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HDR ANNUAL REPORT, FY 1988

Preface

On September 21, 1988, Dr. John E. Mock, Director of the Geothermal Technology Division, Department of Energy, issued new guidance for the preparation of program annual reports. This guidance stressed a programmatic, i.e., a milestone and objective-achievement format, that differs considerably from earlier annual reports of the Hot Dry Rock Program, which stressed scientific and technical achievements.

Acknowledging the importance of the new format, but not entirely ready to abandon its previous approach, Los Alamos prepared the Hot Dry Rock report for this year in two volumes. This is the first volume, and it reports our work in accordance with Dr. Mock's guidelines. The accompanying second volume is a compendium of the scientific and technical publications of the project staff during fiscal year 1988. These publications are arranged in topical order to promote continuity, and the introductory "Technology Summary" abstracts the substance and conclusions of each paper.

With this two-volume approach, we believe that the reader will be able to quickly and effectively grasp the excellent achievements, both programmatic and scientific, of the Los Alamos Staff.

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EXECUTIVE SUMMARY

Conventional, or "hydrothermal," geothermal reservoirs have generated electricity since 1905 at Larderello, Italy. Another famous hydrothermal reservoir, The Geysers field in California, has been investigated since the 1920's. Hence hydrothermal technology is mature. Unfortunately, hydrothermal reservoirs are being found with ever diminishing frequency, and even today the bulk of development is concentrated in just one state, California. In contrast, Hot Dry Rock (HDR) geothermal reservoirs can be developed throughout the US, by drilling deep enough to encounter hot rock, and then creating the reservoir by hydraulically fracturing the rock with the injection of water down the drilled wells at high pressure. Because of this ready availability, HDR represents a vast nationwide resource, with at least 200 million megawatt centuries (500,000) quads of thermal energy. While only 1 to 10% of this huge resource base is likely to be practically accessible, even 1% represents 60 years of current US energy usage. Hence, HDR is essentially a renewable energy technology that could impact the electricity shortages expected in the mid-1990's.

Almost from its beginning, the HDR Program has operated at or beyond the limits of existing downhole technology with regard to equipment, instruments, and experimental techniques. It has therefore been necessary to work with industrial manufacturers, service companies, other laboratories, universities, or independently, to improve such things as high-temperature drilling, drill-guidance and well-completion equipment, borehole-surveying instruments, well-logging and downhole-monitoring tools, and the equipment and techniques for a variety of tests and innovative experiments. Many of these items are now finding useful applications outside of the HDR Program.

Projected HDR economics show that it should be able to compete with fossil fuels, and with no oxide or particulate emissions. A Los Alamos study concluded that HDR could generate electricity for \$0.049 per kWh and a study commissioned by the Electric Power Research Institute reported a similar result. More recently, investigators at Bechtel National Corporation concluded that an HDR plant at Roosevelt Hot Springs, Utah, could generate electricity at a break-even busbar cost of \$0.049 per kWh. A study of HDR electricity costs in the United Kingdom resulted in a cost of \$0.067 per kWh, based on a lower geothermal gradient, requiring greater reservoir depths than those in the US. Hence,

it appears very probable that the program will achieve its fundamental objective of providing HDR electricity at a cost of \$0.05 - \$0.08 per kWh.

Ten years of environmental surveillance at the Fenton Hill, NM, site have indicated negligible adverse environmental impact. HDR power systems can be implemented in small, modular plants and in a relatively short time. Thus, new supply could be brought on-line quickly and at a competitive cost.

However, much remains to be done before commercial application of HDR begins. The Long Term Flow Test (LTFT) must be conducted to provide the necessary data on total heat extraction and reservoir lifetime that industry requires to make sound investment decisions about HDR technology. Despite an unavoidable funding reduction for fiscal year 1988, the reduced HDR staff accomplished remarkable achievements. To ready the geothermal wells for the LTFT, a damaged depth interval in the production well (EE-2) was bypassed by drilling a new parallel interval about 25 to 30 m (80 to 100 ft) away from the damaged interval. It required just 30 days to drill 800 m (2600 ft) of additional well, an average drilling rate of 27 m (87 ft) per day, which is 2-1/2 times faster than was achieved during the original drilling of the well in 1978 and 1979. As a consequence of this favorable experience, HDR researchers believe that if the entire well were redrilled today, its cost would be only \$4 million rather than the \$10 million actually spent. This brightens the future of HDR and other geothermal programs because a 60% saving in drilling costs corresponds to a 30% reduction of overall cost to generate electricity.

During the drilling, the Los Alamos high-temperature acoustic televiewer, co-developed with WBK, a West German company, was successfully run to a depth of 3.69 km (12,100 ft) where the temperature is 240°C. The advantage of this new tool is that not only does it provide detailed data regarding the shape and eccentricity of the borehole wall, and reveal fracture intersections with the borehole, but it does so at unprecedented logging rates - 15 m (50 ft) per minute.

Following the redrilling, which was finished November 11, 1987, just one additional day past the minimum projected schedule, i.e., the one projected accounting for no contingencies, the well was completed by inserting a full-length casing and liner, so that pressure integrity was maintained from the surface to the production zones where the hot

water enters the well. In conjunction with this completion procedure, the well was successfully cemented several times using high-temperature techniques developed by Los Alamos and the Dowell Schlumberger company.

Supporting technology that will be needed during the LTFT was also developed. Automated computer-techniques for determining the onset of compressional and shear seismic waves were improved, so that future fracture mapping can be performed three times faster. Spectral analysis of seismic waves from microearthquakes caused by earlier fracturing experiments confirmed the shear-slippage mechanism triggered by the injection of water in naturally jointed rock masses. The "three-point" fracture-identification method led to the identification of the major fractures in the Fenton Hill reservoir.

Temperature-sensitive, chemically reactive tracers will be used during the LTFT to infer internal reservoir temperature profiles and provide early warning of cold-water thermal breakthrough into the production well. While extraordinarily useful these tracers require very sensitive chemical analysis, down to levels of one part in a billion (1 ppb). In FY88, we began to approach that goal; a technique was developed that already provides sensitivity to 5 ppb, and it has promise of further improvement.

Predictions and performance-matching of LTFT results will be performed with numerical reservoir simulators. In 1988, Los Alamos advanced its Finite-Element Heat and Mass Transfer code by performing 3-dimensional computations, and introduced pressure- and temperature-dependent rock properties and heterogeneous rock treatment. In this manner we accomplished simultaneous computation of the effects of coupling between the rock matrix, its fractures, and changes of tectonic stresses induced by water injection.

An important aspect of HDR development has been its focus on technology transfer, and this continued in FY88. Forty percent of the Los Alamos funding was subcontracted to private industry. In addition, acoustic-tomography tools first developed by Los Alamos for HDR were evaluated by the Amoco Oil Company at their Mounds, Oklahoma test site for potential application to oil reservoir imaging. The three-point method previously mentioned was applied to other funded research, and showed that recent earthquakes at Coalinga, CA, were unexpectedly caused by reverse faulting.

I. INTRODUCTION

1. Background

a. Need/Justification

Geothermal energy is natural heat in the Earth's interior, produced principally by the slow decay of naturally occurring unstable forms of the elements uranium, thorium, and potassium. Because the Earth's surface is cooled by radiation of heat into space, a temperature gradient is maintained between its hot interior and its cool surface which, on a worldwide average, is about 30°C per kilometer of depth (17°F per thousand feet). However, this geothermal gradient is often much higher where the Earth's crust is thin or has been disturbed by volcanism or large-scale earth movements.

When a hole is drilled downward from the Earth's surface, it usually passes first through layers of soil, gravel, and fractured rock that are kept cool by groundwater circulation. With increasing depth, however, the increasing pressure produced by the weight of material above it causes the permeability and free-water content of the formations encountered to diminish, until both are very low. Thereafter, active groundwater circulation rarely occurs, so heat transfer toward the Earth's surface is by thermal conduction alone, and a temperature gradient typical of the location and the thermal conductivity of the formation is established. At depths at which usefully high temperatures exist, permeability and free-water content typically are extremely low -- the "hot dry rock" situation.

Exceptions to this occur where there have been large earth movements. Usually these involve the sliding of one part of the Earth's crust past another part along a large fracture surface called a "fault," accompanied by considerable fracturing of the formations on each side of the fault. Where these fractures have not been sealed by heat, pressure, and mineral deposition, they may permit surface water to seep down far enough to reach hot rock. The heated water expands and, rising buoyantly, it may reach the Earth's surface as hot water or steam. It may also remain trapped in open fractures or porous formations, forming "hydrothermal reservoirs" of hot water or -- very rarely, where pressure in the reservoir is low enough to permit boiling -- of steam. Such reservoirs can be useful and

economical sources of thermal energy, but unfortunately they are rare. At depths where usefully high temperatures exist, the usual geologic environment is hot dry rock.

Estimates of the amount of potentially useful heat present in hot dry rock at accessible depths beneath the United States vary widely with the assumptions made concerning minimum temperature required, practical drilling depths, the characteristics of the subterranean environment, and the effectiveness of the heat-recovery method. 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, which 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 that heat would contribute significantly to the nation's energy future.

A concept for recovering useful heat from this tremendous natural resource originated at Los Alamos National Laboratory. As shown in Fig. 1, it involves drilling two holes down from the surface into the hot rock; connecting them through the rock by means of large cracks created by fluid pressure (hydraulic fracturing); and circulating water through this underground loop to extract heat from the rock and transport it to the surface.

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

In his 1987 report on Energy Security, Energy Secretary Herrington stated that "...the United States and the world will, in time, come to rely largely on energy sources that are essentially inexhaustible, possibly including advanced nuclear fission reactors, fusion, and many diverse sources that are commonly lumped under the term 'renewable energy'." This view is widely held, and HDR is indeed one of those "essentially inexhaustible"

Figure 1. Hot Dry Rock Geothermal Reservoir.

energy resources. Although HDR energy recovery involves mining heat from a body of subterranean rock, it is also "renewable" in the sense that heat extracted from the rock will eventually be replaced by additional heat conducted to it from deeper in the Earth.

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

The economics of HDR systems remain to be demonstrated in long-term, large-scale operations. However, independent analyses by the Electric Power Research Institute, the Meridian Corporation, Bechtel National, Inc., and the United Kingdom Department of Energy, all agree that the energy produced should be competitive in cost with that from fossil fuels or other existing energy sources²⁻⁵. Further, HDR technology is still in the development stage, and obviously can be improved in many ways. With aggressive further development, the cost of energy from HDR systems should certainly decrease with time -- in contrast to the inevitable trend of energy costs from conventional sources.

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

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.

b. History of Research

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

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

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

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

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 Fig. 2. 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

Figure 2. Conceptual Design of Phase II Reservoir.

or connect the two wells hydraulically. (This unusual fracturing behavior is probably the result of a joint pattern in the reservoir rock, related to the presence of a cooling magma body underlying a volcanic caldera a few kilometers east of Fenton Hill.) Because it appeared unlikely that further hydraulic fracturing would establish the required connection, it was concluded that a more promising approach would be to redrill one of the wells directionally through a fracture system created from the other well.

The largest of the potential redrilling targets was the fractured volume produced in December 1983 by the Massive Hydraulic-Fracture (MHF) Experiment during which $21,300 \text{ m}^3$ (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).

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.

After several preliminary experiments, the Initial Closed-Loop Flow Test (ICFT) of the Phase II system was conducted over a period of 30 days in May and June 1986. A total of $37,000 \text{ m}^3$ (9.76 million gallons) of cool water was injected through well EE-3A, of which 66% was recovered through the production well, EE-2, during the test, and an additional 20% was recovered during a subsequent venting of the system -- from temporary storage in the pressurized fracture system. Pumping rates were usually either 10.6 or 18.5 l/s (168 or 294 gpm), at surface pressures around 26.9 MPa (3900 psi) and 30.3 MPa (4400 psi) respectively. To prevent boiling and CO_2 evolution downhole, a back-pressure of about 3.5 MPa (500 psi) was maintained on the production well, resulting in fluid-production rates of 6.3 to 13.9 l/s (100 to 220 gpm). Temperature of the produced fluid increased throughout the 30-day test, to a maximum of 192°C (378°F), and the rate of energy production increased correspondingly, to 10 MW_t (34 million Btu/hr). Overall flow-impedance through the fractured reservoir decreased throughout the test.

As a result of fatigue failure of a flow-line connection to well EE-2 in 1983, an uncontrolled vent occurred that created leaks in the lower part of the 245-mm (9-5/8 in.) casing and an obstruction in the 178-mm (7-in.) transition liner below the casing. Removal of the upper sections of the liner and caliper logs and impression-block runs in November 1986 showed that both the liner and the casing had partially collapsed at a depth of about 3200 m (10,500 ft). Attempts to mill out the obstruction and re-enter the remaining liner were unsuccessful, and several other options for repairing the well were considered. In accordance with the recommendations of a panel of drilling and well-completion experts convened in January 1987 by the Geothermal Technology Division of DOE, the option selected was to seal the casing leaks and add support to the upper part of the casing by cementing the annulus behind it, and to sidetrack and redrill the well from a point above the region of casing collapse.

Accordingly, a drilling rig was mobilized over well EE-2 in early September 1987 to initiate these operations. The bottom of the well was plugged with cement to prevent interactions with the redrilled wellbore and provide a base for subsequent installation of the whipstock needed for sidetracking. The annulus behind the casing was filled with cement to the level of a lost-circulation zone at about 735-m (2410-ft) depth, and casing leaks and perforations were sealed with high-strength cement. A window for sidetracking the well was produced by milling out the casing from 2953 to 2971 m (9688 to 9747 ft). At the end of FY87 on September 30, preparations began to install the whipstock and sidetrack the well. As is discussed in Section II of this report, EE-2 was successfully sidetracked and redrilled during FY88.

Because hot dry rock represents an essentially inexhaustible supply of thermal energy almost everywhere, the US HDR Program has attracted international interest. Parallel and complementary programs have since been initiated in several other countries, notably in the Federal Republic of Germany, Japan, Great Britain, Sweden, France, and the Soviet Union. Under an International Energy Agency (IEA) Agreement, agencies of the Governments of West Germany and Japan (KFA-Julich and NEDO) have participated directly in the Fenton Hill Project. This involved partial financial support, membership in its International Steering Committee, and long-term assignment of scientists and engineers from both countries to the HDR staff at Los Alamos. Under a bilateral agreement between the US

DOE and the Italian Energy Agency (ENEL), a close relation with geothermal programs in Italy was established. There is continuing informal cooperation and information exchange with individuals and organizations in these and other countries.

c. Mandates

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

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

In 1984, the DOE Office of Program Analysis conducted an assessment of geothermal research. In its report,⁶ nine individual projects within the HDR Program were evaluated. Three were rated "outstanding," five were "strong projects deserving of continuing priority support," and one was simply "good."

