HOT DRY ROCK GEOTHERMAL ENERGY IN THE USA - MOVING TOWARD PRACTICAL USE

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Abstract

The technology for extracting geothermal energy from the vast hot dry rock (HDR) geothermal resource has been under development by the Los Alamos National Laboratory for about 25 years. In 1992-1993, an extensive flow-testing program was conducted at the Fenton Hill, New Mexico HDR Test Facility. During two segments of this test, energy was produced at a rate of 4 thermal megawatts on a continuous basis for periods of 112 and 55 days, respectively. Surface and logging measurements showed no decline in the temperature of the water produced from the HDR reservoir during the flow testing. In fact, tracer evidence indicated that the circulating water was continually gaining access to additional hot rock as the testing proceeded. Water consumption was low and all other test data were positive.

The encouraging results of the flow testing at Fenton Hill provided the incentive for the United States Department of Energy (USDOE) to solicit the interest of private industry in a jointly funded program to construct and operate a facility that would produce and sell energy derived from HDR resources. A number of organizations responded positively. On the basis of the interest expressed in these responses, the USDOE subsequently authorized the issuance of a formal solicitation to initiate the project.

Introduction

Background: Hot Dry Rock (HDR) heat mining entails the extraction of useful amounts of energy from the vast geothermal resource in the form of rock at depth that is hot but is not in contact with naturally occuring mobile fluids to transport its thermal energy to the surface. During the past 25 years, HDR has moved from the conceptual stage through scientific verification and, most recently, to engineering demonstration. A patent describing the fundamental aspects of HDR technology was granted to the Los Alamos National Laboratory in 1974 (Potter et al.). The concepts disclosed in that patent have formed the basis for HDR development work conducted during the last two decades at Los Alamos and at other institutions around the world.

Reservoir Development: Over the past 25 years there have been consistent and orderly advances in the development of heat mining technology in the United States. A small, Phase I HDR reservoir was constructed at Fenton Hill, NM during 1974-1978. It was flow-tested intermittently during 1978-1980 to prove the scientific feasibility of extracting energy from HDR (Dash, 1981). During 1980-1986, a larger, deeper, and hotter Phase II HDR reservoir was developed at Fenton Hill. The Phase II reservoir is centered 3.5 km below the surface. Seismic, hydraulic, tracer, and simple geometric evidence indicates that the reservoir has a flow-connected volume of about 16-20 million cubic meters and is ellipsoidal in shape, with axes ratios of approximately 3, 2, 1, respectively (House, 1987; Brown, 1991; Winchester, 1993). The longest axis tends north-south, the shortest axis lies in an approximately east-west direction, and the intermediate axis is tilted to the east at an angle of approximately 30° from the vertical. The reservoir is penetrated by two wellbores, each of which terminates in an open-hole zone approximately 300 meters in length. The distance between the two wellbores at the open-hole depth averages 110 meters.

The Fenton Hill Surface Plant: Between 1987 and 1991, a surface plant, designed to meet power-industry standards and capable of extended operation, was constructed and mated to the large HDR reservoir. Figure 1 is a schematic of the surface plant.

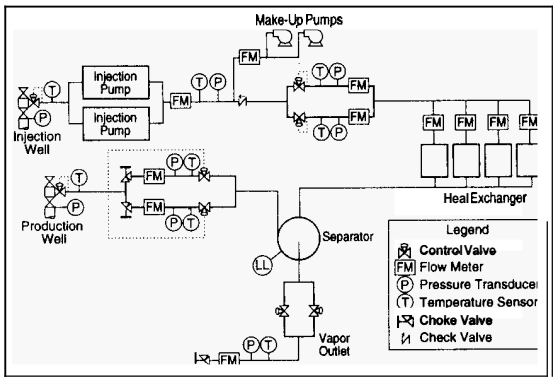


Figure 1. A schematic drawing of the surface plant at the Fenton Hill HDR site. The Plant *is* straightforward in design, completely automated, and highly instrumented.

