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TITLE:

HOT DRY ROCK GEOTHERMAL ENERGY MOVING TOWARDS PRACTICAL APPLICATIONS

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Hot Dry Rock Geothermal Energy
Moving Toward Practical Applications

Introduction:

It is generally known that the temperature of the earth increases with depth. The geothermal energy available in the form of heat stored in rock within reach of the surface is vast in quantity and is widely distributed (Armstead and Tester 1987). In some places, water has penetrated this hot rock and become heated itself. This hot water may find a way back to the surface and manifest itself in the form of hot springs, geysers, or fumaroles, or it may remained trapped within the hot rock. Man has utilized geothermal energy from these natural geothermal sources for heating and bathing for centuries, and many hot springs are world-famous. More recently, drilling technology has been used to tap these geothermal reservoirs of hot water and steam on a larger scale. Today, over 2,500 MW of electricity is produced from geothermal energy in the United States alone (McClarty and Reed 1992) and the geothermal electric power industry is rapidly developing in many parts of the world. Only a tiny fraction of the hot rock at accessible depths is in contact with mobile water, however. Therefore, most of the geothermal resources of the world cannot be extracted using conventional technology.

In 1974, a patent was issued to the Los Alamos National Laboratory describing a radically new method for recovering the earth's geothermal energy (Potter et al.). This technique entails the creation of an artificial reservoir deep underground to gain access to the vast amounts of geothermal energy resident in the hot dry rock prevalent at depth over most of the world. This Hot Dry Rock (HDR) technology for mining the heat of the earth vastly increases the scale of potential geothermal energy development and promises to make geothermal energy as important in the 21st century as energy from fossil fuels is today.

The HDR Process of Mining Heat

HDR technology provides a method for extracting and utilizing the heat of the earth to provide abundant, clean energy. The process begins with the drilling of a well to a depth sufficient to reach hard, crystalline rock of the desired temperature. After lining the well and isolating a section of the wellbore at the target depth, water is pumped into the well under pressures high enough to open the natural joints in the rock. As the water flows into the joints, an artificial geothermal reservoir is created consisting of a relatively small amount of water dispersed in a large volume of hot rock. One or more additional wells are subsequently drilled into the man-made reservoir at some distance from the first, completing the heat mine. Figure 1 shows an idealized drawing of a HDR heat mining facility.

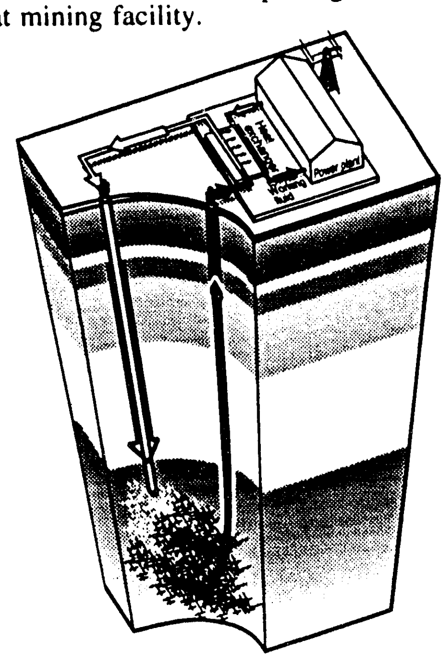

Figure 1. An HDR heat mining facility. Water is pumped down an injection well under high pressure. The pressure forces it to flow through the HDR reservoir to the production well and back to the surface. It extracts geothermal energy from the hot rock as it passes through the reservoir At the surface, the thermal energy of the hot water is transferred to a second fluid and the water is recirculated through the hot rock to mine more heat.

The system is operated by injecting water into one wellbore, the injection well, under pressure sufficient to push it through the artificial geothermal reservoir to the other well(s), the production well(s). The water becomes heated or even superheated as it passes at high pressure through passages in the hot rock. Upon reaching a production wellbore, the pressurized water returns to the surface. There, its accumulated thermal energy is extracted. The same water is then recirculated through the injection well to mine more heat. A heat exchanger may be employed on the surface to transfer the thermal energy to another working fluid. In this case, there is no direct contact between the circulating water and the world external to the HDR system and nothing except waste heat is released to the environment.