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

However, a 1986 review of geothermal-energy programs by the Solid Earth Sciences Panel of the Energy Research Advisory Board⁸ suggested that both the HDR and the Magma Energy Programs should be terminated because geothermal energy would be limited to only a minor role in future energy use. (The panel evidently did not appreciate either the magnitude of the HDR energy resource or the fact that the HDR Program had brought HDR technology to the threshold of economic viability.)

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

In 1987, the Committee on Geothermal Energy Technology of the National Research Council reviewed the DOE geothermal programs. It reported⁹ that the HDR Program was well managed with reasonable and important technical goals directly addressing the program's objectives. It noted that budget cuts and the resulting loss of technical personnel had weakened the Program, and recommended that DOE "stay the course" with adequate funding to maintain a vigorous HDR Program through FY's 88-91.

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

d. Technology Transfer

Industry has been directly involved in the HDR Program from its beginning. Approximately 40% of the total HDR budget has gone to drilling and service companies in a mutually beneficial arrangement in which industrial and program personnel have learned

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

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

As a result of this type of involvement, and with financial support from the US Department of Energy, Bechtel National, Inc., has formed a partnership with the State of Utah and International Geothermal Co. (a wholly owned subsidiary of Chevron Resources Co.) to undertake a feasibility study of HDR development in the Roosevelt Hot Springs geothermal area in Utah. There are close interactions between that partnership and the HDR Program at Los Alamos, which is effective because each participant has a well-defined role. Los Alamos conducts the basic research and technology development, with advice and strong participation from industry. Industry uses its strengths in engineering and in understanding market forces to design and develop a second HDR site, based on the research and technology development done at Los Alamos.

Hot dry rock is a worldwide energy resource, and the successes of the US HDR Program have led to establishment of parallel and complementary programs in other countries. The programs in Japan, the United Kingdom, and the Soviet Union now employ more personnel than does the US Program, and active but smaller programs are also underway in Sweden and in a joint effort by the French and West German Governments.

The DOE-sponsored HDR Program has become a model for technology transfer.

2. Objectives

a. Logical Basis

In accordance with the guidance of the US Department of Energy's Geothermal Technology Division, Los Alamos uses management-by-objectives to direct its research program. The goal of the HDR program is to help implement the DOE's policy that "Americans should have an adequate supply of energy, available at a reasonable cost." To attain this goal the DOE has established three levels of objectives: a level I objective provides targets for decreasing the cost of generating electricity; level II addresses incremental improvements in cost and performance; and level III identifies improvements in cost efficiency and certainty of performance.

b. Hierarchy of Objectives

The complete list of HDR objectives is provided in Reference 10, and is tabulated below in Tables 1 and 2 for the reader's convenience. The primary, level I, objective for HDR is "to improve the technology to the point where electricity could be produced commercially from a substantial number of known HDR resource sites in a cost range of 5 to 8 cents/kWh by 1997." A critically important milestone in attaining this cost target is the level II objective: "Evaluate the performance of the Fenton Hill Phase II reservoir." To appreciate the significance of this objective, a brief background is helpful. During the past 14 years the US DOE has invested \$123 million to develop the technology required to make Hot Dry Rock geothermal energy commercially useful. The Governments of Japan and the Federal Republic of Germany have contributed an additional \$32 million to the US program. The initial objectives of the program were met by the successful development

Table 1. Level II Objectives

1. Evaluate the Performance of the Fenton Hill Phase II reservoir. That performance consists of system operating characteristics, including thermal drawdown, energy output, reservoir impedance, and water consumption.
2. Improve the performance of drilling and completion technology under conditions typical of hot dry rock environments.
3. Determine the environmental acceptability of the technology.
4. Evaluate the economics of the technology.

Table 2. Level III Objectives

1. Improve instrumentation and hardware to control, locate, and measure fracture propagation in hot dry rock reservoirs.
2. Establish reservoir-mapping techniques to locate drilling targets for production wells.
3. Evaluate the large Phase II reservoir at Fenton Hill to determine its drawdown characteristics.
4. Complete studies on water-rock interactions and their effects on flow through a hot dry rock reservoir.
5. Develop technology to monitor changes in reservoir volume and temperature and confirm monitoring data using tracers.
6. Complete detailed reservoir analyses and confirm modeling of hydraulic and thermal performance of the Phase II system.
7. Determine means to locate accurately the intersections of fractures with the wellbore.
8. Develop cement formulations that result in low-density, moderate-strength, zero-free-water cements for casings.
9. Verify that the environmental and social consequences of HDR development are acceptable.
10. 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.

and long-term operation of a heat-extraction loop in hydraulically-fractured hot dry rock. This Phase I reservoir produced pressurized hot water at temperatures and flow rates suitable for many commercial uses such as space heating and food processing. It operated for more than a year with no major problems or detectable environmental effect. With this accomplished and the technical feasibility of HDR energy systems demonstrated, the program undertook the more difficult task of developing a larger, deeper, hotter reservoir, called "Phase II", capable of supporting pilot-plant-scale operation of a commercial electricity-generating power plant. As described earlier in "History of Research", such a system was created and operated successfully in a preliminary 30-day flow test. However, to justify capital investment in HDR geothermal technology, industry now requires assurance that the reservoir can be operated for a long time without major problems or a significant decrease in the rate and quality of energy production. Industrial advisors to the HDR Program have concluded that, while a longer testing period would certainly be desirable, a successful and well-documented flow test of this high-temperature, Phase II reservoir lasting at least one year should convince industry that HDR geothermal energy merits their investment in its commercial development. This test is called the Long Term Flow Test (LTFT), and its completion will be a major milestone in attaining the Level I objective.

However, before the LTFT could be initiated, well EE-2 had to be repaired, as also briefly described in the "History of Research". During this repair operation, superb progress was made toward satisfying the next most critically important Level II objective: Improve the Performance of HDR Drilling and Completion Technology. During the repair of EE-2, Los Alamos sidetracked by drilling out of the damaged well at 2.96 km (9700 ft), and then completed drilling a new-wellbore (EE-2A) to a total depth of 3.78 km (12,360 ft). As a consequence of this drilling experience, Los Alamos believes that if the original wells were redrilled today their combined cost would be only \$8 million rather than the \$18.8 million actually spent (a 60% cost saving). Further details, particularly of the completion of the well, can be found in the major section, ACCOMPLISHMENTS, but it can be seen that the second, Level II objective is already nearing attainment.

A final note concerns the interaction of objectives. Not only does the successful EE-2 repair brighten the outlook for future HDR drilling programs, it also helps accomplish the Level I objective of reducing costs because fully half of the overall cost of an HDR power-

plant stems from drilling. Hence, a 60% saving in drilling cost corresponds to a 30% overall cost saving.

3. Work Breakdown Structure

In the "Work Breakdown Structure," the Hot Dry Rock Program, has as its primary objective the development of an industrially exploitable technology base for HDR energy extraction and the verification that the environmental consequences are acceptable.

The two principal tasks under this category are the Fenton Hill site operations and the scientific and engineering support. The site operations cover the drilling and completion operations at Fenton Hill, the field operation of the performance and evaluation testing of the reservoir, and the supporting environmental monitoring and operations systems. The scientific and engineering support includes the development and operations of tools and instrumentation, the collection and compilation of technical data, and the analyses and reporting of the technical results of the program.

Under the Fenton Hill Site Operations Task are three projects: (1) Phase II Energy Extraction System, covering the wellbore completion and the surface system design, procurements, installation and testing. (2) Phase II Ancillary Activities including diagnostic logging and environmental monitoring. (3) Test-Site Support and Utilities such as water supply and site maintenance.

The Scientific and Engineering Support Task includes the following projects: (1) Tools and instrumentation, covering the downhole instrument and equipment development as needed for the extreme conditions of the experimental work, and calibration and maintenance of existing instrumentation. (2) Reservoir Engineering such as various reservoir analyses including microseismic, size-assessment techniques and geochemical processes. (3) ~~Technology Application, covering~~ Technology Exchange, various report preparation, and the comprehensive HDR Systems Study.

The Work Breakdown Structure is detailed in Table 3. Additional details can be found in the Annual Operating Plan for 1988¹¹.

Table 3. Work Breakdown Structure

<u>Level</u>		<u>Identifier</u>	<u>Title</u>
I	Category		HOT DRY ROCK PROGRAM
II	Task	1	<u>FENTON HILL SITE OPERATIONS</u>
III	Project	12	<u>Phase II Energy-Extraction System</u>
IV	Activities	121	Phase II System Design & Procurements
		122	Phase II EE-2A Completion Preparations
		123	Phase II Drilling/Workover Operations
		124	Phase II System Surface Installation
		125	Phase II System Flow Tests
III	Project	13	<u>Phase II Ancillary Activities</u>
IV	Activities	131	Wellbore/Reservoir Diagnostic Logging
		132	Environmental Monitoring
III	Project	14	<u>Test Site Support and Utilities</u>
IV	Activities	141	Water Supply
		142	Site Maintenance
II	Task	2	<u>SCIENTIFIC AND ENGINEERING SUPPORT</u>
III	Project	21	<u>Tools and Instrumentation</u>
IV	Activities	211	D/H Instrument & Equipment Development
		212	Instrumentation Calibration & Maintenance
III	Project	22	<u>Reservoir Engineering</u>
IV	Activities	221	Reserv. Thermal/Fluid-Dynamic Des./Anal.
		222	Reservoir Microseismic Analysis
		223	Reservoir Size Assessment Technique
		224	Reservoir Geochemistry Processes
III	Project	23	<u>Technology Application</u>
IV	Activities	231	Technology Exchange
		232	Comprehensive HDR Systems Study

II. Accomplishments

The HDR program accomplishments for FY1988 are discussed following the order of tasks and projects given in the Work Breakdown Structure above (Table 3). All tasks are leading toward the Level I objective of improving HDR technology to the point where electricity could be produced commercially. Much work has been done in preparing for the LTFT and meeting the Level II objective of evaluating performance of the Fenton Hill Phase II reservoir (Table 1, 1). Research is ongoing in establishing the environmental acceptability of the technology through seismic and geochemical monitoring at Fenton Hill and meeting this Level II objective (Table 1, 3). Separate activities, discussed below, are also related to the Level II and III program objectives described in Tables 1 and 2.

1. Fenton Hill Site Operations

a. Phase II Energy-Extraction System

(1). Phase II Workover/Redrilling Operations

Preparations for the redrill of EE-2 were completed and the Big Chief rig was mobilized on September 8, 1987. A number of operations critical for stabilization of the well before the actual sidetrack were completed. First, cement was injected to plug the bottom of EE-2 and to eliminate the possibility of any interference of the abandoned wellbore with production from the reservoir after redrilling. Second, the casing was perforated at 3170 m (10,400 ft) and cemented to eliminate flow behind the casing from fractures at this depth to a low pressure zone at 2990 m (9800 ft). In a third cement job, cement was injected through perforations at 2910 m (9550 ft), again cementing the casing - this time to insure a high casing strength against collapse. The casing between 2965 and 2983 m (9727 and 9788 ft) was removed by milling, which was later confirmed by caliper log. In preparation for work shallower in the well, the milled interval was sealed with a protective cement plug. In a last and most extensive cement job, the casing between 730 and 1980 m (2400 and 6500 ft) was cemented, through perforations, to give the casing added strength.

There were numerous interactions between Los Alamos and Dowell-Schlumberger on selection and testing of the various cements used. Logs were run preceding and succeeding

each job to determine borehole temperature on placement of cement and its location after setting, and calculations of wellbore temperature recovery during setting of the cement were made using the WBHT code.

EE-2A was successfully sidetracked as shown in Fig. 3 on October 10, 198⁷~~8~~, and deepened to 2811 m (9224 ft) by October 12, while increasing inclination from 13-1/2 to 14-3/4°. A downhole motor assembly was run in the hole to turn EE-2A to the south along the planned trajectory.

Pressurization of the reservoir through EE-3A began October 18 and ended November 2, 198³~~8~~. The injection pressure was held constant at 14.5 MPa (2100 psi) and a total of 2130 m³ (563,000 gallons) of water was injected. A Parshall flume was installed in the Big Chief mud pits for detection and measurement of the first production from the reservoir during drilling.

Drilling of EE-2A continued to a depth of 3356 m (11,009 ft). The hole was surveyed at N70°E and an angle of 24-3/4° which was very close to the planned trajectory. Fluid chemistry and drilling parameters indicated connection to the pressurized Phase II reservoir. A series of shut-in, flowing, and injection tests confirmed the connection and provided data for evaluation which contributed to the selection of the liner-setting depth.

At noon on November 11, well EE-2A was drilled to its final depth of 3767 m (12,360 ft). The last intersection with a significant reservoir fracture was at 3672 m (12,050 ft), so a rat-hole of 95 m (310 ft) has been drilled below the reservoir, as planned.

The drilling campaign was nearly flawless. There were no twistoffs; no fishing jobs were required; the well was sidetracked perfectly; and it was redrilled precisely, deviating no more than 7.5 m (25 ft) from its target trajectory. Following sidetracking, 29-3/4 days were required to drill 791 m (2595 ft) of additional hole: an average drilling rate of 26.5 m (87 ft) per day, which is excellent for directional drilling deeper than 2950 m (9700 ft) in hard rock at over 200°C. This average rate is slower than the actual drilling rate because it includes the time required to repeatedly survey the hole and to trip the drill string in and out to change drill bits and assemblies. When the bit was actually rotating on bottom, the drilling rate was typically 3 m/hour (10 ft per hour).

Figure 3. Sidetracking and Redrilling of EE-2 Well.

Following completion of drilling, a multishot survey was conducted to confirm the single-shot surveys run during drilling, the drilling mud was displaced with water, and the hole circulated to clean it. A drill-pipe run was made with a casing scraper, and then the 244.5-mm (9-5/8-in.) casing was inspected with a 64-arm caliper to determine how much additional wear, if any, was caused by the redrilling of EE-2A. After the BOP stack was removed, the EE-2A wellhead was prepared for pressurized logging.