The heart of the surface plant is the injection pump which supplies the motive force for moving the fluid through the circulation loop. Originally, two diesel-fuel-powered reciprocating injection pumps were installed in the surface plant. These were designed for use on an alternating schedule, with one pump in operation and the other in reserve at any given time. The pumps could be adjusted to operate over a wide range of pressures and flow rates. Each was capable of injecting a maximum volume of about 11 l/s of water at pressures as high as 34.5 MPa. For reasons unrelated to HDR technology, both these pumps failed within a span of two days during a period of normal operations. Several months of intermittent operations passed before a replacement centrifugal pump powered by electricity was installed in the system. While lacking operational flexibility, the electric pump was extremely simple and very reliable.

The injection pump, piping to the injection wellhead, both wellheads, the wellbores and all flow paths through the reservoir constitute the high pressure portion of the circulation loop. This part of the system has been built for operation at applied surface pressures of up to 34.5 MPa. The remainder of the loop, the low pressure side, includes a particle/gas separator, an air-cooled heat exchanger, a makeup water pump, and connecting piping. This part of the system is capable of operation at up to 6.9 MPa. It feeds directly back to the injection pump. The surface plant is designed for automated operation and instrumented for measurement of fluid temperature, flow, and pressure at numerous points in the loop (Ponden, 1992).

Flow Testing During 1992-1993

Flow Test Goal and Design: During 1992-1993, an extensive program of reservoir flow testing was conducted at the Fenton Hill HDR site. The goal of this long-term flow test (LTFT) program was to demonstrate that the Phase II HDR reservoir at Fenton Hill and, by implication, HDR reservoirs in general could be operated on

a continuous basis to produce useful amounts of energy over an extended period of time. The test program was designed to obtain information about the thermal lifetime of the Fenton Hill HDR reservoir, water consumption, operating and maintenance costs, and the geophysical, geochemical and environmental effects of long-term operation of an HDR system.

As a result of intensive discussions with, and recommendations from, the HDR Program Industrial Advisory Group, the LTFT was conducted under conditions simulating as closely as possible the operation of a commercial HDR power plant. The pressure under which water was pumped into the injection wellbore was adjusted to the highest level that could be maintained without leading to expansion of the reservoir volume, as indicated by the onset of microseismic events and an increased rate of water consumption. Experience had shown that for the Fenton Hill reservoir this pressure was just under 27.6 MPa.

Flow Test Operation: Water was generally injected in the reservoir at a surface pressure of 27.3 MPa. A backpressure of 9.7 MPa was typically maintained on the production wellhead in order to prop open, by means of this imposed pressure, the fluid-carrying joints in the relatively low pressure region of the reservoir immediately adjacent to the production wellbore. The system pressure was reduced to about 4.8 MPa through a pressure control system down stream of the production wellhead, and this pressure was maintained until the water was returned to the injection pump for repressurization and reinjection into the reservoir. The plant was computer-controlled, with fluid circulation maintained continuously, on a 24-hour-a-day basis under these constant operating conditions. For much of the test period, the facility was manned only during daylight hours. On a number of occasions, usually as a result of power failures caused by local weather conditions, the plant went into an automatic shutdown mode. The plant was re-started either by an operator called in especially for that purpose or when the operating staff routinely arrived the next morning.

Important system parameters such as pressure, temperature, and flow rate were monitored continuously. Measurements of the geochemistry of the circulating fluid were made several times a week. Finally, diagnostic procedures such as production-well temperature logging and tracer testing were implemented every few weeks or at critical junctures in the test program.

Continuous operation of the Fenton Hill HDR plant began on April 8, 1992 and proceeded with only minor interruptions for 112 days. Catastrophic failures of both reciprocating injection pumps within a two-day period forced suspension of testing on July 31. Although the pump failures were not related to HDR technology, the ensuing lapse in testing while suitable replacement pumping capacity was being evaluated, procured, and installed, was a serious setback to the LTFT effort. By mid-February 1993, a replacement pump was in place at Fenton Hill and a second continuous phase of flow testing was begun. The new pump was a leased centrifugal unit powered by electricity. Once the appropriate modifications to the electric power supply at the site had been implemented, it proved to be highly reliable. The second continuous test period ran for 55 days until mid-April 1993, when the available funding was exhausted. Typical operating parameters during the two steady-state test phases (designated LTFT Phase 1 and LTFT Phase 2, respectively) are summarized in Table 1.