The Fenton Hill, New Mexico HDR System

The worlds first HDR reservoir was developed during the late 1970's and operated intermittently for a period of about two years (Dash 1981). It provided a concrete demonstration of the feasibility of mining the thermal energy resident in hot rock at depth. Between 1980 and 1991, a larger, deeper, and hotter HDR reservoir, designated the Phase II Reservoir, was created at Fenton Hill and a practical surface plant was constructed to allow operation of the facility as a closed-loop system on a continuous basis for long periods of time.

The Phase II HDR Reservoir

A schematic drawing of the Phase II HDR reservoir and its associated wellbores is shown in Figure 2.

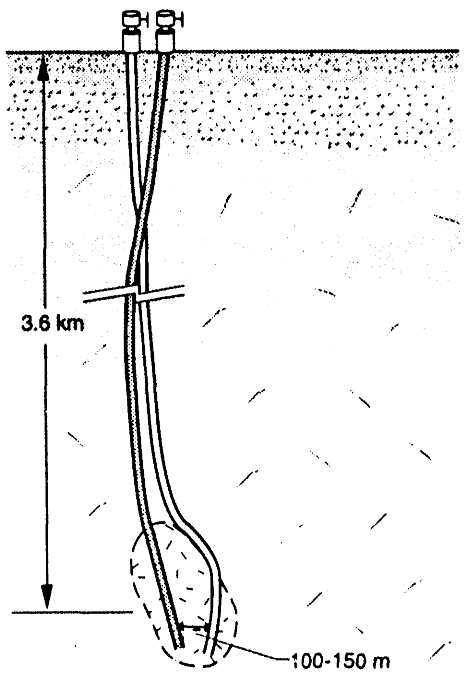

Figure 2. A view of the HDR reservoir at Fenton Hill, NM. The reservoir is centered at a depth of about 3.6 km (12,000 ft) and is tilted somewhat from the vertical. The two wellbores are separated by an average distance of about 100 m (300 ft) along their trajectories through the reservoir.

The creation of this reservoir entailed six years of work and an extensive learning process. As finally constituted, it comprises a flow-connected rock volume of very roughly 16 million cubic meters (750 million cubic feet) penetrated by two wellbores which are an average of about 100 meters (300 feet) apart. It is a flattened ellipsoid with approximate dimensional ratios on the order of 1:2:3. As illustrated in Figure 2, the reservoir is oriented about 30°

from the vertical and is centered at a depth of about 12,000 ft. The reservoir cannot, of course, be directly observed. Most of the information quoted above has been derived by the detection and determination of the locations of the large number of microearthquakes generated during formation of the reservoir, by analyses of the flow patterns of tracers injected into fluid flowing through the reservoir, and/or by hydromechanical studies of water consumption during pressurization of the reservoir under a variety of scenarios (Robinson and Kruger 1992). Taken in total, these practical scientific techniques provide a good picture of the nature of the Fenton Hill HDR reservoir. Their extensive development and application at Fenton Hill have provided the tools needed to make it possible to proceed with the creation of future HDR systems on a much more straightforward and reliable basis.

The Surface Plant

A flow diagram of the surface plant at Fenton Hill is shown in Figure 3.

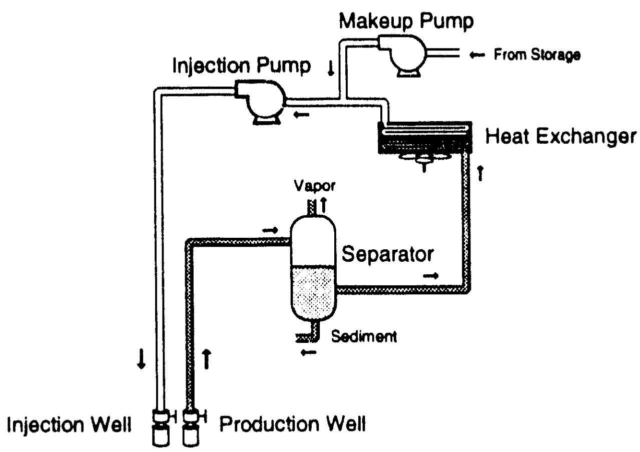

Figure 3. A flow diagram of the surface plant at the Fenton Hill HDR facility. During closed-loop operation, the circulating water is never exposed to the outside environment.