On November 15 and 16 the redrilled EE-2A borehole was first logged with the new temperature/gamma tool and then with the new caliper/gamma tool, both with excellent results. Fourteen reservoir flow connections were detected over a 365 m (1200-ft) open-hole interval extending from 3305 to 3670 m (10,840 to 12,030 ft), with a major set of deep flowing-fractures near 3660 m (12,000 ft). The drilling rig was furloughed November 16 and preparations were begun for Experiment 2074, Post-Drilling Reservoir Testing. Results of this test are presented later in section (5)(a).

EE-2A workover/redrilling operations have demonstrated an improvement in drilling technology under conditions typical of hot dry rock environments and have satisfied this Level II objective (Table 1, 2).

(2). Completion of EE-2A

Four bids were received and evaluated for the 177.8-mm (7-in.-o.d.) casing to be used for the tie-back string in EE-2A. Three bids were for existing casing which was manufactured years ago and had been in surplus until a shortage of casing recently began to develop. Two of the responses did not meet the specifications, and the other did not offer sufficient casing for the entire job. The fourth response offered new casing, to be manufactured by Nippon Steel, and delivered by May 1988. This pipe was not only the best from a materials and technical point of view but also cost the least, so a purchase order was placed for 2895 m (9500 ft).

William Turner, a materials and fabrication consultant to Los Alamos, visited Nippon Steels facilities in Japan to provide quality assurance during manufacture of the 177.8-mm (7-in.) casing. He approved the steel alloy selection, fabrication process, and heat

treatment, then worked with Nippon Steel engineers to set up the threading. No problems were encountered and the casing was completed five days ahead of schedule.

A more detailed procedure for installation of the liner and 177.8-mm (7-in.) casing was developed by LANL consultant Bob Nicholson. The procedure was evaluated and new and more detailed casing-stress calculations, incorporating additional cement-test data, well trajectory, and reservoir test results, were run to optimize the installation procedure.

EE-2A completion operations commenced on May 16, 1988, with reactivation of Big Chief Rig 47. Temperature/gamma, caliper/gamma, and televiewer surveys were run in EE-2A on May 16, 17, and 18 respectively. The logging indicated the borehole was in good condition for upcoming cementing operations.

Prior to running and cementing the 177.8-mm (7-in.) liner, the well was sanded back to 3284 m (10,775 ft). The 177.8-mm, 48-kg/m (7-in., 32-lb/ft) liner was then run into the hole, with the liner shoe at 3282 m (10,769 ft) and the liner hanger at 2895 m (9498 ft), and cemented into place on May 24, 1988.

It was decided to cement the upper 275 m (900 ft) of the 244.5-mm x 339.7-mm (9-5/8 in. x 13-3/8 in.) annulus in EE-2A in order to strengthen the upper casing and to prevent its being overstressed during production. A bridge was formed by dropping frac balls followed by gravel and sand into the annulus. The annulus was then cemented through perforations in the 244.5-mm (9-5/8 in.) casing at 270 m (885 ft). This operation was only partially successful as the cement could not be pumped above 65 m (214 ft) (as determined from temperature and cement-bond logs run May 27 and 28).

The borehole was drilled and cleaned out to the bottom of the liner and pressure tests showed that the top of the liner was well cemented. Samples of cement cuttings taken at 5 depths during cleanout were examined microscopically. As expected the upper cement that was displaced around and over the top of the liner and into the hole contained pipe dope and other contaminants. Deeper samples were clean, hard cement.

The 177.8-mm (7-in.) tie-back liner was run in the hole June 1 and cementing was completed at midnight June 2, 1988. Cement, 53 m³ (330 bbls), consisting of 37 m³ (230

bbls) of light-weight perlite cement followed by 16 m^3 (100 bbls) of high-density cement, were injected, resulting in 2030 m (6650 ft) of light-weight cement on top of 900 m (2950 ft) of high-density cement. A cement-bond log run on June 8 showed good cement-bond density in most of the hole. All critical regions such as the liner, tie-back sleeve, and near-surface (about 60 m [200 ft]) showed good bonding. The casing-collar log run with the cement-bond log confirmed that the tie-back-stem had not stung into the tie-back sleeve.

On June 3 and 4, the 177.8-m (7-in.) casing was tensioned and set in the wellhead grips, cut to length, and the secondary wellhead seals and blowout preventer were installed. The 88.9-mm (3-1/2-in.) drill pipe was run in the hole with a 139.7-mm (5-1/2-in.) bit to drill out cement. After the cement had been drilled, the sand placed at the bottom of the hole was washed out. Prior to drilling the cement plug at 3280 m (10,770 ft) the liner was pressure tested to 17 MPa (2500 psi).

Final cleanout of the hole occurred June 13. On June 14 Los Alamos ran a temperature survey of EE-2A which provided background temperature-measurements for a subsequent experiment and provided a check for any obstructions in the hole. The hole was clear to a wireline depth of 3715 m (12,187 ft) (corresponding to a drill pipe depth of about 3700 m [12,140 ft]) where a drilling ledge occurs. Since this is in the rat-hole below the bottom-most producing fracture, no further cleanout was attempted.

On the next day, the blowout preventer was removed, a bridge plug set inside the 177.8-mm (7-in.) casing and the new high-pressure wellhead installed. The final stage in the completion work was the pressurization test, Experiment 2076 which was conducted June 15. Results of Expt. 2076 are presented below in section (5)(b). A Kuster temperature survey following the experiment showed a thermal anomaly that suggested that at high pressure some injected water leaked behind the casing near the join of the tie-back casing and liner at 2895 m (9500 ft). A Los Alamos survey run later that day did not confirm the anomaly at that depth. A second Kuster survey was then run following a brief injection the next day. It indicated the anomaly was actually about 75 m (250 ft) above the liner-to-tie-back casing joint, ruling out the suspected leak. In addition it seemed to be caused by heating as opposed to cooling. On June 17, following this test, the Big Chief drill rig was released. The final Big Chief truck departed the site June 25, 1988.

Completion operations and pumping tests required 32 days, compared to an initial estimate of 23 days. The extra time was required to (1) perforate and cement the 244.5-mm (9-5/8-in. to 13-3/8-in.) annulus; and (2) evaluate the EE-2A pumping test and temperature logs. Total completion costs, including casing, rig costs, pumping, logging, redrilling, and third-party costs, were \$852,000 or \$64,000 more than initially estimated.

EE-2A completion operations (casing and cementing) have demonstrated the improvement in completion technology under conditions typical of hot dry rock environments and have satisfied the Level II objective (Table 1, 2). The Level III objective (Table 2, 8) of developing special cement formulations has also been met.

(3). Wellhead Configurations

A preliminary proposal for wellhead configurations for both EE-2A and EE-3A was prepared. Equipment available at Fenton Hill was inventoried to establish what additional equipment was necessary to complete the wellhead assemblies.

The production head for EE-2A provides an API 10000 psi (69 MPa) shut-in and low rate production capability for the 52.4-mm (2-1/16-in.) outlet(s) below the bottom master valve and 179-mm (7-1/16-in.) API 5000 psi (34.5 MPa) production and logging head above the lower master valve. The main production line and a production vent line are tied into the outlets on the cross through 103-mm (4-1/16-in.) API 5000 valves. The API 10000 equipment is limited to 62 MPa (9000 psig) service at 232°C (450°F); the API 5000 equipment is limited to 31 MPa (4500 psig) service at 232°C (450°F). The wellhead will provide a minimum 152-mm (6-in.) ID logging accessibility to the wellbore where the drift ID of the 177.8-mm (7-in.) casing is 149.3-mm (5.879-in.).

The wellhead for EE-3A provides a combination ANSI 2500/API 10000 injection head which is limited to an injection pressure of 41 MPa (6000 psig) cold (compatible with the present discharge specification for the high-pressure LTFT pumps). It provides a minimum 103-mm (4-1/16-in.) ID logging accessibility to the wellbore where the 4-1/2-in. tubing has a drift ID of 97.2-mm (3.826-in.).

(4). Preparations for the Long-Term Flow Test

New pump building: Concrete work for the new pump building was completed and the building erected early in FY1988. Master valves, flow meters, thermocouple wells, and instrumentation valves were installed in the pump house. This allows the makeup water tanks to be used for the water supply to the Kobe pumps for reservoir testing during FY1989.

Piping and instrumentation: Twenty-two concrete and steel pilasters for supporting injection piping were installed between the pump house and the high-pressure pump area on 3-m (10 ft) centers. The steel casing pilasters were cemented into solid tuff, 0.75-m (30-in.) deep, using rebar pins to furnish additional anchoring. The pilasters were then cut for height and roller-block assemblies were installed on top of the stands.

The 152-mm (6-in.) schedule 80 pipe that makes up the high-temperature injection piping was cut, beveled, and butt welded on top of the pipe rollers. The roller blocks allow for pipe contraction and expansion during LTFT operation and eliminate the need for a mechanical-type expansion joint. Following installation of the 6-in. Schedule 80 line on top of the steel pilasters, the system was tied together. Pond water will be gravity fed thru this line to the makeup water tanks for reservoir testing.

Instrumentation conduit was installed between the makeup-water frac tanks and the pump building. Flow meters, including the 102-mm (4-in.) makeup flow meter, miscellaneous flanges, and valving were installed in the control building.

Trenching for a steel tunnel between the pump house and first pilaster was completed and the tunnel installed. The tunnel allows safe access throughout the site by vehicles. A 102-mm (4-in.) Schedule 80 line was installed in the tunnel with pipe rollers placed every 18 m (6 ft) under the line, again to allow for thermal expansion and contraction.

Preliminary data entry was begun for implementation of piping-stress-analysis software. A piping analysis workshop was held Dec. 3 and 4.

Other pumps and systems: The Myers make-up pumps were assembled, aligned, and positioned in the new pump building. A new suction manifold and saddles were fabricated. All major pump-building hardware and piping were spotted prior to anchoring.

A new control-interlock system was installed in the Kobe trailer and tested with the $0.002 \text{ m}^3/\text{s}$ (34 gpm) Kobe pump. The new system maximizes versatility and allows automatic operation of the equipment in the selected ranges. Modifications to the controls for the small 0.0006 m^3 (9 gpm) Kobe were also completed.

The $0.025 \text{ m}^3/\text{s}$ (400 gpm) backup pump for the $18,900\text{-m}^3$ (5-million-gallon) pond was installed. The pump can be operated locally but remote control needs to be added. Repair on the cover of the pond was completed.

Valves: A purchase request was written for the refurbishing of five Leslie control valves and a sole-source justification memo was generated to accompany the purchase request. It is estimated that it will cost about \$25,000 to refurbish the valves, but work was deferred because of funding reductions. A data base listing all of the major valves in the LTFT surface system was started.

Pre-LTFT reservoir testing: One of the critical issues to be addressed before initiation of the LTFT is the amount of water required to conduct the test. This water requirement stems from water lost to the rock surrounding the fractured reservoir. As the surrounding rock becomes more nearly saturated as the experiment progresses, the water loss will decline and then approach a long term, nearly steady-state value. Because of the present lack of long-term testing of the reservoir, estimates of the steady-state loss are uncertain, ranging from 5% to 25% of the recirculated flow. Hence there exists a factor of five uncertainty in the amount of local water rights that will need to be retired.

To resolve this uncertainty, Expt. 2077 was planned as shown in Fig. 4. It calls for a stepwise pressurization of the reservoir through EE-3A, with EE-2A shut-in. The Phase II reservoir will be operated at various pressure levels in order to (1) determine water loss as a function of pressure and time, and (2) to measure pressure-dependent water storage within the reservoir region. This is not planned as a flow-through experiment, i.e., the production well will be shut-in. Injection pumping should be accomplished at low flow

Not
a FY88
activity

Figure 4. Reservoir Testing Prior to Long Term Flow Test.

Reservoir Stimulation & Flow Testing Procedure

- High Backpressure Flow Test
- Stimulation of EE-2A (Viscous Frac)
- Repeat HBP Flow Test
Shut In
- Intermediate BP Flow Test
Shut In
- Intermediate BP Flow Test
Shut In
- Steady State Flow Test

rate, minimizing costs, and hopefully avoiding the necessity for round-the-clock staffing. Pressurization of the reservoir would continue through summer 1989 with a shutdown from late December through early January. Then in the mid- to late-summer time frame, the reservoir would be flow tested in a high-back-pressure mode in preparation for an EE-2A stimulation test (viscous fracture) in September or October 1989 (depending on availability of funds). The effectiveness of the EE-2A stimulation would be evaluated by repeating the high back-pressure flow test and Experiment 2074 (seven days of superpump injection at 0.006 m³/sec and 24 MPa [96 gpm and 3500 psi]).

LTFT experimental plan: Following suggestions made at the September 1987 Program Development Council Meeting, the test plan for the LTFT was revised. This revised plan now includes an initial high back-pressure experiment, a long constant-pressure flow test, and a final cyclic injection-venting (huff-puff) test. The flow-rate profile is shown in Fig. 5. Note that the High-Back-Pressure (HBP) segment is completed early in the test, rather than in the middle as formerly planned. SUE stands for stress unlocking experiments. These are short durations of high-pressure pumping designed to relieve frictionally locked-in thermal stresses in the reservoir.

Planning and preparations for the LTFT are aimed at meeting the Level II (Table 1, 1) and Level III objectives (Table 2) of evaluating the Phase II reservoir at Fenton Hill.

*above
material
belongs
with
planned
activities*

(5). Phase II System Flow Tests

Experiments conducted at Fenton Hill this past year have provided an important basis for future evaluation of the reservoir and will help in meeting several Level III objectives (Table 2 - 3, 5, 6, 7, and 9).

(a). Experiment 2074

Experiment 2074 was conducted December 2 - 9, 1987 to assess reservoir characteristics following redrilling of EE-2A. At the end of the 7-day flow test, the reservoir water loss was down to 0.0014 m³/s (22-1/2 gpm) and still declining at a rate of about 0.0001 m³/s (2 gpm/day). From other results -- aseismic reservoir operation, tracer studies, and the elimination of the casing-bypass path to the upper Phase I reservoir -- one can conclude

Figure 5. Flow Rate Profile for Long Term Flow Test.

that most of the water loss during Exp. 2074 was actually in the form of water storage within the Phase II reservoir region rather than due to fracture extension. In contrast to this 22-1/2 gpm water loss after 7 days, the water loss at the end of the 30-day Initial Closed-Loop Flow Test (ICFT), conducted in May and June 1986, was 0.005 m^3 (79 gpm) -- 3-1/2-times greater. However, most of the water loss near the end of the ICFT was attributed to continuing reservoir extension.