Table 1
Typical Operating Parameters
During HDR Flow Testing

Dates Test Phase	July 21-29, 1992 LTFT #1	April 12-15, 1993 LTFT#2
Injection Conditions		
Pressure ,MPa	27.3	27.3
Flow, *Us*	6.8	6.5
Temperature ^{0}C	19.0	22.0
Production Well Backpressure, MPa	9.7	9.7

Flow Testing Results and Discussion

The flow testing during 1992-1993 markedly advanced the state of HDR technology. The most representative flow-test data were obtained during the two extended steady-state production periods. Table 2 shows typical operating data during each of these periods.

Table 2
Operating Data From
HDR Flow Testing

Dates Test Phase	July 21-29, 1992 LTFT #1	April 12-15, 1993 LTFT #2
Production Flow, *Us*	5.7	5.7
Production Temperature, ^{0}C	183	184
Thermal Power Production, MW	3.9	3.9
Water Loss, l/s[a]	0.79	0.46
Water Loss, % of injected volume	12.5	7.3

[a]Water loss figures do not include a small part of the injected flow which returns immediately to the surface through a small leak in the injection wellbore.

The flow testing answered some of the outstanding questions about HDR technology and provided new insight into others. Some significant results are summarized below:

1. Thermally stable production was achieved. As indicated in Table 2, the production fluid temperature at the surface was essentially the same in April 1993 as it had been in July 1992. Production-wellbore temperature logging results are illustrated in Figure 2.

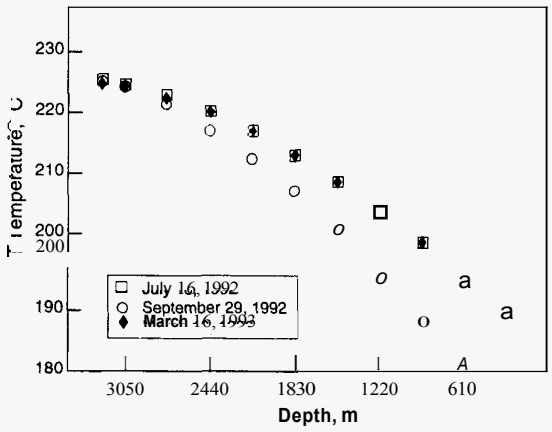


Figure 2. HDR Production wellbore logging results. All the logs showed the same temperature at depth. The temperature was lower at the surface during the logging run of September 29, 1992 because the flow rate from the reservoir was about 30% less at that time than during the other two logs.

The logging runs confirmed that the average temperature of the fluid issuing from the production zone of the reservoir remained stable over the duration of the testing. A close inspection of the logging data showed that a slight decline in the temperature of the water from at least one fluid-producing joint in the production interval occurred over time, but this appeared to be compensated for by decreased flow from the cooled joint coupled with increased fluid production from other joints that had not cooled (Brown, 1994).

2. Contact of the circulating fluid with hot rock increased with time. Figure 3 shows the results of tracer tests conducted during the course of the flow testing.

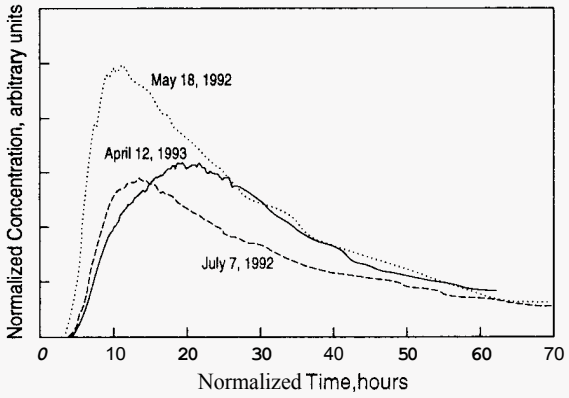


Figure **3.** Results of tracer tests conducted on three occasions during HDR flow testing. The data show that the circulating fluid was being redistributed into longer flow paths as the testing proceeded.

The tracer tests indicated that the fluid volume of the reservoir grew continually and that more of the water appeared to follow longer, more circuitous pathways between the injection and production wellbores as circulation proceeded. This important result implies that HDR reservoirs may be self-renewing, and that useful reservoir lifetimes may be very long.

