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Moving HDR Technology Toward Commercialization

by

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Introduction

Conventional geothermal resources are currently being developed in many parts of the world where naturally occurring steam or hot water can be extracted from the earth. These hydrothermal resources, however, provide access to only a small fraction of the energy contained within the crust of the earth. In most regions, the heat of the earth is contained in hot rock at depth. The total amount of energy available in the form of hot dry rock (HDR) is extremely large. Estimates place the magnitude of the accessible HDR resource base worldwide at greater than 10 million quads (Armstead and Tester 1987) (1 quad equals 15 quadrillion BTU, or the energy content of about 180 million barrels of oil). For the past two decades, the Hot Dry Rock Program sponsored by the United States Department of Energy at the Los Alamos National Laboratory has been directed toward the development of methods to extract the vast amounts of energy which exist in HDR.

The stated Level I Department of Energy objective for the Hot Dry Rock (HDR) Heat Mining Geothermal Energy Development Program is to "...provide the technology to enable industrial hot dry rock projects to generate power at 5-8¢/kWh by 1997." (USDOE 1989) Fundamental to this objective is the ultimate goal of bringing HDR technology to commercial fruition. Indeed, all of the work done in this exciting research and development area will be for naught if we fail to move as rapidly as possible toward the utilization of this abundant and clean energy resource as one of the important elements in the future energy supply of the world. The purpose of this paper is to outline a path toward the commercialization of HDR heat mining technology, to discuss the potential obstacles in such a path, to propose techniques for overcoming those obstacles, and finally, to present a picture of what a commercial HDR facility may look like near the beginning of the next century.

The Economic Promise of HDR

Because drilling down to hot rock is the primary variable cost element in the development of an HDR system, the cost of production of electricity from HDR is highly sensitive to the local geothermal gradient (The rate at which the local temperature of the earth increases with depth). A number of economic analyses have shown that electrical energy could be produced from HDR at costs which are competitive with fossil fuel plants and which meet or approach the Level I objectives of the program. These studies were carried out at different times and relied on a variety of different assumptions regarding factors such as resource quality, drilling costs, and power plant efficiency, among others.

Results of all these studies were recently combined and integrated by the Energy Laboratory at the Massachusetts Institute of Technology (MIT) to produce a cost profile based on the quality of the resource as reflected in the geothermal gradient (Tester and Herzog 1990). Some of the results of the work by MIT are summarized in Table 1. It is clear that electric power from high grade HDR resources, at costs of 5-7¢/kWh, could be economically feasible today, but that for lower grade resources technical and operational advances are needed to lower the energy costs to competitive levels. Possible ways to achieve some of these needed improvements are discussed later in this report.

Table 1

Busbar Electric Power Costs (Current Technology)

Resource Grade	Electric Power Cost, ¢/kWh
High (80°C/km)	5-7
Medium (50°C/km)	8-12
Low (30°C/km)	>15

While the economic promise of HDR energy is bright, the uncertainties associated with some of the assumptions on which all of the HDR economic studies have been based are relatively high. No operating HDR facility exists at present. Thus there is no concrete example by which to confirm or refute the assertions used as the basis of economic calculations of the cost of energy from HDR. Therefore, inferences have been drawn from geothermal industry data, information from related industries, or extrapolations of findings from the tentative and fragmentary HDR experiments conducted to date. Long-term testing of the world's only viable HDR reservoir at Fenton Hill, New Mexico, should put more substance behind current favorable estimates of HDR economics and point the way to future development of the technology.

The Environmental Promise of HDR

In a world in which environmental concerns are becoming ever more important, HDR offers the promise of a clean and abundant energy source. Based on the demonstrated favorable environmental qualities of hydrothermal energy, together with environmentally sensitive plant engineering, HDR systems can be designed to have minimal environmental impacts which put this technology in a class with the best of the other alternative energy sources. When operated as a closed-loop, HDR systems release no atmospheric emissions except waste heat. Because HDR reservoirs are by design located thousands of feet below the water table, there are no problems with contamination of ground or surface waters.

Like hydrothermal plants, land usage for HDR facilities can be confined to the small space required for the wellheads plus the power plant itself. Plant siting, however, should be more flexible than for hydrothermal installations, since HDR reservoirs are fully engineered and thus not dependent upon the existence of hydrothermal anomalies. In the most optimistic scenario, commercial HDR plants could be sited essentially at the point of energy demand, thus eliminating the need for long runs of high voltage power lines together with the attendant land use and electromagnetic field concerns.

