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Hot Dry Rock Heat Mining: An Advanced Geothermal Energy Technology

by

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Introduction:

It is widely known that the earth becomes progressively hotter with depth below its surface, and that the total amount of energy contained as heat beneath the surface of the earth is enormous. Volcanic activity is the most dramatic and obvious expression of the intensity and concentration of this geothermal energy, but in many places around the world geothermal energy manifests itself in more benign forms such as geysers, fumaroles, and hot springs. Man has long utilized geothermal energy from these latter sources to provide heat for domestic, agricultural, and industrial purposes.

More recently, a significant geothermal electric power industry has developed. Today, geothermal sources provide more than 5,000 megawatts of electricity from natural steam and hot water reservoirs located around the world (Huttrrer 1990). In the United States, all of the commercial use of geothermal energy to generate electricity is located in the far west, principally in the states of California and Nevada (Rannels and Duchane 1990).

The conventional geothermal industry relies on naturally occurring fluids, either liquids or gases to transport the internal heat of the earth to the surface where it is applied to useful purposes, but there are only a relatively few places where these hydrothermal resources exist at temperatures high enough to generate electric power. Over most of the world, the hot rock beneath the surface is relatively dry. This hot dry rock (HDR) resource is vast in quantity and widespread in distribution. The purpose of this paper is to describe the technology which is being developed to gain access to, mine, and utilize the thermal energy existing in HDR.
The HDR Concept

The basic concept upon which all work on the development of HDR has been based, was originated in the early 1970's by a group of researchers at the Los Alamos National Laboratory. It builds on developments in the petroleum and geothermal industries and can be implemented by the extension of current technologies (Tester, Brown and Potter 1989). An idealized picture of an HDR system is shown in Figure 1.

In the construction of an HDR heat mine, a well is drilled sufficiently deep to penetrate into crystalline rock at high temperatures. Using fracturing technology adapted from the oil and gas industry, water is pumped down the well under extremely high pressures to open up natural fractures in the rock at depth. A reservoir is thus formed consisting of a relatively small amount of water dispersed in cracks in a very large amount of rock. The size of the reservoir can be controlled by the pressure and volume of water employed in the fracturing operation.

A second well is then drilled to penetrate the HDR reservoir at some distance from the original wellbore. Water is pumped down one well and across the reservoir, becoming heated in the process. After reaching the second wellbore, the thermal energy absorbed in traversing the reservoir is transported to the surface. There, a heat exchanger is used to extract the useful energy, and the water is reinjected to continue the heat mining process. In such a closed-loop system, only heat is removed from the earth.

Economic and Environmental Considerations

The costs of developing HDR resources are closely tied to the depth at which sufficiently hot rock is found. This is most readily expressed in terms of the geothermal gradient. Figure 2 is a geothermal gradient map of the United States. The map shows that high gradient resources are located primarily west of the Mississippi. In the east, it is generally necessary to drill much deeper to reach suitably hot rock. Since drilling is the most
expensive single factor in the development an HDR heat mine, it is anticipated that economic factors will dictate that initial HDR electric plants be built in the west. As more efficient drilling techniques are developed and the other aspects of plant operation are optimized, exploitation of lower grade HDR resources will become more likely.

A number of studies have been conducted by industrial firms, governments, and research laboratories to assess the economics of producing electricity from HDR. Estimates of busbar electricity costs ranged from 4-10¢/KWh. In a recent report, the Energy Laboratory of the Massachusetts Institute of Technology combined the results from all the earlier work to develop cost figures based on the quality of the HDR resource as reflected in the local geothermal gradient (Tester and Herzog 1990). Results of that study are summarized in Table 1.

It is clear that electric power from high grade HDR resources may be competitive today, while medium grade resources are marginally competitive and the use of low grade resources for electricity production awaits improvements in the cost picture for implementing the technology.

Direct heating applications of HDR were also addressed in the MIT report. Table 2 shows the projected costs of thermal energy from HDR, again on the basis of the quality of the resource. Because direct heating applications do not require temperatures as high as needed for electricity production and do not suffer the losses inherent in conversion of thermal to electric energy, even lower grade HDR resources may prove to be competitive in site-specific space- or industrial-heating applications.