3. Water consumption was low and continually declined. During steady-state flow testing, Table **2** shows that water consumption declined from about 12% of the injected volume in July **1992** to 7% in April **1993.** In fact, the results of the recent flow testing support earlier static pressurization data that indicate a steady decline in water consumption with time at any imposed reservoir pressure. Other evidence demonstrates that the apparently "lost" water is stored in microcracks in the rock surrounding the reservoir, and would be ultimately recoverable if the reservoir were to be vented back.(Brown **1991).**

4. There was significant net energy production. Calculations indicated that the thermal energy produced during routine operation of the Fenton Hill HDR reservoir was more than six times the thermal energy equivalent of the fuel oil and electricity consumed in running the plant during Phase 1 of the LTFT. Energy balance calculations during Phase **2** of the LTFT, when the system was powered entirely by electricity, gave similar results. The achievement **of** net energy production from the Fenton Hill reservoir provides important evidence that HDR reservoirs can be practical sources of heat or electric power.

5. The production fluid geochemistry was benign. The circulating fluid was essentially free of any suspended particulate matter. Dissolved solids levels rapidly stabilized in the range of 3,000-4,000 ppm (about a tenth the salinity of sea water). The species present in the circulating fluid were those usually observed in slightly saline fluids, mostly sodium, potassium, calcium, and chloride, but with small amounts of other materials such as silica which are characteristically found in crystalline rock. The fluid was slightly acid but not corrosive, with pH levels generally in the range of 5-6. The dissolved gas content was consistently less than 3,000 ppm, and this was practically all carbon dioxide. Hydrogen sulfide, an irritating and potentially dangerous component of many geothermal fluids was typically found at concentrations of less that 1 ppm, well below the level at which it would present any operational hazard.

6. There were virtually no emissions except heat wasted to the atmosphere during normal flow operations. Under normal flow conditions, the same water was continually recycled through the reservoir in a closed-loop mode. Even the production side of the loop, the lowest pressure part of the system, was maintained at more than **2** MPa. This included the separator which was designed to release evolved gases. As mentioned above, the concentration of gas never exceeded 3,000 ppm. This is well below the concentration at which free gas would be present in the circulating water at pressures existing anywhere in the system.

7. The plant operated reliably with almost no human intervention. The surface plant was fully automated and controlled from an IBM PC. Much of the time the plant operated with no on-site personnel, except for a security guard. On several occasions, lightning strikes interrupted power to the site. A fail-safe system designed to shut down the loop under such conditions operated flawlessly in every case where this occurred. Operation of the Fenton Hill plant during this flow-test period therefore conclusively demonstrated that HDR plants, like highly automated hydrothermal power facilities, can be run with a minimum of manpower.

8. Generally, there were few maintenance problems. With the exception of the failure of both injection pumps midway through the testing program (for reasons subsequently shown to be fundamentally unrelated to this geothermal application), maintenance of the surface plant was confined to routine procedures and minor casual events such as sticky valves, for example. An inspection of the injection wellbore casing after completion of the test indicated no significant corrosion or scaling in spite of the fact that the casing has now been in place for nearly ten years. This and other plant and equipment inspections provided tangible proof that the geothermal fluid produced from the Fenton Hill HDR reservoir was essentially non-corrosive.

9. Evidence showed that the operation of much larger reservoirs should be feasible. At times when fluid production was halted by closing-in the production wellhead and halting fluid injection, the pressures measured at the production and injection wellheads rapidly approached equivalent values. As shown in Figure **4,** this was invariably evidenced by a large increase in the production well pressure and a much smaller sudden decrease in the injection well pressure, followed by a continued but more gradual approach toward pressure equilibrium.

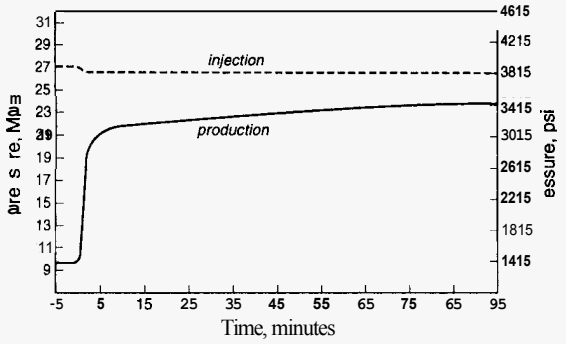


Figure **4.** Pressure changes at the production and injection wellheads upon shut in of the Fenton Hill HDR system show that the majority of resistance to flow through the reservoir is concentrated in the vicinity of the production wellbore.

