volume should be considered after the LTFT. However, this topic is beyond the scope of this memo.

To a lesser extent, the caveat stated above with respect to the microseismic rock volume estimates are also true for the tracer-determined and hydro-mechanical rock volumes. These experiments were carried out at conditions more similar to the proposed conditions of the LTFT, and in fact the tracer-determined rock volume was computed from the results of a circulation experiment. However, neither estimate considers the fact that a nonuniform flow field will exist between the wells, resulting in an effective heat transfer rock volume that is somewhat smaller than either of these estimates. In the experiment used for the hydro-mechanical method, the accessible rock is compressed uniformly, regardless of whether all flowpaths contribute equally to the circulating flow system. As long as the paths are physically connected to the well (directly or through other paths), the volume is included in the measurement. Likewise, the tracer-determined volume includes all rock bathed by the flowing fluid, regardless of the flux through a given region.

When using these estimates to predict heat transfer behavior, the appropriate rock-volume measurement to use depends on the heat transfer model. For Kruger's one-dimensional heat transfer model, *the swept volume estimate of $5.3 \times 10^6 \text{ m}^3$ is recommended* because it is more likely to represent the effective, one-dimensional swept volume. By contrast, Robinson's tracer-based heat transfer model implicitly accounts for flow nonuniformities. Thus *the larger values of $22 \times 10^6 \text{ m}^3$ (tracer-determined rock volume), $20 \times 10^6 \text{ m}^3$ (hydro-mechanical rock volume), or $28 \times 10^6 \text{ m}^3$ (estimate based on altered S wave velocity)* should be used for the tracer-based heat transfer model of Robinson.

Of course, only LTFT thermal cooldown data will validate these models. Nonetheless, it is important to perform pre-test predictions to guide the test planning and to determine whether our current understanding of the flow and transport processes is sufficient to allow for adequate *a priori* prediction of reservoir size and heat exchange potential. Predictions will be carried out jointly by Robinson and Kruger using these latest size estimates and flow conditions anticipated for the LTFT.