This facility was constructed to power plant standards. It was designed to allow energy to be extracted from the reservoir on a continuous basis with provisions for monitoring all the important parameters associated with the operation.

The plant consists of high-pressure and low-pressure sections. The injection pump, piping to the injection wellhead and the injection wellhead itself constitute the high pressure part of the plant. All components in this section have been designed to operate at pressures of up to 35 MPa (5,000 psi). The injection pump provides the sole motive force for circulating water through the loop. It can inject water at pressures of more than 28 MPa (4,000 psi). The injection wellhead includes a variety of safety and control valves (not shown in Figure 3) to permit routine and specialized fluid circulation operations, as well as wellbore interrogation.

The production wellhead is similarly configured. A series of control valves just downstream of the production wellhead reduce the pressure of the circulating water to 6.9 MPa (1,000 psi) or less in order to meet the operating specifications of the low pressure side of the plant. The low pressure section components include a particle/gas separator, a heat exchanger, make-up water pumps and associated piping. The particle/gas separator was designed to clean the fluid of entrained gases and sediments picked up during its passage through the reservoir. Experience has shown the quantities of these contaminants to be essentially nil at Fenton Hill so the separator has served no real function in practice.

The heat exchanger extracts the energy from the circulating fluid and wastes it to the atmosphere. This component would be replaced by an electricity generator in a facility designed for the production of electric power. The make-up water pumps supply additional water to replace the small amount lost in circulation through the underground reservoir. Two types are installed. Low pressure/high volume pumps can be used for filling the reservoir orrapidly changing operational conditions while high pressure/low volume pumps are employed when the reservoir is operating at steady-state conditions in a closed-loop mode.

Long-term Flow Testing During 1992-1993

A number of flow tests conducted in the United States, Japan, and England have demonstrated that HDR technology can be used to extract geothermal energy (Dash 1989, Yamaguchi et al. 1992, Parker 1989). These tests provided valuable information about the performance of HDR reservoirs, but they were invariably designed to attain specific experimental objectives rather than assess the overall performance of a practical HDR energy system on a long-term basis. In fact, until the completion of the Fenton Hill surface plant in 1991, no facility existed which combined a reservoir capable of sustained energy production at temperatures high enough to be used in electricity generation with a surface facility designed for routine operation. The Fenton Hill system provided the opportunity to move HDR technology from the field-laboratory stage to the point of pilot demonstration. The goal of the long-term flow testing effort of 1992-1993 was to prove that a HDR reservoir could be operated routinely over an extended time period to produce useful amounts of energy on a continuous basis.

The Flow Test Protocol

Upon the advice of an industrial review committee, a long-term flow test (LTFT) was instituted that simulated as closely as possible the anticipated operation of a commercial HDR energy production plant. The fundamental control variable was the injection pressure, which was set at the highest level that could be achieved without inducing growth of the reservoir, as indicated by the onset of microseismic activity and a sharply increased rate of water consumption. To the extent possible, a constant injection pressure was maintained on a 24-hour-a-day basis throughout the term of the testing.

In practice. the injection pump delivered a constant volume of water at any particular setting and the injection pressure was maintained by carefully controlling the injection rate. Changing conditions within the reservoir made it necessary to adjust the settings on the injection pump periodically, but the magnitude of the adjustments required was small in relation to the overall volume of fluid being injected. At times, power failures or maintenance requirements led to brief shutdowns of the system. On these occasions, the system was brought back to the standard operating conditions as rapidly as possible after it was restarted.

The original plan called for a one-year, steady-state flow test, but operating and funding problems led to two phases of full-scale flow testing with a period of sub-optimal testing between them. The first phase of the test lasted for 112 days and was terminated by a breakdown of both injection pumps within a two day period. These diesel powered, reciprocating pumps had been operated on an alternating ten-day schedule so both had seen about the same amount of service This failure was subsequently shown to be due to fabrication problems with the pump units rather than any factors related to their application, but several months of operation with lower-capacity pumps incapable of sustained operation ensued before an adequate replacement injection pump could be procured and installed.