No long-term wastes accumulate as a result of the operation of an HDR power plant. There are no by-products of the process except waste heat, and shut-down of the facility at the end of its useful life can be accomplished by straightforward procedures already proven in the geothermal, oil and gas industries.

HDR Development to Date

The HDR Program grew from ideas conceived in the early 1970's by researchers at the Los Alamos National Laboratory. They reasoned that the vast store of energy contained in the crust of the earth could be extracted by employing drilling and hydraulic fracturing techniques already being used successfully in the oil industry. A patent describing the essence of the HDR process was issued in 1974, but has since expired (Potter, Robinson, and Smith 1974).

Also in 1974, work began on the construction of the world's first HDR reservoir at Fenton Hill. It was constructed at Fenton Hill, a site in northern New Mexico about 35 miles by road west of Los Alamos. The purpose of this effort was to demonstrate that thermal energy could be mined from the earth by drilling a pair of wells deep enough to penetrate into hot, crystalline rock, connecting the wells by means of hydraulic fracturing, and circulating water through the fractures to extract the heat from the rock and bring it to the surface (Tester, Brown, and Potter 1989). By 1977, this "Phase I" HDR system had been developed at a depth of 2,600 m (8,500 ft) in rock at temperatures of 185°C (365°F). This system was enlarged in 1979, and operated for about a year. It was clearly demonstrated that heat could be extracted from the earth at reasonable rates without insurmountable technical problems or serious environmental effects.

In 1980, work was begun at Fenton Hill on a larger, deeper, and hotter HDR system. Under the auspices of the International Energy Agency, Japan and West Germany became involved in the project both technically and financially. In developing this "Phase II" system, two wells were sunk, with the lower portion of each well drilled at an angle of 35° to the vertical. Fracturing operations were carried out in the lower well with the expectation that vertical fractures would be opened to form a connection to the upper well.

After numerous attempts, however, it became obvious that no connections between the two wells were likely to be achieved in this way. In fact, signals from the microearthquakes caused by the fracturing operations indicated that a large reservoir was being formed, but that it was tilted approximately along the trajectory of the angled portion of the lower wellbore and would never intersect the upper well. In 1985, a decision was made to redrill the lower portion of the upper wellbore into the region of microseismicity. Once this had been done, a connection was rapidly established. The Phase II reservoir as it appears today is illustrated in Figure 1.

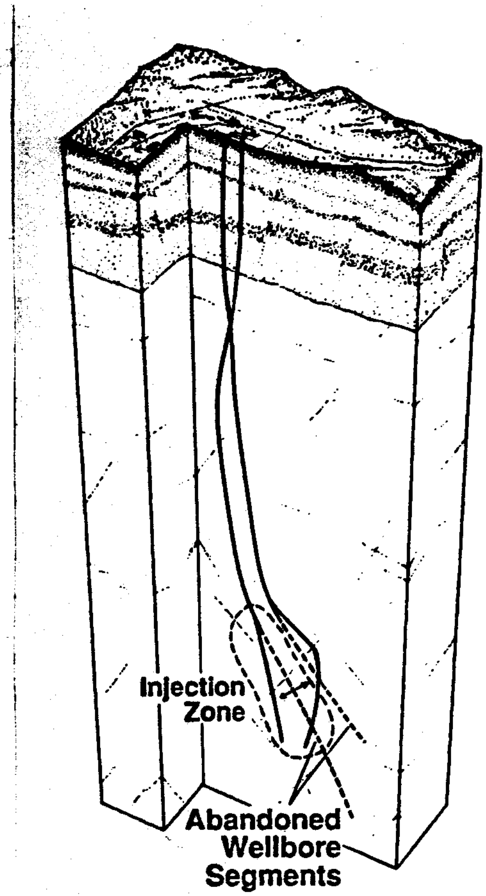

Figure 1. The Phase II HDR Reservoir.

During the late spring of 1986, a 30-day closed-loop flow test of the Phase II reservoir was conducted (Dash 1989). This test included numerous brief shutins, and other pressure and flow rate variations. It is possible, however to generalize the results in regard to some important system parameters as shown in Figure 2.