These pressure-drop data clearly indicate that the majority of the resistance to flow in the Fenton Hill HDR reservoir is concentrated in the vicinity of the production wellbore . Therefore, a significant enlargement of the body of the reservoir and an increased separation between the injection and production wellbores should lead to only a marginal increase in the overall reservoir impedance.

10. Testing indicated that improvements in productivity may be enaineered into the system. Two short tests entailing simple modifications of the system flow schedule provided impressive examples of how deliberate steps can be taken to increase the productivity of HDR reservoirs. The first experiment entailed briefly shutting in the production well for a few minutes on succeeding days (DuTeau, **1993).** The hypothesis was that such shut-ins would rapidly boost the reservoir pressure in the vicinity of the production wellbore and further dilate the joints, thereby leading to an increase in the flow rate upon re-opening of the production well. Indeed, that is exactly what occurred and, over the three-day period of the experiment, the total daily energy production from the system increased by **1-2%** each day. The short shut-in procedure reversed a slow, but steady production decline observed during periods when the system was operated for long periods of time without even brief shutdowns.

In a subsequent experiment at the very end of the fiow test period, production was shut in for 16-hour periods on sequential days while injection was maintained continuously (Brown, 1993). On the third day of this experiment, a sudden large flow rate increase occurred. The system was then returned to steady-state production flow conditions and operated for twelve additional days. Even after nearly two weeks, the flow rate was still about 35% higher than it had been prior to the sudden flow increase. Even at a reduced injection pressure, it appeared that a permanent change in the reservoir flow characteristics had occurred. In spite of the higher flow, both surface measurements and production-well temperature **logs** showed no decline in the average temperature of the fluid being produced. In fact, the temperature rose at the surface as the fluid traveled faster up the production wellbore and thereby suffered less thermal loss in transit.

Significance of Flow Testing During 1992-1993

The highly positive results of the flow testing conducted during 1992-1993, and the absence of any negative findings have moved HDR technology significantly closer to commercial practicality. Operation of an HDR system with low levels of water consumption was demonstrated. Excess energy production over that required to operate the system was shown. The environmental claims for HDR technology were verified. Benign fluid chemistry, a minimum of maintenance problems, lack of scaling and corrosion, and highly automated and reliable operation of the plant in a routine manner provided ample evidence that HDR systems could perform on a sustained basis under practical industrial conditions.

Because the flow testing period lasted only a little more than **a** year with a total circulation time of about 8 months, it was not possible to assess the useful thermal lifetime of the Phase II HDR reservoir. Nonetheless, all the experimental indicators were positive. No signs of short-circuiting or decline in the production temperature were observed. In fact, all the tracer data indicated increasing fluid access to hot rock with time, implying a longer reservoir lifetime than might be expected from straightforward calculations based on fixed fluid flowpaths. In addition, experimental results showed that it should be possible to construct significantly larger reservoirs with higher thermal capacities and longer lifetimes without markedly increasing the difficulties or costs of fluid circulation.

Another limitation of the flow testing was the relatively low fluid production rate, which was below the level that will be required for commercial applications of HDR technology. The flow improvement noted at the end of the test, while significant, moved the system flow rate only marginally toward a practical level and, in any case, requires further investigation if it is to be fully understood and verified. Installation of a second production well at Fenton Hill would improve the productivity of the Fenton Hill HDR reservoir substantially, but would require a major capital commitment. Thus, at the close of the flow test period, HDR energy production on a commercial scale had not been demonstrated. That issue will not be resolved without a significant expenditure of funds to develop a larger HDR system at Fenton Hill or elsewhere.

Obviously, capital costs associated with the construction of HDR facilities and the applicability of the technology at locations geographically and geologically different from Fenton Hill could not be evaluated during the 1992-1993 flow test program, and these remain major uncertainties that must be addressed before widespread commercialization of HDR technology will take place.