The environmental characteristics of HDR make it among the most promising of the developing energy resources. When operated as a closed loop, no significant amounts of air, water, or terrestrial pollutants are produced. Because the active reservoir is located thousands of feet below the water table, there is no danger of ground or surface water contamination. Heat, and only heat, is permanently removed from the earth, so there are no long term residues to deal with. Finally, when the plant is decommissioned at
the end of its useful life, the underground system can be permanently shut in by techniques already well-known and proven in the oil, gas, and geothermal industries.

Because the energy production zone is far underground, HDR plants will occupy a minimal space on the surface. In addition, if siting requirements prove to be as versatile as it currently appears they may be, the locations of the facilities can be chosen for minimal visual impact or to eliminate the need for long runs of high tension lines and the environmental problems they pose.

The Los Alamos HDR Project

Field work on the development of HDR at the Fenton Hill site in the Jemez Mountains of northern New Mexico was begun by the Los Alamos National Laboratory in 1974. The location is adjacent to a large volcanic caldera. The increase in temperature of the earth with depth, the geothermal gradient, is approximately 150°F per mile (2.8°F/100 ft) at the site. This is considerably above the worldwide average geothermal gradient of about 80-90°F per mile (1.5-1.7°F/100 ft), but thermal gradients as high or higher are found in many parts of the western United States.

Over a period of several years, two wells were drilled to a depth of about 10,000 ft, where the initial rock temperature was approximately 365°F. A small heat mine was developed using the hydraulic fracturing techniques described above. It was subsequently enlarged somewhat and operated for more than a year (Dash, Murphy, and Cremer 1981). During this time, water was brought to the surface at 275-285°F and power was produced at rates of up to 5 thermal megawatts. Operating problems were minimal. No significant scaling or corrosion was detected, and no negative environmental effects were observed. The thermal energy was even used for part of the time to run a binary electric generator to make power for the site.

Analytical work indicated that this first HDR reservoir, the Phase I system, consisted of vertical fractures connecting the two wellbores within the rock body. In 1980, plans were made to build a
much larger Phase II system based on the results of the initial work. Two deeper wells were drilled to reach rock at temperatures of 480-570°F. The goal was to connect them with a series of vertical fractures, so the bottom 3,300 ft of each well was angled at about 30° to the vertical, with one wellbore positioned 1250 ft directly above the other.

A number of fracturing operations were carried out during 1982, 1983, and 1984. Newly developed microseismic analysis techniques were used to locate microearthquakes generated by the movement of the rock under pressure as the reservoir was being created. These indicated that a reservoir was being formed along the injection wellbore but, even after repeated fracturing attempts, there was no indication that a connection would ever be achieved between the two wells. In the largest of these operations, 6 million gallons of water was injected at surface pressures as high as 7,000 psi.

A decision was thus made to redrill the upper well to penetrate the cloud of microseismic events indicative of the location of the fractured reservoir. In 1985, this redrilling effort was successful and the underground portion of the Phase II HDR system was established. Figure 3 is an illustration of the Phase II HDR reservoir as it appears today, including a modification to the lower wellbore completed in 1988 to repair damage done by the extensive fracturing operations. The reservoir is centered at about 12,000 ft in rock at a temperature of 465°F.

**Reservoir Testing Results:**

The volume of the reservoir determined by the locations of microseismic events is quite imprecise ranging from a few hundred million to as much as 5.4 billion cubic feet depending upon the interpretation of the data. Tracer and hydraulic studies have indicated a flow-connected volume of about 180-720 million cubic feet. The latter figures may be much more indicative of the useful reservoir size. As a point of comparison, the volume of the Phase I reservoir was estimated to be in the range of 3.6 million cubic feet.

In 1986, the Phase II system was operated in a 30-day flow test
Some important results of that test are shown in Figure 4. As the production wellbore warmed, the temperature increased throughout the course of the experiment reaching a value of 390°F by the end of the test. The flow rate also increased continuously under each of the two injection pressures employed during the test. Water consumption declined at first, then increased sharply when the injection pressure was raised and declined again from the initial level at the higher injection pressure. While Figure 4 indicates that about 30% of the injected water was being consumed by the system at the end of the test, much of this apparently lost water was recovered when the system was vented at a later date.