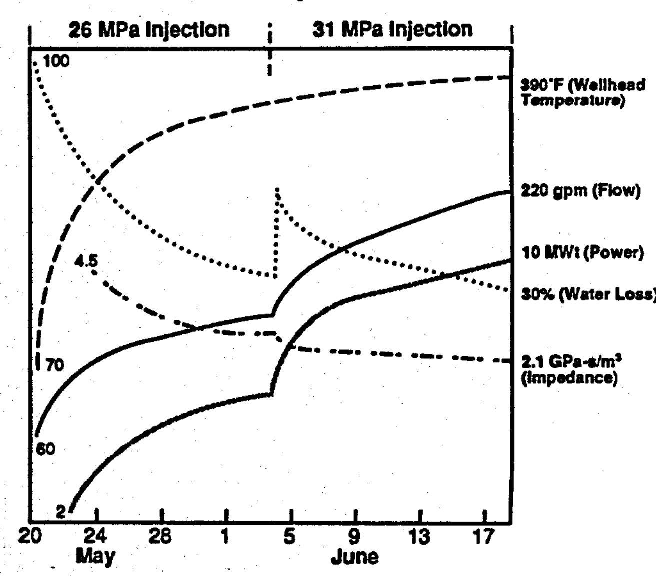

Figure 2. Results of the 30-day flow test of the Phase II HDR System.

The production flow rate, fluid temperature and, consequently, the thermal power increased throughout the duration of the test. By the end of the experiment, the power level had reached about 10 MWt, with water being returned to the surface at a rate of about 220 gpm and a temperature of 190°C (375°F). The flow impedance continually declined during each constant injection pressure phase, as did the rate of water loss. At the conclusion of the test, the flow rate at the production well was approximately 70% of the fluid injection rate.

Subsequent experiments have demonstrated that most of the "apparent" water loss in this reservoir is due to storage of water in the microcracks of the reservoir rock and at its periphery (Brown and Robinson 1990). As these fill up, water consumption declines under conditions of constant pressure, as illustrated in Figure 3.

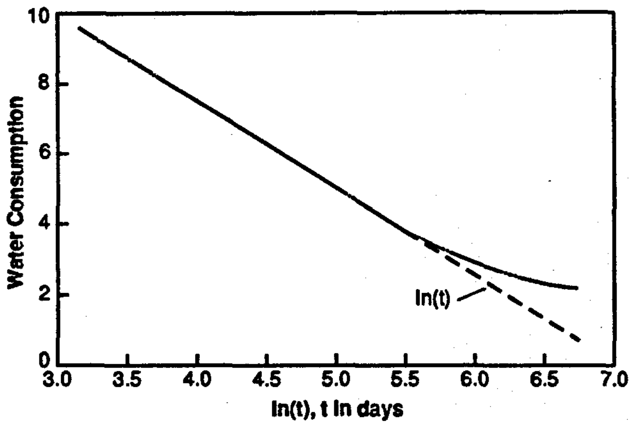

Figure 3. Water Consumption in the Phase II HDR Reservoir at 15 MPa Pressure.

During the period 1987-1991, preparations have been underway for a long-term flow test (LTFT) of the Phase II HDR reservoir. In 1987, repairs were made to the production wellbore to assure that it has the integrity to withstand extended circulation tests (Dreesen, et al., 1989). Since 1988, we have been building a surface plant for the LTFT. While the details of the design and construction of this plant are discussed in a separate paper, it is important to note here that it is being constructed to industrial standards which should permit continuous, reliable operation and assure that the plant itself does not become a stumbling block in the conduct of the LTFT.

Future Plans for HDR Development

The Long-Term Flow Test (LTFT)

The primary purpose of the LTFT is to demonstrate that energy at useful temperatures can be extracted from the Phase II HDR reservoir over an extended period of time. If successful, it will provide an example of the potential of HDR and a benchmark for the development of future HDR systems.

The objectives of the LTFT fall into three broad categories. Technical goals are associated with evaluating the useful thermal lifetime of the reservoir, quantifying water consumption rates, measuring production fluid flow and temperatures, and determining the power production of the reservoir. Operational goals are directed toward understanding the important operating parameters of the system including maintenance requirements, ongoing costs, and other relevant information. Finally, the scientific goals of the test are aimed at increasing our levels of understanding in seismology, tracer technology, and underground reservoir engineering.