Near the end of Exp. 2074, the reservoir flow impedance was $5.7 \text{ GPa} \cdot \text{s/m}^3$ (52 psi/gpm) at an injection-pressure level of 24 MPa (3475 psi). Based on the ICFT results, one could probably have increased the EE-3A injection pressure to about 29 MPa (4200 psi) without measurable reservoir extension, significantly reducing the observed flow impedance during this test.

The measured instantaneous shut-in pressure (ISIP) values during Exp. 2074 generally ranged from 20 MPa (2900 psi) early in the test to 22.8 MPa (3300 psi) late in the test, intermediate between those measured during Exp. 2070 and the ICFT. This strongly suggests that these ISIP measurements do not reflect the true minimum earth stress in the Phase II reservoir, but instead indicate the closure stresses on the most favorably oriented, and continuous, joints intersecting the EE-2A wellbore. Further, this closure stress level varies temporally, depending on both the degree of reservoir inflation and near-wellbore cooling, as well as on the injection flow rate and the possible redistribution of stresses within the reservoir region.

Flowing temperature logs indicated four major fracture intersections with the redrilled EE-2A: 3307 m, 3508 m, 3606 m, and 3652 m (10,850 ft, 11,510 ft, 11,830 ft, and 11,980 ft). In addition, numerous other small flowing fractures were also observed between these major fracture connections. Figure 6 shows a typical producing-temperature and gamma-ray (tracer) log run during the experiment.

The annulus above the cemented-in liner in EE-3A appears to be connected to the high-pressure reservoir through a high-impedance fracture (about $66 \text{ GPa} \cdot \text{s/m}^3$ [600 psi/gpm]) which is activated at reservoir pressures above 21 MPa (3000 psi). That the annulus flow observed at EE-3A stems from a fracture system that connects the high-pressure reservoir to the annulus above the cemented-in liner is supported by three observations:

Figure 6. Producing-Temperature and Gamma-Ray (Tracer) Log Run in the Open Hole
Below the Production Casing on 12/6/87.

- (i) The presence of significant amounts of both CO_2 and H_2S in the outflow;
- (ii) The rapid dropoff in this annulus flow with only a few hundred psi drop in the reservoir shut-in pressure;
- (iii) The S-shaped nature of flow buildup curve with time, i.e., the flow began after 4 days, then increased rapidly for the next two days, and finally leveled off for the last two days.

A post-experiment temperature survey also supports the case for a "behind-the-liner" leak. This bypass flow enters the annular region at 3309 m (10,855 ft), 26 m (85 ft) above the top of the liner cement. There is no evidence of polished-bore-receptacle (PBR) seal leakage or direct flow-bypass around the liner through the cement.

Two tracer experiments were conducted using radioactive ^{82}Br : the first injection into EE-3A used a small 10-mCi (millicurie) source and the second a larger, 100-mCi source. The 10-mCi pulse was detected at low levels at the surface of EE-2A but not with a downhole gamma-logging tool. The 100-mCi pulse was measured both at the surface and downhole with the gamma-logging tool. The modal volume was determined to be 246 m^3 , compared to 270 m^3 and 350 m^3 determined for the ICFT, which leads to the conclusion that the reservoir was not fully inflated for this experiment. The gamma logging showed a major entrance of tracer at the lowest temperature anomaly, at about 3660 m (12,000 ft.) in EE-2A, with lower tracer concentrations entering the wellbore coincident with temperature anomalies higher up in the wellbore (Fig. 6). The flow appears to be quite evenly distributed without any major short circuits. Only 28% of the tracer was recovered, suggesting the existence of many long-residence-time flow paths.

An organic tracer, p-toluenesulfonic acid, was injected one hour after the 100-mCi radioactive tracer. The goal was to determine, with this theoretically inert tracer, whether organic tracers can be measured accurately in the Fenton Hill reservoir. The tracer was slightly attenuated compared to the non-sorbing ^{82}Br , but the peak concentration of organic tracer arrived at EE-2A after the same amount of time, suggesting a chemical reaction rather than adsorption. The concentration was measured accurately in the range of 100 to 500 ppb, which is higher than our ultimate goal of detecting tracer concentrations as low as 1 to 10 ppb, but encouraging because previous measurements could only be done at concentrations of at least 1 ppm.

During the experiment four seismic stations, PC-1, PC-2, GT-1, and EE-1, were monitored with the smaller MASSCOMP data-acquisition system. In addition, wellhead pressures at EE-2A and EE-3A were digitized and stored at intervals of approximately 8 seconds. This is the first experiment in which a new version of the data-acquisition software was used that could record data from continuous channels in addition to the event-detect mode that is used for seismic data. Also, this was the first time in which the small, single A/D MASSCOMP was used at Fenton Hill. The advantages of this system are that its small size makes it easy to transport and thus we do not tie up our large system in an experiment, leaving the large machine available for data analysis. The major disadvantages of this is that the small machine has only one A/D converter and its disk is very slow

Very few seismic shear-events were detected during Experiment 2074, but we did detect some long-period earthquakes, which we believe represent tensile opening of fractures. These earthquakes were particularly interesting since they were well recorded at station GT-1.

(b). Experiment 2076

Experiment 2076 was conducted on June 15, 1988. The main objective of this brief 6-hour experiment was to perform a full-cooldown pressure test of the EE-2A cemented-in liner and tie-back string. Nearly 190 m^3 (50,000 gallons) of water were injected into EE-2A at injection rates ranging from 0.0026 to $0.0405 \text{ m}^3/\text{s}$ (1 to 15.3 bpm) with corresponding wellhead pressures ranging from 10 to 30 MPa (1500 to 4300 psi).

Conclusions from this injection test were:

- (i) The liner and tie-back string appear to be pressure tight to at least 30 MPa (4300 psi).
- (ii) The same set of fractures identified during the post-drilling evaluation (Experiment 2074) are still present and active.
- (iii) At comparable pressure levels and approximately the same reservoir-intersection lengths, almost twice as much fluid can be injected into the reservoir from the EE-2A side as from the EE-3A side. This would suggest that the residual pressure-induced fracture self-propping accompanying the MHF test (Experiment

2032) extends outwards from the old EE-2 wellbore to the region traversed by EE-2A.

- (iv) Given an injection rate of $0.106 \text{ m}^3/\text{s}$ (40 bpm), the EE-2A wellhead pressure would be only about 32 MPa (4600 psi) (neglecting pipe friction) -- not sufficient for much pressure stimulation in comparison to the 41 MPa (6000 psi) that occurred at $0.106 \text{ m}^3/\text{s}$ (40 bpm) during the MHF test.

During the experiment, seismicity was monitored for approximately 6 hours using four downhole stations; PC-1, PC-2, GT-1, and EE-1. Waveforms that were recorded on analog tapes during the experiment were digitized. Two events were recorded across the network (all four stations) but the signal-to-noise ratios of these events were too small to allow locations to be determined. A few long-period events were detected during the early part of the experiment.

b. Phase II Ancillary Activities

- Diagnostic Logging

(1). Televue Measurement of In Situ Stress

The digital televue was successfully run in EE-2A on May 18, 1988. Logging was conducted downward at 0.25 m/s (50 ft/min) over a short segment of the casing to 3690 m (12,100 ft) in the open hole. A detailed survey was conducted from 3535 m (11,600 ft) upward to about 3090 m (10,150 ft). For measurements of in-situ stress, the televue has provided an improvement, at Fenton Hill, over previous methods, of two orders of magnitude in number of separate observations, and one order of magnitude in resolution. Fenton Hill currently holds the depth record (3.5 km) for a televue determination of in-situ stress, compared to the previous 1.5 km at the Auburn, N.Y. geothermal well. The direction of minimum horizontal principal stress is now estimated, at a depth of 3444 m (11,300 ft), to be 110.7 ± 10.3 degrees E of N, and appears to be rotating at a rate of one degree with every 15 m (50 ft) increase in depth.

Use of the televue and analysis of the data provided improves determination of fracture propagation in the HDR reservoir and locates fracture intersections with the wellbore accurately, meeting Level III objectives (Table 2, 1 and 7).

- Environmental Monitoring (missing!)

c. Test-Site Support and Utilities

(1). Site Electrical Power

Jemez electric responded to our letter requesting increased electrical service at Fenton Hill by requesting that Los Alamos work with their electrical consultant and perform a load study using LANL's network model. The load study using LANL's network model was completed as were recommendations for the substation and switch gear.

(2). Diesel vs Electric Power Study

A study was started comparing the cost of operating the main circulating pumps with diesel engines as opposed to electric motors. Preliminary results favor the diesel when capital costs and fuel costs are considered. An informal report documenting the results will be issued in November 1988.

(3). Water Rights

The leasing of water rights to offset usage of water at Fenton Hill is required by the New Mexico State Engineer's Office as a condition for further use of water at Fenton Hill. Several problems associated with obtaining water rights and methods for dealing with the problems developed. An initial list of owners of water rights in the Rio Guadalupe drainage was obtained and negotiations were initiated. To identify other owners, advertisements were placed in local media (from San Ysidro to La Cueva) for water rights. DOE-LA, who will do the actual leasing of water rights for Fenton Hill, prepared a package for solicitation of bids that was provided to water-rights owners.

(4). Site Maintenance

A water-filter system for the EE-1 pond was constructed for Fenton Hill and filter media were purchased. Testing was begun during March. Each backwashing of the filtering media, sand and activated charcoal, resulted in better performance. While the quality of the filtered water was adequate for disposal it did not reach the ultimate objective of being clean enough for reuse in reservoir testing.

The EE-1 pond was then flocculated with lime and $\text{Al}_2(\text{SO}_4)_3$ to precipitate the dissolved silica which limited filtering performance. However, the flocculation of the pond was adversely affected by cold temperatures, and water continued to be treated at a rate of about $0.0025 \text{ m}^3/\text{s}$ (40 gpm), with the concentration of suspended solids in the range 10 to 30 ppm. About 760 m^3 (200,000 gallons) of water from the pond were treated, providing enough space in the EE-1 pond to allow venting of the Phase II reservoir for EE-2A completion operations.

An uninterruptable power supply (UPS) system was installed on the intercom amplifiers to allow for its limited useage during a power failure. A combined totalizer and flow meter (Parshall flume) was installed at the weir located below the GT-2 pond-fill area to measure water discharged from the EE-1 pond down the canyon, in compliance with EPA NPDES permit requirements.

In preparation for the proposed stepwise pressurization of the reservoir, Expt. 2077, new piston-seal kits and pistons were installed in the Kobe pumps. All the transducers were installed and balanced for the initiation of the experiment.

Two tower sections were installed on the concrete pad to protect the EE-3A wellhead during the winter months. Heaters were installed for additional protection. High-pressure plumbing and appropriate instrumentation were installed on the frontside for the pending pumping experiments.

Two tower sections were also installed on the concrete pad to protect the EE-2A wellhead during the winter months. Communication between the vent piping for each annulus was verified.

2. Scientific and Engineering Support

a. Tools and Instrumentation

A major milestone was met with the successful operation of the high temperature borehole acoustic televiewer (BAT) in EE-2A. Several modifications to the instrument design

resulted in significant improvements in downhole performance. The critical pressure balance piston and cylinder that maintained a very small differential pressure across the TFE teflon acoustic window was originally located on the forward downhole end of the sonde and was mechanically supported by the motor drive shaft used to rotate the piezoelectric transducer assembly. This configuration was susceptible to lateral stress loading which occasionally caused a binding of the motor shaft. The pressure balance system has been moved to the present location above the AC drive motor thus eliminating any lateral stresses on the drive shaft (Fig. 7).

Several upgrades were also incorporated in the downhole microprocessor electronics and associated power supply that greatly enhanced the reliability of the data processor.

As mentioned in section II 1 b, the BAT was successfully run in EE-2A on May 18, 1988. The primary purpose of the BAT survey was to obtain information concerning the geological structure of the EE-2A wellbore, and to test the BAT tool in the harsh geothermal environment. Major concerns included the sensitivity and resolution at different logging rates, transmission of high speed digital data over the 6 km of 7 conductor, armored wireline, performance of the pressure balance system, and allowable lifetime in the high temperature environment.

The results of the tests exceeded expectations. The output data had sufficient sensitivity and resolution to detect fractures and breakouts at a logging rate of 0.25m/s (50 ft/minute). Logging with this system at slower rates with improved resolution could revolutionize the ability to interpret geological structure in very deep boreholes. Internal dewar temperature was only 60°C after subjecting the instrument to the borehole fluid temperature approaching 270°C for the 6 hour test. The test results showed significant improvements in system sensitivity, resolution, and signal-to-noise over analog methods even when the logging rates were increased by a factor of five.

Additional improvements are now needed in the surface data acquisition and retrieval areas to provide for on-line, user-friendly host computers such as the IBM-PC-AT. How to handle the large data base and analyze this data in a reasonable time frame is the next milestone.

Figure 7a. Borehole Acoustic Televviewer: Lower Assembly.

Figure 7b. Borehole Acoustic Televiewer: Upper Assembly.

The successful operation of the BAT in EE-2A aroused much interest in the industrial community and news media. Press releases appeared in the Albuquerque Journal, University of California News Service, Federal Computer Week, etc. Several articles on the BAT are scheduled to appear in the American Institute of Physics, Popular Mechanics, and Machine Design. Recognition of the achievement was also included in the Regents of the University of California Report to the President of the University, 1988.

Use of the televiewer and analysis of the data provided improves determination of fracture propagation in the HDR reservoir and locates fracture intersections with the wellbore accurately, meeting Level III objectives (Table 2, 1 and 7).

b. Reservoir Engineering

(1). Seismic Studies

Reanalysis of the microseismic events from the 1983 Massive Hydraulic-Fracture (MHF) experiment (Expt. 2032) was initiated in January 1987. The reanalysis was prompted by the improvements made during the last four years in data acquisition and our desire to obtain a more complete data set for detailed reservoir-seismicity studies. In addition, we desire a better understanding of the seismicity of the 2032 HDR reservoir. Data were digitized into the MASSCOMP system from analog tapes. Through the end of FY1988, we located approximately 6500 events from the beginning of the experiment. This compares with 850 events mapped for the entire 80 hours of the experiment using data collected by the old, Biomation-based data-acquisition scheme. The new analysis technique has so far yielded seven times the number of good-quality events determined during the original analysis of the entire experiment. To illustrate this improvement, Fig. 8 shows 3500 good-quality events located after reanalysis of the first 20 hours of the experiment compared to Fig. 9 which shows the original locations over the same time interval and Fig. 10 which shows the original locations for the entire experiment. We anticipate obtaining between 10,000 and 15,000 locations by the time this effort is completed.