Water consumption has always been an issue in the development of HDR technology. Any water required to run an HDR system must be provided from an outside source. It adds to the operating costs and may be difficult to procure in the required quantities in areas where water resources are scarce and valuable.

Recent work at Los Alamos has contributed significantly to the understanding of water consumption in the operation and maintenance of HDR reservoirs (Brown 1991). In a long experiment conducted during 1989-1991, the Phase II HDR reservoir was manipulated by pumping water into the system at a rate required to obtain or maintain a specific pressure. Figure 5 is a plot of the pressurization schedule of the reservoir over a span of more than two years. As shown, the pressure was established and held at a level of 2180 psi during a number of intervals over the two-year term of the test.

Careful measurements of water consumption during each of these 2180 psi pressurization plateaus demonstrated clearly that the amount of water required to maintain the reservoir at 2180 psi declined linearly with the logarithm of time over an extended period. This implies 2-dimensional diffusion from the reservoir region, which is not surprising since seismic data indicate that the Phase II reservoir has the shape of a flattened ellipsoid.
As shown in Figure 6, the amount of water required to maintain the reservoir at a pressure of 2180 psi declined to less than 3 gpm (less than the flow from a household garden hose) over a period of a little more than a year. These findings will be evaluated more directly when the reservoir is tested in the circulating mode. Based on the promising pressurization results, it is anticipated that water consumption will be less than 3% of the production fluid volume during aseismic flow testing. In aseismic operations, the pressure on the reservoir is kept below the threshold level at which additional hydraulic fracturing and reservoir growth take place.

The Phase II Surface Plant

Construction of the surface plant for long-term flow testing of the Phase II HDR reservoir was begun in 1988 (Ponden 1991). The facility consists of a piping loop and associated equipment connecting the production well to the injection well. It allows the geothermal fluid to be circulated in a closed loop during normal operations, or the fluid in the reservoir to be drained and refilled if desired for testing or control purposes. A highly simplified schematic of the system is shown in Figure 7.

The surface plant was designed to use either equipment on hand from earlier HDR experiments or commercially available components and materials, and for the maximum flexibility of operation. Redundancy has been built into all critical portions of the facility. It has been constructed to meet applicable power plant standards and pressure piping codes.

The most important and expensive components of the loop are the high pressure injection pumps. Each of these pumps is capable of delivering up to about 200 gpm of fluid at pressures as high as 5000 psi. They are of a somewhat standard design except that the fluid-wetted surfaces have been constructed of Inconel or Nitronics 50 alloys to resist corrosion.

While some piping and valves from earlier tests have been used in the new surface plant, the only major piece of equipment retained is the large heat exchanger used to extract the thermal energy from the geothermal fluid. This unit was purchased in the 1970's and has
seen a total in-service life of a little over a year during a number of tests of the Phase I and Phase II reservoirs. Prior to incorporation into the new surface plant, it was evaluated for corrosion and scaling. While some iron carbonate scale was found, there was no significant deterioration of the tube walls and it has not been necessary to lower its pressure rating.

The loop also includes a separator to remove free gases and particulates from the produced geothermal fluid, and a number of control and relief valves for safe operation in either an automated or manual mode. A make-up water system feeds into the loop at a point just upstream of the injection pumps. Two types of make-up water pumps are available to supply either large quantities of water at low pressure or smaller amounts of water at pressures as high as 1000 psi. This combination allows rapid purging of the system when desired, as well as providing the capability to operate the loop under high-pressure during extended testing. The system is instrumented for automatic diagnostic measurements at numerous points.

**Long-Term Flow Testing**

A long-term flow test (LTFT) of the system is planned with a primary goal of demonstrating that energy can be extracted from the system at useful rates and temperatures over an extended time period. The test will be designed to be as straightforward as possible in order to provide a clear basis for developing potential commercial HDR facilities. All important operating parameters will be carefully monitored. In particular, production temperatures, thermal drawdown, flow rates, energy production, system impedance, and water consumption will be documented. Operational and maintenance requirements will be established and verified.