The detailed protocol for the conduct of the LTFT is still being developed, but the general schedule of operations will include a short start-up/shakedown period to verify system operating parameters, an extended term of operation under conditions of constant injection pressure, and a series of short experiments toward the end of the test to explore the potential of some novel techniques for operating HDR systems. The term of the LTFT will be one to two years contingent upon the funding provided by the Department of Energy. While the physical plant needed to conduct the test will be in place by late summer of 1991, the actual start-up date of the LTFT will again be subject to funding considerations and time constraints imposed by the necessity to put in place contracts for operating personnel, services, and fuel.

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 monthly. Other logging schedules 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 allow us to study 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 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 the 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.

If significant thermal drawdown of the Fenton Hill Phase II reservoir takes place during the LTFT, modifications in the design concepts and operational schemes for HDR reservoirs, as well as additional experimental work, may be required prior to building a second HDR plant. Rapid temperature decline or severe and prolonged operational problems during the LTFT are not anticipated based on all our experience with HDR heat mines to date. Were they to occur, it would force a rethinking of our basic ideas about HDR heat mining.

The Second HDR Heat Mine

The construction of a second HDR heat mine at another site is extremely important to prove that HDR can be developed in a variety of locations and that the success achieved at Fenton Hill represents the general case and not just a fluke of nature. In addition, the second site must be more oriented toward economic considerations than has been the case at Fenton Hill. While the next HDR facility does not have to be strictly competitive with fossil fuel power plants, it should clearly demonstrate that HDR can be an economic energy source. In order to do this it will be necessary to produce and market power on a regular and continuous basis over a period of years. In effect, the second HDR facility will be the pilot operation for commercial HDR plants of the future.

A number of factors of more or less equal importance must be considered in selecting the second HDR site. Resource quality is, of course, a paramount consideration. At this stage of its development, any hope for economic exploitation of HDR lies in reaching the resource at a reasonable cost, and this can only be done today in high gradient areas. The details of the local geology are also extremely important, and for the same basic reason. Insurmountable technical difficulties in drilling, completion, or reservoir creation could result in failure of the project and lead to a major setback in the acceptance of HDR technology by the energy community. Excessive water consumption could also make continuous operation impossible and cast the economics in an unfavorable light.

Political considerations will play a key role in the selection of the second HDR site. A receptive political climate will speed the process of obtaining the required permits and local cooperation will be needed to obtain the water to run the facility. Finally, marketing factors will be very important. Since the production and sale of electric power is primary consideration in the development of another HDR site, proximity to a market for such power is essential.

The Clearlake, California HDR Initiative;

At this time, perhaps the most promising location for development of a second HDR facility is the area of Clearlake, California. Located just to the north of The Geysers geothermal area, Clearlake has many of the qualities desired in a second site. Numerous dry geothermal wells have been drilled in the vicinity, and there is no doubt that a resource of extremely high quality exists there. Generally, thermal gradients are on the order of 100°C/km, among the highest in the country.

A significant amount of general information about the HDR resource potential at Clearlake has already been reported (Burns and Potter 1990). Los Alamos is currently working with the City of Clearlake, Lake County, and the California Energy Commission to investigate the HDR potential of the region in more detail. The relationships being developed in connection with this effort will provide a good basis for rapid solution of political questions regarding HDR at Clearlake as they arise. In addition, there is a potential market for power in the area. San Francisco is less than 100 miles away, and production declines at The Geysers may result in locally available transmission capacity.

The most important question regarding the Clearlake area is the local geology. The rock at depth is a mixture of greywacke, chert, greenstone and andesite, rather than granitic as at Fenton Hill, and the area is highly faulted. In addition, as in many parts of the west, water supply may be a problem. As part of the current effort at Clearlake, the local geological regimes will be documented and the most promising site for further investigation of HDR development selected. There is also a possibility of obtaining treated municipal effluent as a source of water for a commercial HDR facility. Pending the outcome of the current study, Clearlake may or may not be the ideal second site for an HDR plant.

Advanced HDR Systems

Profitable operation of commercial HDR plants will depend on implementing the most economic mode of operation that is safe, practical, and environmentally sensitive. Work to date has concentrated on simply demonstrating the HDR is technically feasible, but in the future enhanced modes of production must be developed to make the technology as efficient and reliable as possible. A number of techniques for increasing the efficiency of operation of an HDR plant have been conceived and evaluated in a preliminary fashion on paper (Robinson and Brown 1990, Robinson 1990) but none has yet been tested in practice.