Work on developing a computerized method for determining the arrival of seismic compressional ("P") and shear ("S") waves was very successful. The automatic arrival-time pickers are referred to as the P-picker and S-picker. In the past, automating the

Figure 8. Relocations of Experiment 2032 Seismic Events for the First Twenty Hours.

Figure 9. Original Locations of Experiment 2032 Seismic Events for the First Twenty Hours.

Figure 10. Original Experiment 2032 Locations for Entire Experiment.

picking and location procedure was not attempted because of the difficulty of picking shear-waves out of the noisy P-coda. The P-picker implemented by NEWT, Inc., for picking P waves on our seismic data has been tested as an S-picker. The picker is based on work of Carl Johnson (formerly with Cal Tech, now with the USGS) and Rex Allen (USGS) and operates by searching for a change in amplitude and frequency content of the signal. The automatic picker can thus be made sensitive to changes in both amplitude and frequency. Since the S-wave arrival often contains high frequencies relative to the P-coda and since the picker can be tuned to maximize its sensitivity to changes in frequency, the picker can be used to successfully obtain shear-wave picks. Continued work on the arrival-time picker has shown that it picks an arrival time correctly with about an 80% probability. The manual picking program was modified to allow the analyst to use the automatic picks and modify only those picks that appear incorrect. This allows a significant increase in the rate at which events can be analyzed. A production test of the automatic arrival-time picker was conducted at the end of FY1988 and the results will be evaluated early in FY1989.

Application of the three-point method to the new location data set was reviewed. Some uncertainty was felt in the application of the three-point method to the new 2032 data set since the location density is much larger than the old data set. Kathy Campbell, a statistician from LANL group A-1, made several suggestions to improve the three-point method, in particular on how to decrease the amount of CPU time required to apply the method to large data sets. In addition, she provided a statistical test to determine if it is justified to consider that two parallel planes exist in a data set.

Efforts continue to obtain an improved estimate of the seismic factor "Q" which is inversely related to attenuation of the seismic waves through the reservoir. This value is important because Q is used in calculating the physical parameters of hydraulically-induced microearthquakes: namely, stress drop, moment, and slippage area and extent. The approach now used is to perform a joint generalized inversion of a large set of microearthquake spectra to determine individual values of the spectra low-frequency amplitude and corner frequency for each event, and a lumped Q, simultaneously. Preliminary indications are that stress drops calculated using this new method will be lower than previous estimates.

A total of 180 events were found to have enough first motions and to be well enough located to obtain most reliable individual-event fault-plane solutions. These are some of the larger events that were induced during the MHF. The fault-plane solutions are summarized in the lower-hemisphere, equal-area plot of Fig. 11.

Figure 11 shows P and T axes for all reliable (best) fault-plane solutions obtained. Note, first of all, the broad scatter of orientations of both the P and the T axes. The P axes generally plunge very shallowly, less than about 20° , but have bearings that scatter over more than 180° , ranging from NW clockwise through SSW. The wide azimuthal scattering of the P axes is, in part, the result of the projection used. Because the P axes are nearly horizontal, slight differences in plunge can result in large differences in the azimuth at which the P axes plot. There is a fairly prominent cluster of P axes with a bearing of about 150° and a plunge of 10 to 20° . Interestingly, Barton, et al. (1988)¹¹ find a least principal horizontal-stress orientation of 119° from televiewer data taken at Fenton Hill. Clearly, the fault-plane solution data and the televiewer data are discrepant. Although the T axes are fairly scattered in orientation, there is a cluster with a bearing of about 260 to 270° and a plunge of about 50 to 70° . Interpreting the T axis information in a simplistic way, the minimum principal-stress direction appears to plunge steeply to the SW.

The latest version of the MASSCOMP RTU operating system and all associated software were installed on the big data-acquisition MASSCOMP and on the data-analysis machine. These installations were necessary for the new version of the seismic-data acquisition software, "RAVEN" version 5.(89). Version 5.8 is a simple a/d version that runs on the small MASSCOMP. Version 5.9 is the full-blown three a/d version that runs on the big MASSCOMP. In addition, the new RAVEN has the ability to synchronize the MASSCOMP system clock with an externally supplied standard broadcast (IRIG) clock so that event times will be correctly written by the system.

Ongoing studies of the seismology at Fenton Hill provide assurance that the technology is environmentally acceptable, meeting a Level II (Table 1, 3) and Level III (Table 2, 9) objective. In addition these studies improve reservoir-mapping techniques, aid in monitoring changes in reservoir volume, and provide indications of fracture propagation and location meeting Level III objectives (Table 2 - 1, 2, 5, and 7).

Figure 11. Lower Hemisphere Equal Area Plot of Fault Plane Solutions.

P, T Axes of best solutions

(2). Geochemistry

Chemistry support during the redrilling of EE-2A consisted of collecting and interpreting fluid samples during the drilling campaign. During the redrilling, EE-3A was kept at an elevated pressure so that when the new wellbore penetrated a fracture, its fluid would enter the wellbore. The chemistry of the drilling-fluid samples from 3260 to 3350 m (10,700 to 11,000 ft) was modeled to determine the depths and flow rates of the fracture intersections with the newly drilled wellbore. The concentrations of B, Cl, and Br, three inert chemical species, increased during this time due to inflow from the reservoir. The concentration of this produced fluid was measured from a downhole fluid sample collected at 3260 m (10,700 ft). Flow rates into the wellbore at discrete depths were adjusted to obtain a good fit between the data (concentration versus depth) and the model. The results showed an influx of small quantities of fluid above 3290 m (10,800 ft), flows of intermediate rates at depths around 3290 m and 3305 m (10,800 ft and 10,840 ft), and a major inflow accounting for roughly half the total flow at 3335 m (10,940 ft). This technique provided the first estimates of the depths and relative flow rates of the fracture connections to the new wellbore.

Tracer data were collected both downhole and at the surface during Experiment 2074, the first flow test performed after the redrilling campaign. Radioactive ^{82}Br measurements at the surface showed that the reservoir size was similar to that measured before the redrilling, with somewhat smaller fracture volumes attributable to the fact that the reservoir was not fully inflated during the test. Downhole measurements using gamma logs indicated that fluid is entering at many different depths, with no main flow path dominating the flow field. This conclusion suggests that short-circuiting should not be a problem in the Phase II reservoir.

An organic tracer, p-toluenesulphonic acid, was injected simultaneously with ^{82}Br to test the feasibility of using organic tracers in the Phase II reservoir. This tracer was previously tested in the laboratory and found to be conservative (non-adsorbing). Although some analytical-chemistry difficulties were encountered, the tracer appeared to match the ^{82}Br tracer curve fairly closely (Fig. 12), implying that organic tracers can be used in this reservoir. Thus the proposed chemically reactive tracers, organic compounds similar to p-

Figure 12. Comparison of the Normalized Tracer RTDs Calculated From the Second ^{82}Br and p-toluenesulfonic Acid Tracer Tests.

toluenesulphonic acid, should also prove to be compatible with the Fenton Hill fluid and rock.

Analytical-chemistry development work was initiated this year to improve the measurement sensitivity of the organic tracers, using High-Pressure Liquid Chromatography (HPLC). Techniques must be developed to measure tracer concentrations accurately to 1 ppb or less. One factor making this goal difficult to achieve is the presence of dissolved organics in the reservoir fluid from past drilling operations. This year the effort has focused on 1-bromo-4-nitrobenzene, the first choice for a reactive tracer in the Phase II reservoir. Currently, we have achieved an analytical sensitivity of 5 ppb. Further improvements will be made through experimentation with different chromatographic columns and resins, or through different detection techniques.

Ongoing studies of the geochemistry at Fenton Hill provide assurance that the technology is environmentally acceptable meeting a Level II (Table 1, 3) and Level III (Table 2, 9) objective. In addition these studies provide the technology for monitoring changes in the reservoir, allow detailed reservoir analyses and modeling of hydraulic and thermal performance, aid in determining fracture locations, and provide information on water-rock interactions and their effects on flow through the reservoir, meeting Level III objectives (Table 2 - 3, 4, 5, 6, and 7).

(3). Reservoir Modeling

A reasonable match to the pressure-drop, water-loss, and tracer behavior of the Phase II reservoir during the ICFT was achieved with a 3-dimensional finite-element model of the reservoir. Based on these model results, predictions of the system behavior during the long-term flow test were carried out. The results showed that due to the longer openhole section in the production wellbore, the reservoir should be somewhat larger and the flow impedance should improve significantly.

Heat-transfer and fracture-network models were also developed for the Phase I and Phase II reservoirs. In the heat-transfer studies, the Phase I reservoir results were used as a calibration of the model before making predictions for Phase II. Two distinct sets of the adjustable parameters were found which provided an adequate fit to the Phase I, Run

Segment 5, thermal data. The first model used a small fracture spacing of between 1-5 m, resulting in a very efficient heat sweep from the reservoir. The model predicted that the outlet temperature would have started to rise after about 300 days, the time at which the thermal depression from previous heat extraction experiments was swept from the reservoir. The true thermal drawdown from Run Segment 5 operations would then occur after about 900 days. A second match was also achieved with a different reservoir size and larger fracture spacing. These results are more pessimistic, implying that the cooldown observed in Run Segment 5 was true thermal drawdown and not an anomaly created by previous experiments. This nonunique result shows that a thermal-drawdown experiment needs to be performed in a reservoir with simple, known, initial conditions to be useful for model validation.

This heat transfer model was then used to predict the thermal-drawdown behavior of the Phase II reservoir. The model will predict a wide variety of results depending on the choice of the reservoir-rock volume. Using the rock volume estimated from the microseismic-event locations determined during the massive hydraulic-fracturing experiment which created the current reservoir, the model predicts a thermal drawdown of only a few degrees after one year of operation at the anticipated flow rate of the LTFT. However, if this estimate of rock volume proves to be optimistic and a smaller value is actually correct, rapid thermal drawdown of about 60°C could be observed in the first year.

The fracture-network model is a two-dimensional, steady state simulator of fluid flow and solute transport. The network is assumed to consist of two sets of equally spaced fractures, and intersections of the network by wellbores are modeled as point sources or sinks. Particle-tracking techniques are used to model the tracer behavior, which includes both conservative and sorbing tracers along with diffusion into the rock matrix. Tracer data from the Phase I reservoir is adequately simulated assuming a network with fracture spacings of 25 m (82 ft) and apertures of all fractures of 0.4 mm (0.016 in.). Smaller fracture spacings also result in good fits to the data, but it is unlikely that larger spacings are realistic since they produce tracer-response curves with multiple peaks not present in the field data. The simulations also identified areas in which future research is required to constrain this type of model. More experimental and theoretical work is required to understand the difference between the hydraulic aperture and the effective aperture for

solute transport. Also, reliable techniques for estimating the in-situ matrix porosity in fractured reservoirs is needed to quantify the effect of matrix diffusion on tracer transport.

Much progress has been made in meeting the Level III (Table 2, 6) objective of being able to complete a detailed reservoir analysis and model. Appropriate reservoir models will also aid in meeting the objective of determining whether the performance of the Fenton Hill reservoir, when considered as a unit reservoir in a commercial-scale project, could support production of electricity at an economical busbar cost (Table 2, 10).

(4). Sealing of Reservoir Fractures

A task effort was initiated to study the possibly deleterious effects of high pressure and high temperature on fracture transmissivity. Our concern is that, with a delayed start of the LTFT, reservoir impedance may increase due to the sealing of the fractures through physical/chemical effects.

Samples of granite (one smooth, the other with a saw-toothed surface) were pressed together, immersed in water from the Fenton Hill reservoir, and placed in an autoclave to simulate reservoir temperature and stress conditions. After exposure for various time intervals, the specimens will be removed from the autoclave in FY1989 and examined microscopically for signs of sealing, which could include mineral diffusion and transfer and rock-grain creep.

In addition to the fracture-healing experiments, EE-3A cuttings with distinctive white fracture coatings were mounted and carbon-coated for scanning-electron microscopy. To further investigate the possibility of fracture sealing, an effort will be made to identify the fracture-coating material and to determine whether it is of recent origin.

The initiation of this study of water-rock interactions will help to meet a Level III objective (Table 2, 4).

c. Technology Application

(1). Economic studies

In 1988, the Meridian Corporation projected the costs of HDR electricity for the years 1980, 1990, and 2000³. At the DOE's request, Los Alamos reviewed the projections and found them to be 30 to 60% higher than earlier estimates^{2,3,4,5,13,14}.

The primary cause of the difference in cost estimates stems from drilling costs. For the 1980 cost-projection scenario, Meridian assumed that each of the 37 new wells required for a 160 MW_e plant would be drilled with the same difficulty and high costs that were encountered during the drilling of GT-2 and EE-1 in the early 70's. However, these two wells were the first of their kind, and when one considers the unanticipated difficulties and the numerous experiments conducted during their drilling (i.e., drilling with air and clean water to prevent contaminating the core with mud, frequent stops to experiment, and testing of new bits and coring heads, etc.) one can readily understand why their costs were high. If another 37 wells were drilled into the same reservoir, there would be no need to continue these experiments, and with repetition and experience the day-to-day drilling would greatly improve. In fact this was observed. The 1985 redrilling of EE-3A and the 1987 redrilling of EE-2A, as well as the British HDR drilling, resulted in 60% cost savings compared to GT-2 and EE-1. We believe that these savings could have been achieved by repetitive drilling in 1980 as well as in 1990, hence we see little reason to differentiate costs for reservoirs created in either 1980 or 1990, and collapsed these to one case when recomputing the Meridian cost projections.

For the year 2000 we assumed that drilling cost would approach the "commercially mature" values provided by Armstead and Tester¹³ and determined that the well cost would be \$2.2 million.

When stated in 1986 dollars, our results indicate that the break-even cost of HDR electricity would be \$0.075 per kWh if the reservoir were created in 1980 or 1990, and \$0.052 if created in 2000. This compares with Meridian's values of \$0.10 and \$0.079 for 1990 and 2000. Interestingly, our revision of Meridian's analysis is in good agreement with previous more detailed HDR studies. Murphy et al.¹⁴ concluded that HDR could generate electricity for \$0.049 per kWh (also with 13% interest rate) and Cummings and Morris² reported a similar result. More recently, investigators at Bechtel National⁴, concluded that an HDR plant at Roosevelt Hot Springs, Utah, could generate electricity at

a break-even busbar cost of \$0.05 per kWh. A study of HDR electricity costs in the UK⁵ determined a cost of \$0.067 per kWh, based on a lower geothermal gradient, 35°C/km, compared with the present 60°C/km, and a reservoir depth of 6 km compared to the present 3 km.