Extensive monitoring, logging, and tracer programs will be mounted during the LTFT. Regular geochemical analysis and corrosion monitoring schedules will be maintained and automated recording will be employed to measure important operating parameters such as fluid temperatures, pumping rates, pressures, water consumption, etc. A continuous seismic monitoring effort will be carried out in shallow wells located at various points near the reservoir, with
additional seismic observations in a deep-well station during periods of anticipated seismicity. Downhole temperature logs will be run regularly. Other logging operations are still being worked out.

Two types of tracers will be employed on a periodic basis. A radioactive tracer will be used on a regular schedule to follow changes in fluid flow paths through the reservoir over the span of the test. A newly developed temperature sensitive tracer (Birdsell and Robinson 1989) will see its first field application during the LTFT. This tracer is an organic compound which reacts with the reservoir fluid at the high temperatures characteristic of the hot reservoir, but not at lower temperatures. It should enhance the study of the thermal drawdown of the reservoir over the course of the LTFT, and even provide information which can be used to predict the useful thermal lifetime of the reservoir for many years into the future.

By the close of the LTFT, we should have sufficient information about the operation of an HDR facility to permit critical decisions about a second HDR site to be made. If the Fenton Hill system operates as anticipated with limited thermal drawdown and minimal operational problems, then construction of a second HDR heat mine will be relatively straightforward although lessons learned in the LTFT may be applied to increase the efficiency and/or improve the economics of the second facility. In the event the LTFT is plagued by operational problems, these will be addressed prior to final design and construction of the second system.

Long term testing of the Phase II HDR reservoir will commence as soon as the surface plant has been thoroughly checked out, comprehensive safety and emergency plans have been developed, and standard operating procedures have been put in place. This may be as early as the final months of 1991.

Additional HDR Heat Mines

The long-term flow test of the Fenton Hill Phase II HDR reservoir should set the stage for the development of commercially viable HDR facilities at other locations. Additional sites for the construction
of HDR reservoirs in the United States have been considered on a number of occasions. A 1982 report provided a geologic assessment of ten potential areas for further HDR development (Goff and Decker 1982). A detailed study by Bechtel Corporation in 1988 concluded that HDR resources could be developed at one of these locations: Roosevelt Hot Springs, Utah (Bechtel 1988). Exploratory work is currently underway by a private organization to assess the HDR potential at another of the sites near Springerville, Arizona with funding from the USDOE and the state of Arizona.

Perhaps the most promising location for a second HDR heat mine at present is in the vicinity of Clearlake, CA. This area, adjacent to the commercially-developed Geysers geothermal region of northern California, has long been known for its high thermal gradient. Work is currently underway by the Los Alamos National Laboratory with funding provided by the California Energy Commission through the city of Clearlake, CA, to assess the potential for development of a HDR plant there.

During the past decade, a significant program in HDR research and development has also been mounted in a number of other nations around the world. The Japanese have three experimental HDR sites including two with deep, hot reservoirs. The Japanese flow tests have been plagued with water-loss problems, but they are developing a deeper reservoir and expect to begin long-term testing in 1993-1994.

The British have had an ongoing program at a site in Cornwall since 1978. Recently, however, they have decided to de-emphasize their domestic effort in favor of greater participation in the European effort at Soultz in northeastern France. This latter project is sponsored by the European Economic Community with intensive participation by the German and French Governments. In 1990, drilling and fracturing operations were completed at a Soviet HDR site near Tirniaus in the Caucasus Mountains, where a direct-use facility is planned by the Soviets to supply thermal energy for use at a tungsten mine located nearby.

Advanced HDR Technology Developments
To date, the development of HDR technology has focused on simply transporting water through the reservoir from an injection to a production well. Modeling work at Los Alamos and limited experimental data have suggested that several as yet uninvestigated techniques may lead to significant improvements in system performance, however. Calculations indicate that operation of an HDR system with high backpressure on the production well may significantly reduce the flow impedance near the production wellbore, thus lowering the overall system impedance. This may in turn lead to nearly equivalent production rates at smaller pumping power requirements, thereby reducing pumping costs and increasing the efficiency of the operation.