The pump used for the second steady-state phase of the test was an electrically driven centrifugal unit. It operated with 100% reliability for the 65 days of the second phase of the LTFT. While two diesel pumps were needed so that each unit could be periodically shut down and serviced without interrupting the test, the electric pump was virtually maintenance free. It should be mentioned, however, that the electric pump lacked the operating flexibility of the diesel pumps and it could be employed only because the test operating conditions had been firmly established with the diesels prior to and during the initial part of the LTFT.

Results of Recent Flow Testing

Operating data from the two steady-state phases of the LTFT are summarized in Table 1.

Table 1. Operating Parameters During the Two Phases of the LTFT

Phase	One	Two
Measured Performance Period	July 21-29 1992	April 12-15 1993
Injection Conditions		
Flow Rate, l/s (gpm)	6.74 (107)	6.49 (103)
Pressure, MPa (psi)	27.3 (3960)	27.3 (3960)
Production Conditions		
Flow Rate, l/s (gpm)	5.65 (89.7)	5.70 (90.5)
Backpressure, MPa (psi)	9.7 (1400)	9.7 (1400)
Temperature, °C (°F)	183 (361)	184 (363)
Water Loss		
Rate, l/s (gpm)	0.79 (12.5)	0.46 (7.3)
Percent	11.7	7.0

Note: A small amount of injected water returned to the surface through a leak in the injection wellbore.

It is clear that in spite of several months of sub-optimal operations, it was possible to reproduce the conditions of the first phase of the test during the second phase of the test to a remarkable degree. The only notable difference was the decline in water consumption, and, in fact, this decline was simply the continuation of a trend noted throughout the entire flow-test period. As the longest steady-state demonstration of the operation of an HDR system involving energy production at commercially viable temperatures, the LTFT provided significant new information about a number of issues critical to the practical implementation of HDR technology. The most important results are discussed below:

Reservoir Thermal Stability

The data of Table 1 indicate that there was no decline in the temperature of the fluid produced at the surface over the course of the flow-test period. At several points during testing, the production temperature was measured at depth by conducting a wire-line log of the production well while circulation was maintained. Figure 4 compares the temperature profiles obtained from three such logs.

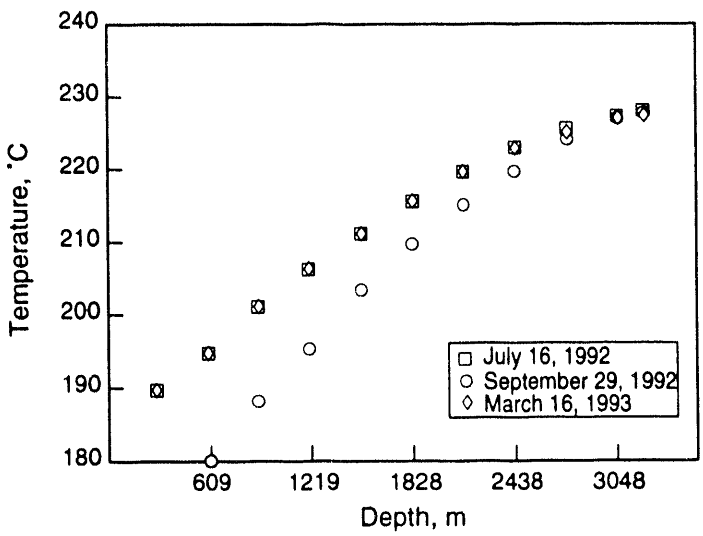

Figure 4. Temperature profiles obtained from logging runs during recent flow testing. The temperature remained constant at the deepest part of the wellbore but the heat lost to the surrounding rock was greater in September when the flow rate up the wellbore was lower.

In all cases, the temperature measured at 10,800 ft, the depth which marks the top of the reservoir, was essentially the same. The logs show that energy is lost to the surroundings as the water travels to the surface. If the water travels more slowly, more energy is lost. For this reason, the log conducted in September 1992, during a period of sub-optimal pumping and lower flow, shows the same temperature at depth as the other two but a lower temperature at the surface.

As part of the reservoir surveillance effort, tracer materials were periodically injected with the circulating fluid. An analysis of the tracer return at the production well provided a snapshot of the fluid flow through the reservoir at that point in time. The results of three of these tracer tests are shown in Figure 5.