In summary it appears very probable that the program will achieve its Level I objective of reducing HDR electricity costs to \$0.05 - \$0.08 per kWh.

III. MANAGEMENT

1. Organization

As shown in Fig. 13, 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 James Rannels, HDR Program Manager in the DOE Geothermal Technology Division (DOE/GTD). George Tennyson of the Albuquerque Operations Office is the DOE Field Manager. Chaired by Robert Greider, The Program Development Council provides advice and offers an industrial and academic perspective on major issues.

In September 1988, two program offices at Los Alamos were merged. Michael Berger, who formerly served as Director of Renewable Energy Programs as well as a Deputy Leader of the Mechanical and Electrical Engineering Division, now directs the combined Renewable Energy and Energy Technology Offices. He reports directly to John Whetten, Associate Laboratory Directory for Energy and Technology. Berger continues to act as Program Director for the HDR and Energy Security programs, and now will also serve in the same capacity for the Central America, Hazardous Waste Disposal, and Advanced Technology programs. The remainder of the HDR organization remained unaffected, with Hugh Murphy continuing as HDR Program Manager.

The LANL management function encompasses two categories of effort: (a) cognizant program management per se and (b) management support services.

Los Alamos program management is responsible for overseeing controlling, representing, and communicating on behalf of the Program in both the technical and the administrative sense. Among the specific responsibilities of management are:

- * day-to-day programmatic direction of the Program's functional personnel;
- * technical and fiscal program planning, including the Annual Operating Plan (AOP); technical plans for LTFT installation and major experiments; and budgetary accounting analyses;

Figure 13. Program management Structure.

HDR Program Organization Chart

- * informal daily telecons, quarterly and annual written reports, and semiannual presentations to DOE/GTD;
- * providing information or supporting requests from DOE/GTD;
- * supporting liaison with other HDR-related research programs.

Management support and services provide:

- * LANL upper-management attention to HDR Program matters as required;
- * procurement, personnel, clearance and badging, and legal services;
- * editorial and publication support; and
- * budgetary and accounting support.

2. Interfaces

Los Alamos responsibilities include:

- * in concert with DOE/ALO, providing required reports to local government agencies and locally cognizant offices of other federal agencies including the USGS, US Forest Service, EPA, BLM, New Mexico State Engineer, 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;
- * supporting liaison with, and fostering technology transfer to, interested industrial organizations;

- * providing information, and tours when appropriate, to ranking governmental, industrial and institutional visitors;
- * conducting reviews of the Program with the HDR Program Development Council;
- * coordination of the HDR Program with other LANL programs and representation of the Program to LANL upper management.

Significant events in FY88 included:

Richard Thomas, Geothermal Officer with California's Division of Oil and Gas, visited the Laboratory in November 1987 to discuss the potential for applying HDR technology to improve understanding of reservoir and well conditions in The Geysers geothermal field.

On January 20, 1988, Mike Berger and Hugh Murphy met with personnel of the Electric Power Research Institute. Berger and Murphy outlined HDR's funding difficulties, concerns about delaying the Long-Term-Flow Test, and hopes for non-DOE funding to maintain a timely start of the LTFT. Murphy later provided a list of needed equipment for the LTFT, with estimated costs, and described the benefits that could be expected as a consequence of participation in the LTFT.

On January 25-26, 1988, Derek Corlett, Deputy Directory of the British HDR Program, visited Los Alamos and presented a seminar which highlighted future plans for their program. Later discussions included reactive tracers, borehole acoustic televiewer, and reservoir engineering.

William Turner, a materials fabrication consultant to LANL, visited Nippon Steel's facilities in Japan in March 1988 to review quality assurance during manufacture of the 178-mm (7-in.) casing later inserted in well EE-2A. He approved the fabrication process and heat treatment, and then worked with Nippon engineers to set up the threading.

Donald Dreesen, Los Alamos staff member, traveled in March to the National Research Institute for Pollution and Resources (NRIPR), Tsukuba, Japan, where he met with Isao Matsunaga and Michio Kuriyagawa. Recent well-completion work at Fenton Hill was

discussed and a short talk on the repair and redrilling of EE-2A was presented. Well-completion plans for the Japanese HDR program's first liner in Well HDR-1 at Hijiori were reviewed and discussed.

While on personal vacation, Hugh Murphy also visited NRIPR on April 22-23, 1988, and reviewed testing results at the Hijiori HDR reservoir and explored means of reducing the high flow resistance.

On May 23rd and 24th, 1988, the program was visited by Haydn Scholes and David Nichol of the British HDR Program. Discussions were held concerning their effort to extend the FRIP fluid/rock interactions program to three dimensions and their new MEIKO parallel-processor computer system.

Bruce Robinson traveled to the British geothermal project in June where he held discussions with the geochemistry staff, and collaborated on the modeling of Rosemanowes HDR reservoir.

On June 13, 1988, Ralph Haenel and Hans Draxler of the Continental Deep Drilling Programme of the Federal Republic of Germany visited the program. They were interested in the use of HDR high-temperature logging tools in their work, and held discussions with Bert Dennis and Hugh Murphy.

James Rannels, DOE/GTD, George Tennyson and Nyles Lackey, of DOE/Albuquerque, visited Los Alamos on July 26, 1988, to review the draft Annual Operating Plan for FY89.

In August, Christopher Joyce, US editor of New Scientist, interviewed Hugh Murphy in Los Alamos regarding the HDR Program.

John Whetten, LANL Associate Director, and Hugh Murphy briefed Nobuo Matsunaga, Japan's Ambassador to the USA, on the status of HDR programs in both countries. Ambassador Matsunaga toured Los Alamos and met with Governor Garrey Carruthers and New Mexico business leaders on his two-day trip to New Mexico, which was aimed at increasing business relationships between the two countries.

Hugh Murphy, Mike Berger, and Paul Kruger of Stanford University met with representatives of Chevron Resources, San Ramon, CA. The major purpose of the meeting was to enlist Chevron's assistance in obtaining high-pressure injection pumps for the LTFT. While such pumps were not being used by Chevron, they agreed to canvass their operating units and contact their suppliers to determine if a pump meeting HDR needs could be made available. In November 1988 Chevron identified some of its used pumps that they might offer for sale, and this option is being explored.

Derek Elsworth, Penn State, Department of Mineral Engineering, met with HDR staff on September 19-20, 1988 for technical discussions on reservoir modeling.

Hugh Murphy traveled to Cornwall, UK, to the site of the British HDR program, September 26-30, 1988. That program continues to flourish. A new 3-year phase had just started in which the 75-person staff will plan for a 6-km (20,000-ft) deep reservoir, with a final discussion as to how, and whether, to proceed expected from the UK DOE by January 1990. In the meantime, the French and West German joint HDR project at Soultz is also thriving, and possibilities of a collaborative British-French-German project are being discussed.

3. Meetings/Reviews

A meeting was held at Los Alamos on October 6, 1987 to coordinate safety oversight roles at Fenton Hill during redrilling. A coordination committee was comprised of personnel from the main HDR operating group, ESS-4, LANL health and safety groups HSE-3 and HSE-5, and the Big Chief Drilling Co.

Hugh Murphy, Bob Hendron and Mark Malzahn (LANL consultant) attended the Geothermal Resources Council meeting in Sparks, Nevada, October 11-14, 1987. Malzahn presented a paper on Tracer Based Heat Transfer Modeling, as well as Identification of MHF Fracture Planes and Flow Paths. Hendron presented a paper on Hydraulic and Thermal Performance of the Phase 2 Reservoir During the Initial Closed-Loop Flow Test and the Redrilling of Well EE-3.

At a meeting in Albuquerque on December 18, 1987, Los Alamos staffers met with James Morris of Jemez Electric and Jim Bardwell of Witter & Associates concerning Fenton Hill electric power requirements for the LTFT. They discussed load studies and conducted independent studies with the Witter & Associates' computer program. We were able to reconcile and match calculations. A letter then was drafted by James Morris to Los Alamos stating that Jemez Electric could partially meet our request for additional service at Fenton Hill. If the existing site load does not exceed 325 kW, then four, not five, 300-hp motors can be added to the system if the starting kVA is limited to 150% of running kVA, and the starting power-factor is greater than 0.5, and if line-voltage regulators are added to the power lines (at a cost of \$90,000).

Hugh Murphy, Michael Fehler, and Leigh House attended the December 1987 meeting of the American Geophysical Union in San Francisco, CA. Murphy cochaired a session on Potential Use of the Fenton Hill Geothermal Site as an Earth Science Facility. Fehler presented a paper on his "Three-Point" Method for determining discrete fracture planes in the midst of seismic locations, and House described his work, Seismic Fault-Plane Solutions.

James Miller, Ronald Aguilar, Raymond Jernance and Stephen Birdsell (LANL consultant) participated in the Geothermal Resources Council Geothermal Energy Symposium, January 10-14, 1988, in New Orleans. Birdsell presented a paper by Paul Franke on the "Current Status of HDR" and also presented "Prediction of Thermal Front Breakthrough Due to Fluid ReInjection in Geothermal Reservoirs." Aguilar presented his work on "High Temperature Drilling Fluid Field Experience and Analysis," and Miller presented "Developing HDR Reservoirs with Inflatable Open Hole Packers." Jernance presented "Applications of a Downhole Programmable Microprocessor for a Geothermal Borehole Inspection Tool."

On January 11, 1988, Robert Hendron, Hugh Murphy and Michael Berger met with DOE/GTD personnel in Washington, DC, to provide technical briefings and discuss options for future funding. Also discussed were Los Alamos recommendations regarding DOE's response to Congress's request for DOE's long-term HDR plans (see ISSUES section for further details).

On January 19-21, 1988, Hugh Murphy, Bruce Robinson, Michael Berger, and Mark Malzahn participated in the Stanford University Geothermal Reservoir Engineering Workshop. Robinson presented papers on 3D Transport Modeling and Fracture Network Modeling, and in collaboration with Paul Kruger of Stanford, A Comparison of Two Heat Transfer Models for Thermal Drawdown. Malzahn and Murphy presented their paper, "Wellbore Interference in Fractured Media", and Malzahn presented, "Locating Hydraulically Active Fracture Planes".

John Whetten, Associate Laboratory Director, presented Advanced Geothermal Technologies at the Energy Technology Conference and Exhibit, Washington, DC, February 17-19, 1988.

James Rannels, DOE/GTD, visited Los Alamos on March 15, 1988, to review HDR technical progress. Discussions covered general topics as well as EE-2A casing, geochemistry and tracers, reservoir modeling, fracture healing, water rights, expandable liners, reservoir engineering and earth-stress measurements.

The Interwell Seismic Surveying Workshop was held at Los Alamos on March 24-25, 1988. The workshop was sponsored jointly by Los Alamos and the Society of Exploration Geophysicists. While not financially supported by the HDR Program, much of the Los Alamos technology discussed stemmed from early HDR research.

Two papers, "Drilling and Completion at Fenton Hill" by R. H. Hendron, et al., and "Hot Dry Rock Fracture Propagation and Reservoir Characterization" by Hugh Murphy, et al., were prepared and presented at the DOE Geothermal Review on April 18-21, 1988, in San Francisco, CA. The Laboratory's HDR Program Office was represented by Hugh Murphy and Michael Berger.

The National Hot Dry Rock Program Development Council (PDC) met on June 8, 1988, in Santa Fe, NM, at La Posada de Santa Fe. Drs. Carlos Garcia and Alan Jelacic and Mr. James Rannels represented the Department of Energy at the meeting. The PDC members present were: Stanley Bazant, Plains Electric Generation and Transmission Cooperative; Robert Greider (Chairman), Geothermal Resources International; Michio Kuriyagawa, Japanese National Research Institute for Pollution and Resources; Robert Lacy, San Diego

Gas and Electric; Parker Mathusa, New York State Energy Research and Development Agency; Martin Robbins, Colorado School of Mines; Vasel Roberts, Electric Power Research Institute; Randall M. Ward, California Department of Conservation; Daniel Yueh, Stone & Webster; Duayne Johnson, Consultant; and Paul Kruger, Stanford University. The PDC reviewed the status of the Program, including technical accomplishments and programmatic status and budget. The PDC also offered its advice concerning HDR goals, the Long-Term Flow Test (LTFT), and funding options to achieve goals. The major recommendation of the PDC was that the LTFT should be started as soon as possible. Several members expressed interest in helping Los Alamos acquire the expensive, high-pressure injection pumps, so following the meeting the specifications for the pumps were mailed to PDC members.

Don Brown presented "Anomalous Earth Stress Measurements During a Six-Year Sequence of Pumping Tests at Fenton Hill, New Mexico," at the 2nd International Workshop on Hydraulic Fracturing Stress Measurement on June 16, 1988. This paper reviewed pressurization and flow-testing of the Phase II reservoir during the past six years.

A meeting was held in June with personnel from the DOE's Los Alamos Area Office in connection with the leasing of water rights. The bid package was completed and the DOE was provided a list of people who own water rights in the Rio Guadalupe drainage area.

The semiannual HDR Program Review for the Department of Energy was held on July 14, 1988, in Washington, DC. Don Brown, Bob Hendron, Leigh House, Hugh Murphy, and Bruce Robinson made presentations covering EE-2A completion, logging and televiwer results, seismic fault-plane analyses, thermal-drawdown modeling, and LTFT planning including pre-LTFT reservoir testing.

4. Issues

a. Funding

In December 1987, the Subcommittee on Energy and Water Development of the US Senate Committee on Appropriations requested the DOE's advice and information regarding the long term plans for HDR development. Donna R. Fitzpatrick, Assistant DOE Secretary for

Conservation and Renewable Energy, responded on June 24, 1988, with a four-year plan that recommended constant funding of \$3.6 million per year for fiscal years 89 through 92. The DOE recommended that the program prepare for the long-awaited Long-Term Flow Test in FY89 and much of FY90, start the LTFT in late FY90, complete it in late FY91, and decommission the Fenton Hill site in FY92.

After examining the DOE program, the level of work required, and the schedule, Los Alamos recommended the funding profile shown below.