The next step in the implementation of HDR technology is to build upon the favorable flow test experience at Fenton Hill by constructing a facility to produce and market energy from HDR in commercial quantities. Government financial participation will be essential to reduce the high risk inherent in bringing this new energy technology to market. To the extent possible, the plant should be built and run by private industry and should meet all the operating objectives needed to compete in today's very competitive energy markets..

The Future Course of HDR Development in the USA

Plans for a Joint HDR Project Involving the US Government and Private US Industry: In early September 1993, based in part on the test results described in this paper, the US Department of Energy (USDOE) formally asked for input from US private industry in regard to the formation of a joint industry/government project to develop a facility to produce and market energy from HDR resources. A total of 41 responses were received. About 30 of the organizations responding appeared to be interested in participating in the proposed program.

In early summer of 1994, the Director of the USDOE Geothermal Division, in a memorandum to the DOE's Albuquerque Operations Office located in Albuquerque, New Mexico, authorized the preparation of a formal solicitation seeking industrial partners in a project that would involve..."constructing a prototype facility to produce and market electric power or heat generated from geothermal energy in hot dry rock." This memo further stated that the Department of Energy's 1995 budget would include at least $2 million for the project and requested that the solicitation be issued sometime during August-September 1994, for execution in the 1995 Fiscal Year.

The project is envisioned as a staged, multi-year effort that will be carried out by a team probably consisting of a resource owner, a project developer, a plant operator and a customer for the energy. The industry team will specify the site, design and construct the facility to extract energy from the HDR resource, operate the plant, and deliver the energy to the customer. If the project entails electric power production, as seems most likely, the team will be responsible for designing and operating the power plant for converting the thermal energy to electricity.

The USDOE will contribute up to 50% of the cost of the HDR energy production and marketing project. The private development team will finance the balance of the project. It is anticipated that with this significant degree of government participation, an HDR facility can be constructed that will market energy at a competitive rate, pay its own operating expenses, and return a profit commensurate with the risks and opportunities involved.

It is expected that the industry-led HDR project will address the remaining technical issues associated with HDR including capital construction cost for HDR systems, reservoir thermal productivity and lifetime, and perhaps geological and geographical adaptability of the technology (if a site other than Fenton Hill is selected). One goal will be to design and construct the facility as a production plant rather than a research facility in order to obtain the actual experience base needed to back up the numerous economic studies of capital construction costs of HDR systems. It is essential that the project generate sufficient revenue to pay its operating costs and return a modest profit to assure that the plant will continue to run over the long term, thereby inherently providing the long-term reservoir thermal data so important in assessing HDR as a credible commercial source of energy. To achieve the most competitive operational costs, it will be essential to apply the most up-to-date technical concepts of HDR reservoir engineering and to design the reservoir for maximum sustainable productivity.

The industry-led project may be implemented either at the current Fenton Hill HDR site or at a new location. Because a significant HDR infrastructure, including wellbores and a high-quality reservoir, already exists at Fenton Hill, it is an attractive candidate for a power producing and marketing facility. At present, however, the HDR system there cannot produce energy at a rate high enough to make a marketing effort practical. Enlargement of the productive capacity by drilling another production well would be a necessary part of any power production and energy marketing plan at Fenton Hill. In the final analysis, the selection **of** the site for the industry-led project will be determined by a combination of factors including resource, environmental, transmission, and customer considerations.

The Loneer Term Future of HDR in the **USA:** With the issuance of the solicitation for an industry-led HDR project to produce and market power, and initiation of the project in FY 1995, the course will be set for the commercialization of HDR technology before the turn of the century. After preliminary site and permitting work, it should be possible to carry out drilling and reservoir development in 1996, conduct flow testing and construct a surface plant in 1997, and bring the jointly financed plant on-line in 1998. As that plant operates and proves that HDR technology can be commercially competitive, the prospects for the development of additional HDR facilities will grow. Once a number of HDR sites have been developed, the economic and social benefits of other applications of HDR, such as production of thermal energy for direct use in low-grade resource locations and water purification in conjunction with energy production, will become increasingly apparent. At the same time, improvements in the technical understanding of HDR reservoirs and in the design of HDR surface plants will continually improve the competitive position of this new energy technology. As HDR technology matures in the 21st century, it will command a significant share of the worldwide energy market.

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