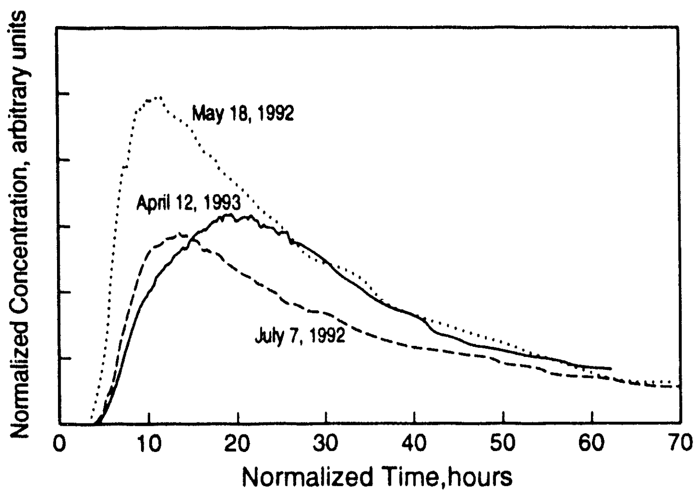

Figure 5. Results of tracer tests conducted during recent flow testing. The time to initial appearance of the tracer and to the point of maximum return became longer as shorter, ostensibly cooled, flow paths closed and longer, more circuitous flow paths through the reservoir rock developed.

Remarkably, the tracers took longer to appear at the production well as the testing proceeded. The time to the point of maximum tracer return also lengthened. In effect, the tracer material (and by implication the circulating water) was taking longer and longer to get through the hot rock reservoir, indicating that more of the fluid was traveling across the reservoir via longer flow pathways and the shortest, perhaps most rapidly cooled, flow paths were closing off. This is exactly the opposite of the typical behavior in which water, once having found a route through a medium, continually enlarges that pathway. The reason for this seemingly anomalous behavior has not been determined but it may be related to fluid viscosity increases in the cooled pathways. In any event, this strong tracer evidence suggests that the reservoir is self-sustaining to at least some degree since the flowing fluid is continually gaining access to new hot rock within the reservoir.

Water Consumption

As noted earlier, the amount of water apparently lost in transit through the underground reservoir declined throughout the test period. Previous static tests had indicated that water which appeared to be "lost" was actually stored in microcracks in the reservoir rock and in the unfractured rock mass at the periphery of the reservoir (Brown 1991). As these rocks become saturated at any imposed pressure, the water consumption would be expected to decline. This is exactly what seems to have happened during the LTFT. At a final level of only 7% of the injected volume, the water consumption rate during the LTFT was markedly lower than that seen in any previous HDR flow test. These results have demonstrated that water consumption will not be a major problem in the long-term operation of properly-designed HDR systems.

Environmental Effects of HDR Plant Operation

The chemistry of the circulating fluid was continually monitored during the flow-test period. As shown in Table 2, the composition and concentration of the dissolved species remained essentially constant throughout the test.

Table 2. Dissolved Species in HDR Fluid

	Concentration in Production Fluid (parts per million by weight)	
Component	April 15, 1992	March 15, 1993
Chloride	1220	1002
Sodium	1100	899
Bicarbonate	552	556
Silicate (as Si O2)	458	402
Sulfate	285	342
Potassium	95	91
Boron	47	34
Calcium	19	17
Lithium	19	15
Fluoride	14	13
Bromide	6.5	5.1
Arsenic	3.8	3.5
Iron	1.0	0.3
Aluminum	0.9	0.8
Ammonium	0.8	1.3
Strontium	0.8	0.8
Barium	0.2	0.2
Magnesium	0.2	0.2
Sulfide	0.2	0.9
Bisulfate	<0.3	
Total Dissolved Solids	3845	3388
Gases		
Carbon Dioxide	2747	1830
Nitrogen	58	45
Oxygen	0.25	1.38
Hydrogen Sulfide	0.45	0.45

The levels of dissolved gases, principally carbon dioxide, remained low enough so that all the gas would stay dissolved in the circulating fluid at the pressures maintained in the loop. In effect, there were no environmental emissions except waste heat when the system was operated under the standard closed-loop conditions.