	Fiscal Year				<u>Total</u>
	<u>89</u>	<u>90</u>	<u>91</u>	<u>92</u>	
DOE Funding Recommendation (\$M)	3.6	3.6	3.6	3.6	14.4
LANL Cost Estimate (\$M)	3.6	3.6	5.0	5.0	17.2

There is no difference in the DOE and Los Alamos funding requests for FY89 and FY90, but in both FY91 and 92 Los Alamos believes that an additional \$1.4 million will be required for the large expenses associated with the actual operation of the LTFT. The round-the-clock nature of the operation will require the services of a subcontractor to provide the additional shift personnel and additional funding will be required for water consumption and energy usage

The lack of contingency funding by the DOE is also of concern. While the recent technical successes at Fenton Hill may have encouraged the DOE to reduce contingency funds, it must still be recognized that equipment does age, and repairs and modifications will be necessary. Los Alamos sympathizes with the DOE's aggressive, optimistic program planning in the face of severe budget constraints, but planning for contingencies is necessary in R&D programs, particularly those, like HDR, that must incur the technical risks associated with field operations.

In addition to the Fenton Hill project discussed by Assistant Secretary Fitzpatrick, Los Alamos recommends that a follow-up program be aimed at HDR advanced technology and ultimate HDR commercialization. During this follow-up program a reduced funding of

\$2.5 million per year should be continued after completion of the LTFT so that Los Alamos could continue basic R&D in areas that will further reduce HDR costs, and also serve in an advisory role to industry.

Los Alamos is attempting to resolve the funding shortfall in ways other than simply requesting additional DOE funding. For example, for the surface plant equipment necessary for the LTFT, Los Alamos is refurbishing heat exchangers, valves, and pipes that were installed at Fenton Hill for the Phase I reservoir tests conducted in the late seventies. Exceptions to this reuse philosophy are the high-pressure injection pumps, where the pressure requirements of the new reservoir exceed the old one's by 17 MPa (2500 psi), but even here Los Alamos is attempting to save at least part of the estimated cost of \$1,300,000 by buying old pumps if these can be found in government or private industry.

b. Land Usage

The Fenton Hill Experimental Site covers an area of approximately 8.5 hectares (21 acres) in the western section of the Santa Fe National Forest, about 35 km (21 mi) west of Los Alamos, NM. It is occupied by the HDR Program under a letter of understanding between the US Forest Service and the US Department of Energy, which requires that -- at the conclusion of experimental work there -- the site shall be restored as nearly as possible to its original condition except for such buildings and facilities as the Forest Service may choose to retain.

Because of the superb facilities located there, and the expenses of decommissioning Fenton Hill, it may be more advantageous to the DOE to retain the site for post-HDR usage. Such usage would be aimed at continuing geothermal research, either the HDR advanced technology program mentioned above, or other, non-HDR geothermal research, and other earth science programs. The latter include seismic reservoir-imaging for the DOE's enhanced-oil-recovery programs, development of new drilling and logging technology to aid the DOE's scientific-drilling programs, and investigation of new rock-mass interrogation techniques to aid the DOE's Basic Energy Sciences program as well as both nuclear and chemical underground-waste-storage programs. While actual wastes, either chemical or nuclear, could not be used at Fenton Hill, harmless chemical analogues could be used to improve understanding of basic processes of underground transport, sorption and retention.

An initial meeting with the DOE and the scientific community was held in Los Alamos in July 1987 and a report was prepared that discussed Fenton Hill facilities, and appropriate avenues of research. In December 1987, a special session of the American Geophysical Union was convened in San Francisco to alert an even larger scientific community to Fenton Hill research possibilities. Working with members of the External Advisory Committee to Los Alamos's Earth and Space Sciences division, Los Alamos will solicit and integrate multi-disciplinary, multi-purpose proposals from academia, private industry and other national laboratories and present these to the DOE for its consideration.

c. Water Supply

A considerable quantity of water, 60,000 to 150,000 m³ (50 to 120 acre-ft), will be required for the long term flow test (LTFT) at Fenton Hill. Experiment 2077 will be conducted in FY1989 to measure the leak-off rate at three pressure levels and thus provide a more definitive estimate of water requirements. Meanwhile, we are examining water-supply options and estimating their advantages and disadvantages. Currently the principal water supply at Fenton Hill is from an on-site water well. Under permit RG-2483-Temp(2) issued by the New Mexico State Engineer's Office, the HDR Program is authorized to appropriate underground waters of the State of New Mexico from that well. While this permit was amended on August 4, 1987 to limit the appropriation to 3700 m³ (3 acre-ft) per annum, this can be increased to a maximum of 18,500 m³ (15 acre-ft) if the program leases and sets aside water rights elsewhere without water usage, requiring 1 hectare (2.4) acres of irrigated land for 5 years. Because of the multi-year duration of this commitment, letting a contract for setting aside the land has been difficult, but at the time of this report it was nearing completion. When it is approved, the 18,500 m³ (15 acre-ft) per year can be used as follows: We will store the 1989 allotment in our covered storage pond. When the LTFT is started in the Fall of 1990, the stored supply will be available, as will the 1990 allotment. As the LTFT continues into 1991, the third year's allotment will be available also, for a total supply of 56,000 m³ (45 acre-ft). If additional water is required, as seems likely, it will be obtained via one or more of the following options.

- (1) Obtain an additional water-use permit from the State and obtain the additional water by pumping it from the existing water well, FH-1. While it appears likely that the aquifer can supply this water, a backup option should be ready if indeed the well runs dry during the LTFT. To put this option

into effect, we would need to lease even more water rights to offset our water usage, and our application for additional water usage would be subject to challenge by anyone lower in the Jemez drainage.

- (2) Drill, or preferably, deepen either of water wells FH-2 or FH-3 to 300 m (1000 ft), into the lower aquifer of the Abo formation. These wells are presently 140 m (460 ft) deep. It is probable that this lower aquifer contains brackish water, so we will have to arrange to keep it separate from domestic water. Drilling these wells deeper requires another water-use permit and leasing offsetting water rights.
- (3) Purchase water from the local contractor, Hoffheins. His water-use permit specifies that LANL can purchase up to 6.22 acre-ft per year, and it expires on Dec. 31, 1990. If we use this option, we still will need another source because 12 acre-ft may be insufficient for our needs.
- (4) Purchase water from the Jemez Springs Water Cooperative. They have water rights of approximately 70 acre-ft, and the cost they initially quoted was \$1500 per acre-ft. To make use of this water, we would have to transport it to Fenton Hill from some diversion point on San Antonio Creek. Pumping stations to lift the water to Fenton Hill would be needed. In addition, we would have to apply to the State to establish a diversion point along San Antonio Creek. We would also need to obtain a right of way along which to lay the pipeline.

The best and least expensive possibility for obtaining additional water is to pump it from our existing well. This requires another water-use permit from the State of New Mexico and leasing additional water rights to offset the additional water use. It probably would require that we have a backup system to cover the possibility of the well being pumped dry. Drilling well FH-2 or FH-3 into a lower aquifer is the next most desirable option. It requires well drilling for 150 m (500 ft), which is less expensive than building a pipeline and pumping from either Hoffheins' property or Jemez Springs Water Coop. Transporting water by truck is the most expensive and least attractive alternative.

IV. Budget

The Hot Dry Rock Program Budget is presented in Table 4. Shown are budgets for FY 1988, three previous years, plus one future year to cover a five-year period.

A gradual decrease in the overall budget has resulted from two major program changes. First, the International Energy Agency's foreign participation ended in FY 1985 and FY 1986. This reduced the funding by \$2.5 million at the end of each of those fiscal years. Second, the continuing reduction in the overall Department of Energy Geothermal Budgets reflected in category reductions and schedule changes.

Over the five-year period FY 1985 - FY 1989, the predominant funding need has been for the Fenton Hill Site Operations. This was for the development of the Phase II reservoir, including well completions, surface-system procurement and installation, and supporting utilities. In FY 1988 this amounted to 67% of the total budget.

In FY 1988 the expensive effort was the redrilling and completion of wellbore EE-2. Procurements of hardware and installation of the Phase II surface system were started in FY 1988 and will be continued in FY 1989 and FY 1990.

As part of its omnibus spending bill, on December 15, 1987, Congress approved a funding level of \$5.8 million for HDR for Fiscal Year 1988. While this was \$2.2 million more than the President's request, it was \$2.2 million less than Los Alamos had requested. This disappointing funding news closely followed the redrilling of EE-2, for which \$1.8 million had already been committed, and yet another \$0.85 million had to be spent to complete the well. As a consequence of these large expenses, incurred early in the fiscal year, and the lateness of the Congressional funding decision, HDR staffing had to be halved, from 30 to 15 full-time personnel. It was only because of the extraordinarily successful drilling and well-completion described earlier that enough drilling-contingency-fund expenses were saved to avoid even deeper personnel cuts, which would have made program continuation extremely difficult.

Table 4. Budget*

Task/Projects	Fiscal Years				
	1985	1986	1987	1988	1989
1. Fenton Hill Site Operations					
12 Phase II Energy Extraction System	6698	3756	2539	3099	1989
13 Phase II Ancillary Activities	1234	1246	710	466	284
14 Test Site Support Activities	853	860	667	311	599
2. Scientific and Engineering Support					
21 Tools and Instrumentation	3120	1405	1191	502	164
22 Reservoir Engineering	1947	1663	1411	628	683
23 Technology Applications	248	224	357	214	288
Reserve and Miscellaneous	400	847	1125	600	
Totals	14500	10000	8000	5820	3600

* In thousands of current dollars

V. End of Year Status

This year was marked by significant progress in the preparation of physical facilities at Fenton Hill for the LTFT, including the redrill of EE-2, new and better predictive capabilities for estimating the long-term performance of the Phase II reservoir, and an improved fundamental understanding of the character and hydraulic behavior of the reservoir.

1. Well Redrilling and Completion.

EE-2A was redrilled on a trajectory close to EE-2, yet penetrating seismically active zones. Prior to redrilling, some of the original EE-2 casing was strengthened through remedial cementing. Following drilling, the EE-2A completion casing was cemented-in a departure from past practice, from above the production zone to the surface in order to provide additional reliability during the upcoming viscous fracturing and LTFT operations. The high-performance cement formulation for EE-2A, which serves as a prototype for future HDR wells, was developed in collaboration with Dowell-Schlumberger, Inc. The drilling and completion of EE-2A was completed within budget although project cash flow and the limited availability of casing caused a 4-month delay in the completion of the well. In short, excellent progress was attained in achieving the critically important level II objective, improving HDR drilling and completion technology.

2. LTFT Physical Facilities.

A "Butler" building was constructed on site during the Spring. The building houses the pumps and plumbing for the injection of makeup water into the LTFT surface loop from the 5-million-gallon pond and water-storage tanks. Following the demobilization of the drilling rig, electrical power was brought to the building, and 4 low-pressure pumps and related plumbing were installed. Water tanks were sited and plumbed into the Butler building. Pipe and compressor lines were run from the Butler building to the area where the high-pressure injection pumps will be sited.

Equipment was fabricated for filtering EE-1 pond water in preparation for cleaning and relining the pond. Storage facilities for fuel and hazardous chemicals were brought into

compliance with directives of the New Mexico Environmental Protection Agency. Monitoring equipment for discharge of overflow water was also brought into compliance. The comparison of actual work-completion dates with scheduled dates shows compliance with 92% of interim milestones, with no slippage severe enough to jeopardize LTFT start-up in September, 1990.

3. LTFT Analytical and Predictive Capabilities.

Reactive tracers will be used during the LTFT to measure the amount of cooled rock within the reservoir as a function of time. The reaction rates of a suite of prospective tracers were measured as a function of temperature using a method developed for the purpose that is called temperature-programmed reaction (TPR). Application of the method enabled the reaction rates of a large number of tracers to be measured in a small fraction of the time that is required by other methods. The threshold of detection in water representative of LTFT circulating fluids, for the tracer that is most likely to be used during the LTFT, was reduced to 5 ppb.

Development continued on the code for modeling hydraulic, thermal, tracer-transport, and water-loss properties of the Fenton Hill reservoir. Model simulations successfully replicated the performance of the reservoir during the 1986 ICFT test. The model was also successfully applied to simulate the performance of the British HDR experiment at Rosmanowes Quarry. In summary, the excellent progress this year indicates that Los Alamos will attain, on schedule, the other extremely important Level II objective, evaluation of the Phase II reservoir.

4. Reservoir Character and Hydraulic Behavior.

A profound advancement in our understanding of the Phase II reservoir occurred as a consequence of an extensive re-examination of injection experiments conducted at Fenton Hill during the past 6 years. The original interpretation of injection experiments suggested the presence of a very large discontinuity in the minimum earth-stress located between the Phase I and Phase II reservoirs which gives rise to the comparatively high injection pressure of the Phase II reservoir. If this interpretation were correct, it would be difficult to predict the earth stress and related hydraulic properties of new HDR reservoirs

constructed elsewhere. Discovery of subtle inflection points in pressure-decay records as well as new information on the orientation of fractures in the reservoir derived from 3-point seismic analyses, indicate that this stress discontinuity does not occur. It is now apparent that a structural, rather than a stress, discontinuity occurs just above the Phase II reservoir, due to a change in the orientation of predominant and continuous joints. The Fenton Hill findings were recently reported at an international rock-mechanics meeting and promise to cause a widespread re-examination of anomalous earth-stress determinations by other investigators using the hydraulic fracture method.

In other related work, it was shown that televiwer measurements of the orientation of borehole breakouts provide a continuous determination of the orientation of horizontal stresses in the reservoir. Stress directions derived from televiwer records in the Phase II reservoir closely correspond to determinations from hydraulic-fracture seismicity. Because of the availability of the HDR televiwer, individual stress determinations from Fenton Hill far exceed those available for any other site or region in the world.

IV. Future Plans

1. The LTFT.

The project activities in FY89-90 are focused principally on preparations for the LTFT with a schedule that will allow the startup of the test in September of 1990. In FY89, procurement specifications will be completed for the high pressure-pumps, the gas-separation system, the high-pressure makeup-water pumps, and the EE-2A and EE-3A wellheads. Approximately 50% of the pumping capacity for the test, and as many of the foregoing items as allowed for within the \$600K budgeted this year for equipment, will be procured and installed in FY89. The control and monitoring system for operation of the surface facilities will be designed in FY89, and procured and installed in FY90. The EE-1 pond, which will be used to store production from the reservoir during LTFT fresh-water flushes, will be cleaned, relined, and brought into compliance with Environmental Protection Agency directives. The design of the high-pressure piping section from the high-pressure pumps to EE-3A will be completed.