Multiple production wells per injection well may allow for a greater utilization of the reservoir volume by tapping into what may otherwise be dead end flow paths. Indeed, the strategic placement of production wells around an injection well may allow an HDR system to operate at extremely high pressures without causing growth of the reservoir, since the production wells can act as pressure relief valves for the entire underground system and inhibit further hydraulic fracturing if properly located.

Finally, operation of the an HDR reservoir in a cyclic mode, wherein the production well is flowed only periodically, offers a number of potential advantages. In this mode of operation, the pressure on the system would increase and the reservoir would expand as water was injected during the production well shut-in stage. Water would flow to the far corners of the reservoir, thus tapping the heat in the entire region. Under flow conditions, the pressure would decrease and hot water would flow back toward the production well. In this operational scenario, even dead-end fluid pathways would eventually contribute to energy production.

HDR plants operated in a cyclic mode may prove very attractive as an augmentation to a conventional power plant to provide peaking power. They could also be used in conjunction with intermittent alternative energy forms such as solar or wind power to provide clean energy on a 24-hour-a-day basis.
It is likely that as HDR technology matures, some of these more sophisticated operational schemes will be developed and implemented. Ultimately, these advanced operating techniques may be combined to produce energy from HDR at costs significantly cheaper than those that can be presently forecast based on the state of the technology today.

Summary

Geothermal energy in the form of hot dry rock (HDR) is abundant, widely distributed, and accessible. Energy extraction from HDR promises to be economically competitive and can be accomplished with essentially no adverse environmental effects.

For the last two decades, the Los Alamos National Laboratory has been working to develop techniques for mining HDR energy. Early worked proved that it is feasible to extract thermal energy using drilling and fracturing techniques adapted from the petroleum and geothermal industries. Recently, results have demonstrated that it should be possible to operate HDR plants in a closed-loop mode with minimal water use.

Long-term testing is about to begin at the HDR facility operated by Los Alamos at Fenton Hill in the Mountains of northern New Mexico. The goal of this test will be to demonstrate that useful amounts of energy can be produced from HDR on a sustainable basis. Results of this work will form the basis for design, construction, and operation of economic HDR plants in the future. Significant HDR programs are now underway in a number of countries. As the technology matures, HDR should take its place as a clean, economically competitive energy source for the world.
References


Table 1
Costs of Electricity from HDR Resources

<table>
<thead>
<tr>
<th>Geothermal Gradient of Resource</th>
<th>Breakeven Electricity Price</th>
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<tbody>
<tr>
<td>°F/mile</td>
<td>$/kWh</td>
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<tr>
<td>280</td>
<td>0.05-0.06</td>
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<td>195</td>
<td>0.08-0.09</td>
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Table 2
Costs of Thermal Energy from HDR Resources

<table>
<thead>
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<th>Geothermal Gradient of Resource</th>
<th>Cost of Thermal Energy $/10^6$BTU</th>
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<tbody>
<tr>
<td>°F/mile</td>
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<tr>
<td>280</td>
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<td>195</td>
<td>4-7</td>
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<tr>
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<td>10-17</td>
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Figure Captions

Figure 1. Idealized conception of an HDR heat mine. The inset depicts the fluid flow from the injection to the production well.

Figure 2. Geothermal gradient map of the United States.

Figure 3. The Phase II HDR heat mine.

Figure 4. Results of a 30-day flow test of the Phase II HDR heat mine.

Figure 5. Phase II HDR reservoir pressure during the extended pressurization test.

Figure 6. Water consumption as a function of the logarithm of time during extended pressurization of the Phase II HDR reservoir.

Figure 7. Simplified schematic of the Phase II HDR surface plant.
Injection Pressure

3800 psi

4500 psi

390°F (Wellhead Temperature)

220 gpm (Flow)

10 MWt (Power)

30% (Water Loss)

May 20 24 28 1 5 9 13 17

June

20 24 28 1 5 9 13 17
Experiment 2077

Water Loss Rate, gpm

\[ \text{In}(t) \]

\( t \) in days

- measured values

Figure 6
Makeup Water Pump
From Storage

Injection Well
Injection Pump

Vapor Exchanger

Separator
Sediment

Production Well

Figure 7