Table 2 provides a synopsis of the important advantages and disadvantages associated with a number of possible ways of operating an HDR system. Running an HDR facility under conditions of reservoir stability represents the base case. This approach is technically the most conservative and it and minimizes water consumption. It may be far from the most economic method of operating an HDR reservoir, however.

Table 2

Possible HDR System Operational Modes

Operational Mode	Important Advantages	Significant Disadvantages
• Non-Extensional (Stable Reservoir)	• Demonstrated • Minimal Water Use	• Limited Energy Production
• Reservoir Extension	• Increased Energy Production • Demonstrated	• Increased Water Use • Reservoir Growth • Increased Pumping Costs
• High Backpressure	• Lower Pumping Costs	• Not Yet Demonstrated
• Multiple Production Wells	• Greatly Increased Energy Production • Minimal Water Use • No Reservoir Growth	• Higher Capital Costs • Higher Pumping Costs • Not Yet Demonstrated
• Cyclic	• Eliminates Short Circuit Problems • Provides Peaking Power	• Intermittent Energy Production • Not Yet Demonstrated

Under conditions of reservoir extension, energy production may increase significantly but so do pumping costs and water consumption. Modeling has indicated that applying a high backpressure at the production wellhead should lead to lower pumping costs while not deleteriously affecting energy production, although at a slight additional penalty in water consumption. Both of these production strategies will be experimentally investigated during the LTFT or in related reservoir tests.

Perhaps the most promising technique for increasing the efficiency of HDR systems is the 3-well design. In this concept, two production wells are utilized, one on either side of the injector. Each well not only produces energy, but also functions as a pressure relief device to prevent seismic growth. The net effect is to increase production very significantly while virtually eliminating seismic growth of the reservoir and attendant water consumption.

Unfortunately, funds are not currently available to build a three-well HDR system, but experiments to simulate multi-production well systems will be carried out as part of the LTFT. While these will not fully demonstrate the potential advantages of multiple production wells they should provide enough information to determine whether or not further investigation of this concept is warranted.

Yet another technique for operation of an HDR heat mine entails a cyclic schedule wherein the production well is alternately flowed and shut in. During the shutin period the reservoir would be in a charging mode with an anticipated increase in temperature and pressure of the geofluid. In the production phase, this stored fluid would be brought to the surface and utilized. In a two well system, this mode of operation might be used for peaking power applications or to provide a continuous energy supply when used in conjunction with other intermittent energy sources such as solar or wind.

Short circuits, in which the bulk of the geothermal fluid flows rapidly from the injection well to the production well, are considered a major potential problem in HDR systems because short circuiting fluid will not remain in contact with reservoir rock long enough to efficiently extract its thermal energy. While no signs of short circuiting have been seen at in the Phase II HDR reservoir, they apparently have been observed in HDR circulation tests in a shallower reservoir in the United Kingdom (Parker 1989). During cyclic operations, the geofluid is stored in the HDR reservoir some definite period of time as an inherent part of the operating procedure. By employing cyclic operating techniques, it may thus be possible to eliminate the potential for production fluid temperature declines due to short circuiting without imposing significant operational penalties. No field tests of cyclic operation of an HDR system have yet been carried out, but we plan to investigate this concept near the end of the LTFT.

When fully developed commercially, HDR heat mines may consist of systems with multiple production wells, each operated in a cyclic mode but on schedules designed to provide a constant supply of energy. In this type of system, continuous injection could be coupled to steady production from a network of producing wells.

Summary

The technical feasibility of HDR heat mining has already been proven in field testing. The potential for future geothermal development of the HDR resource as an economically competitive source of energy with negligible environmental impact is extremely large.

A long-term flow test (LTFT) of the Phase II HDR system at Fenton Hill, NM, is scheduled to begin this year. Its primary purpose is to demonstrate that energy can be produced from HDR on a sustainable basis.

Development of a second HDR heat mine will be based on what is learned at Fenton Hill during the LTFT. The second facility will be designed to serve as a model for commercial HDR plants. A large number of operational strategies which may increase the production capacity and efficiency of HDR heat mines have yet to be investigated. These may have a significant impact on the design and operation of future HDR systems.

The national energy strategy predicts that by 2030, geothermal sources will account for about 3% of electric power production in the U.S. (USDOE 1991). It is difficult to conceive of this level being achieved without the development of HDR. The march toward orderly development of HDR technology must be strong and deliberate, and the necessary resources must be committed to do the job. Such an investment will yield substantial and timely returns both financially and in the form of national energy security.

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