The process for obtaining a permit for the LTFT makeup-water from the State Engineer will begin in FY89 and be completed in FY90. Results from Experiment 2077, which is described below and will be completed during the 4th quarter of FY89, will provide a measure of the volume of the current reservoir and establish the upper limit of water losses that can be expected from the reservoir during the LTFT. The results will determine the volume of water required to conduct the LTFT.

2. Characterization and Performance Predictions for the LTFT Reservoir.

Experiment 2077 will run for 6 months beginning in early FY89. The objectives of the experiment are: to determine rate of water loss as a function of pressure and time; to measure reservoir volume; and to gather additional shut-in data related to the hypothesis of low-opening-pressure fractures in the body of the reservoir. In addition, the experiment will result in inflation and pressurization of the reservoir prior to an attempt to reduce reservoir impedances in the first quarter of FY90 through viscous fracturing of EE-2A. Following the fracturing, the impedance of the reservoir will be measured for comparison with Experiment 2077 results. Borehole televiewer data acquired on completion of the EE-

2A redrill will be processed for information relevant to the structure of fractures providing production in the reservoir as well as the state of stress through the production region. These data will be combined with new information on the focal mechanism of hydraulic-fracturing-induced microearthquakes to elucidate stresses on the network of fractures making up the reservoir.

In preparation for the LTFT reactive-tracer experiments, laboratory measurements will begin in FY89 of the sorption properties of prospective tracers on granite. Included will be a combination of batch and column experiments at different temperatures and representative geochemical reservoir conditions. The results will be integrated into a sorption model of the individual tracers for prediction of tracer performance during the LTFT that will be based on our current understanding of the reservoir. Development is also continuing on high-pressure liquid-chromatographic techniques for measuring the concentrations of the prospective tracers in the presence of dissolved organic solids down to the ppb level.

The capability of the code, Finite Element Heat and Mass Transport, will be extended in FY89 to include modeling of pressure-dependent permeability. Results from the previous test will be modeled to validate the code and predictions will be made on the performance of the reservoir for the LTFT.

3. HDR Opportunities in California, Mexico and New York

California. Based upon meetings with the California Energy Commission (CEC) in Sacramento and the City of Clearlake, it appears that Los Alamos might be able to expand HDR development in California. Los Alamos now has a \$30,000 contract to identify HDR borehole prospects in the Clearlake area, and has nearly completed that work. An intriguing prospect is the Wilson No. 1 well, which is about 2 km deep and is 400°C at its bottom. Los Alamos, in partnership with either the City of Clearlake or Lake County, plans to request additional CEC funding through its Geothermal Grant and Loan Program for Local Jurisdictions.

New York. During the Program Development Council meeting in June, 1988, Parker Mathusa, NYERDA, suggested that HDR has excellent prospects in the mid-Atlantic states

because these states face a more imminent energy shortage and are very concerned with environmental effects. He suggests HDR development on Long Island. Earlier studies there indicate a geothermal resource of 50 quads. While this is a low-temperature resource, Long Island does have a low-temperature direct-heating need of 0.5 to 1 quad per year, which HDR might satisfy. Mathusa has invited DOE/GTD officials to New York to discuss this proposal.

Mexico. Paul Kruger, of Stanford and ESS-Division's External Advisory Committee, helps the DOE conduct the joint US-Mexico (Comision Federal Electricidad) geothermal R&D program. In some meetings with the Mexicans he informed them of HDR work underway at Los Alamos, and they were interested in seismic fracture-mapping and chemically reactive tracers. As a consequence of this interest, Hugh Murphy will participate in the DOE/CFE program planning meeting in Calxico on October 6 and 7, 1988. The advantage of the joint work that Murphy will propose is that, with little use of DOE funds, Los Alamos could conduct HDR-related experiments in Mexico, and gain access to data in different reservoirs and rock types. In return, CFE gains access to newer technology for reservoir diagnostics, and they may indeed assign personnel to LANL for training in these technologies.

4. Initiatives in HDR Technology

Below are described several technical initiatives which are currently unfunded, but which could accelerate the completion dates and reduce the costs of attaining present HDR objectives.

Reduce The Reservoir Flow Impedance. Conduct a high pressure viscous-fracturing operation at Fenton Hill to lower the overall impedance, i.e., the resistance to flow within the reservoir. The Phase II reservoir has three impedance components; 1) inlet, 2) body of the reservoir and 3) reservoir region near the production well. During operation, the circulating water will cool the rock around the inlet, reducing its impedance to a negligibly small value. The balance of the remaining impedance will be evenly divided between the body of the reservoir and the reservoir region near the production well. While the impedance in the body of the reservoir is more difficult to reduce, the impedance in the near-wellbore region can be reduced by injection of water that has been viscosified by

cross-linking polymer gels. Viscosities as much as 100 times that of water can be achieved, resulting in much higher injection pressures, greater fracture openings, and enhanced fracture propping.

This initiative addresses the most fundamentally important program goals, including the level I objective of reducing electricity production costs and the level II objective of evaluating the reservoir performance. Because most of the reservoir-development cost is fixed by the capital investment in wells, surface plant and fracturing, an effective method of reducing cost per kWh is to maximize the power extractable from the reservoir. This can be accomplished by increasing the rate of water flow through the reservoir. Flow rate can be increased by either increasing the injection pressure or reducing flow impedance. Increasing pressure results in higher pumping costs, and such increases are limited, in any event, by the necessity to restrict normal operation to pressures no greater than the fracturing pressure. Hence, the most effective method of increasing power production is to reduce flow impedance. In this manner, evaluation of the reservoir performance during the LTFT is also greatly enhanced. For example, accurate estimates of the reservoir's total heat capacity requires a measureable thermal drawdown, i.e., observed reduction of production-well temperature. Thermal drawdown increases linearly with flow rate, but depends upon only the square root of time. Hence, halving the impedance and therefore doubling the flow rate provides the same assurance of accurately assessing thermal performance as quadrupling the LTFT test period. Estimated cost of this initiative is \$320,000.

Advanced Thermal Spallation Drilling. Traditionally, rock has been drilled by imparting mechanical stresses to crush the rock. This causes severe bit wear and limited penetration rate. Hard formations such as crystalline rock are particularly difficult to drill by conventional rotary means, and low penetration rates (1-8 m/hr) and short bit lifetimes (30 to 100 m) are observed typically. Consequently, an alternative method, such as thermal spallation, should have great economic potential. Indeed, an economic study by Rinaldi (1984) of spallation in granite indicated that thermal spallation drilling could halve drilling costs.

Los Alamos would conduct investigations of rock spallability. While some work has previously been conducted, often it was done under unspecified conditions. For example,

basalt is generally thought to be unspallable, but some basalts will readily spall under slow heating conditions. Controlled tests are needed that use carefully characterized rock samples, complete time-temperature profiles of rock surface temperature, and detailed observations of results, including spall-size-distribution and spalling rate. Both field and theoretical studies would be carried out to improve understanding of how heat flux correlates with spallation rates for a wide variety of rocks. This initiative addresses the level II objective of improving HDR drilling and completion technology. Estimated cost is \$500,000.

Earth Stress Measurements. Knowledge of the magnitudes and directions of the principal earth stresses is particularly important in developing HDR reservoirs because the direction and extent of fracture propagation is largely dependent upon these earth stresses. Results at Fenton Hill show that stress magnitudes and directions can change drastically over surprisingly short depth intervals. This has important implications for the design of hydraulic-fracture propagation. A convenient, preferably wireline-operated, stress-measuring logging tool is desired. With such a tool, stress measurements could be made quickly and inexpensively by simply moving the tool and conducting measurements with a logging van. During hydraulic pressurization the borehole radial displacement would be measured with an array of displacement transducers. Using downhole multiplexing, we estimate that displacements should be resolvable to a micron, which should suffice for stress measurements accurate to 1 MPa (145 psi). This initiative addresses the level III objective of improving instrumentation and hardware to control, locate and measure fracture propagation. Estimated cost is \$450,000.

Shock-Induced, Hydraulically-Driven Fracturing. Conventional hydraulic fracturing of wells results in the propagation of just one fracture, or at best a few discrete fractures, whereas multiple fractures are desired to increase the amount of heat that can be extracted from the rock-mass. Explosive fracturing provides multiple fractures, but these propagate only a few meters from the borehole. A hybrid technique, shock-induced, hydraulically-driven fracturing, combines the advantages of both stimulation methods. The technique consists of prestressing the rock by filling the borehole with pressurized fluid at a pressure high enough to drive a fracture but not high enough to initiate one, and then generating an explosively-generated shock wave strong enough to overcome the strength of the material, but not strong enough to cause casing or formation damage. This initiative addresses the

level III objective of improving instrumentation and hardware to control, locate and measure fracture propagation. Estimated cost is \$300,000.

Triaxial Seismic Fracture Mapping. The triaxial, or hodographic, method of detecting and recording seismic events will save money during development of future Hot Dry Rock reservoirs because it allows one to locate fractures from just one or two seismic stations. The conventional seismic method locates fractures by triangulation using at least three, and usually four, separate seismometers. In contrast, in addition to direction, the hodographic method determines distance from the triaxial tool to a seismic event from the polarization of the oncoming compressional P-wave from the event. Because fewer seismic-observation locations are required with the triaxial method, large cost savings result, since the need for drilling special seismic-observation holes is eliminated.

To date the major problem with the triaxial method is that the particle motion of the direct P-wave is not linear for a long enough time to determine a reliable direction to the seismic event. This departure from linearity has been observed in all triaxial data collected for microearthquake studies, and is believed to be caused by a coupling problem — the seismic tool does not faithfully reproduce the ground motion. Los Alamos proposes to further investigate the causes of this departure from linearity and to suggest remedies. Initially, we will analyze existing data and determine the tensor relating measured P-wave polarization to the known direction of the incoming wave. A large data base exists for this study. Simultaneously, we will develop a dynamic model of the seismometer package to determine tool resonances, and then compute geophone output for assumed input ground motions. The results of these calculations will be compared with our data-analysis effort. Laboratory measurements will be carried out to verify the dynamic model. Using the results of these studies we will propose design changes to improve current seismometer tools. This initiative addresses the level III objective of establishing reservoir-mapping techniques to locate drilling targets and another level III objective, verifying that environmental consequences of HDR are acceptable. Estimated cost is \$475,000.

Expandable Metal Liners for Completing Geothermal Wells. Conventional well-completion requires the insertion of a casing, or liner, and cementing the space between it and the borehole wall. Unfortunately, cementing in hot geothermal wells is expensive and risky, but could be avoided by the use of a very ductile metal liner. After lowering the liner it

can be hydraulically pressurized so that it will be plastically deformed outward. It will then contact, conform to, and form a seal with the rock wall. If sections of ductile liner alternate with sections of conventional liner, only the ductile sections will be deformed into contact with the rock while the conventional liner remains unaffected, leaving a large interval of open-hole annulus behind it. A simple casing-perforation then provides unimpeded access to this open-hole annulus, enhancing geothermal productivity. This initiative addresses the level II objective of improving HDR drilling and completion technology. Estimated cost is \$200,000.

Low Cost, Continuous Gas Lift. If a compressible gas is added to the water circulating through an HDR reservoir and its wells, this gas will be highly compressed in its passage through the injection well because typical injection pressures will be several tens of MPa. The resulting density of the water-compressed gas mixture will be high. However, after the mixture passes through the reservoir and begins to travel up the production well (which is typically operated at just 2 MPa [300 psi]), the gas begins to expand and the mixture density decreases. The density differences between the injection-well and production-well mixtures causes a natural pressure difference across the reservoir which augments that induced by pumping. In this manner, more flow can be transmitted through the reservoir, increasing power-production rates, thus helping achieve the level I objective of producing HDR electricity in a cost range of 5-8 cents/kWh. Estimated cost is \$375,000.

Fractal Evaluation of Seismic Events. The fractals method of evaluating seismic data could provide insight into the physical configuration of a geothermal reservoir. It is the logical extension of the 3-point method which has been so successful in identifying fracture planes in a seismic cloud. This initiative addresses the level III objective of establishing mapping techniques to locate drilling targets. Estimated cost for the preliminary, scoping phase of this work is \$150,000.

Utility Load-Leveling. Utility load-leveling is critical to the efficient management of utility resources. Los Alamos would conduct an experiment at Fenton Hill to evaluate the applicability of HDR technology to utility load-leveling. The storage of pressurized water underground has been evaluated in the past. Most of the applications dealt with the pumping of water down a hole and extracting it in a thermally unenhanced mode. This results in a Coefficient of Performance (COP) of about 0.6, but has the advantage of using

off-peak power to pressurize the water, and producing power previously pumped underground during periods of peak power requirements. If the site is selected carefully, the water can also be heated using HDR technology, raising the COP by as much as 1.0, to a combined COP of 1.6. The proposed experiment would extend over a twelve-day period. Pumping equipment would be rented and the reservoir would be cycled daily, injecting for 12 hours and producing for 12 hours. As a result of the experiment we would be able to evaluate the applicability of HDR technology to such diverse situations as providing preheating for boiler feedwater, binary cycle power generation, and flash-steam generation systems. This initiative addresses the level I objective of producing HDR electricity for 5 to 8 cents/kWh. Estimated cost of the preliminary experiments at Fenton Hill are \$600,000.

Investigation of Northeast Hot Dry Rock Sites. The Northeast United States has recently experienced brownouts and voltage reductions as a result of increasing power requirements. With the current emphasis on energy security and sensitivity to environmental impact, HDR systems can help solve this growing need. Although there are few surface manifestations of geothermal energy in the Northeast, nevertheless it exists. The average thermal gradient for the US is 25°C/km. In the West, gradients as high as 55°C/km are not unusual, which is why geothermal development has heretofore been concentrated there. Nevertheless, in the East areas with gradients as high as 35°C/km are available. At these gradients, a hot dry rock project for electrical-power generation similar to the one being designed in Britain could be built. Los Alamos proposes a site evaluation for a commercial HDR project, followed by completion of a reservoir design utilizing the results of on-site experiments and the preliminary results from the LTFT at Fenton Hill. Los Alamos would provide R&D support for the reservoir development and guide private HDR development. This initiative addresses the level I objective of producing HDR electricity for 5 to 8 cents kWh. Estimated cost is \$10,000,000.

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