One important gas often encountered in underground fluids is hydrogen sulfide. This extremely toxic compound is heavier than air and tends to settle in low spots if it is released. Although signs posted at the Fenton Hill site warn of the potential danger from hydrogen sulfide and a number of automatic alarms would signal its presence at a level well below that at which it would present any danger, the concentration of hydrogen sulfide in the circulating fluid at Fenton Hill has always been extremely low (typically less 1 ppm). Even in the event of an unexpected release to the atmosphere, the risk arising from this low level of hydrogen sulfide would be very small.

The dissolved solids found in the circulating fluid were generally those characteristic of normal slightly saline fluids: mostly sodium, magnesium , calcium, and chloride, but with small amount of other elements, such as arsenic, which tend to be present in crystalline rock. At a total solids content of about 0.4%, the Fenton Hill fluid was nearly an order of magnitude less salty than the ocean which contains about 3% salt.

Net Energy Production

Thermal energy was regularly produced during the LTFT at a rate of about 4 thermal MW. This is approximately 6.3 times the thermal energy content of the diesel fuel and electricity consumed in running the system during the first phase of the LTFT. In other words, the heating value of the fuel used to operate the plant was increased by a factor of more than six by using it to pump geothermal energy to the surface rather than using it directly as a heat source.

In the second phase of the LTFT, electric power was used to run all parts of the surface plant. While no electricity was produced, the electric generating potential of the facility can be calculated by assuming a thermal-to-electric conversion efficiency. For conversion rates on the order of 10-15% (typical values for geothermal fluids at these temperatures) the calculated excess electricity production potential is 50-130%. This means that, if operated as a electric power production plant under the conditions prevailing during the LTFT, the Fenton Hill HDR facility would use about 43-67% of the power produced simply to run the system. While this is a high "parasitic" power load, it is important to note that Fenton Hill was developed solely for research and development. The recent flow testing has shown that net power production from an HDR facility is readily achievable even in the absence of production efficiency as a consideration in plant design.

The Future of HDR Development

The uniformly positive results obtained during the recent flow-testing program at Fenton Hill have provided a solid demonstration of the potential of HDR to provide clean, efficient, energy for the 21st century. Some of the important concerns regarding implementation of the technology, such as water consumption rates, have been laid to rest, while others, such as the thermal lifetime of the resource, have been at least partially allayed.

On the basis of the recent flow-test results, the United States Department of Energy recently issued a solicitation eliciting the interest of private industry in the development of a facility to produce and market energy from HDR. This pre-commercial HDR power plant will be designed from the start with operational efficiency in mind. A plant with a generating capacity of 1-25 MW is envisioned, small enough to keep the total capital commitment within reasonable bounds but large enough to benefit from the economies of scale. With government participation to help reduce the capital liability and with engineering design aimed at a more efficient plant in order to get greater excess energy generation than could be achieved at Fenton Hill, it may be possible to operate a pre-commercial HDR power plant with a very favorable cost structure.

The joint industry/government venture will provide a means for documenting the capital costs involved in developing HDR resources for power production. If constructed at a site geographically and geologically different from Fenton Hill, the facility will also help demonstrate the practicality of utilizing HDR resources in a variety of geological and geographical settings. Perhaps, most important, the revenue generated in operation of the plant will provide the financial incentive to operate the plant for several years or even decades, thus building the kind of track record required to convince even the harshest skeptics of the value of HDR technology.

Summary

The thermal energy present in hot rock at depth is a vast resource which has so far been tapped only in those unusual locations where natural fluids exist to transport that energy to the surface. For the past twenty years work has been underway at the Los Alamos National Laboratory to develop the technology to access and recover the heat present in rock which is hot but contains no natural mobile fluid. The world's first plant capable of sustained production of geothermal energy from HDR was completed in 1991. This facility combined an artificial geothermal reservoir of sufficient size and high enough temperature to deliver large amounts of useful energy with a surface plant built to power industry standards and capable of sustained, routine operation.

During the past two years, extended testing at Fenton Hill has demonstrated that energy can be extracted from HDR on a continuous basis. Thermal energy was produced continuously at a rate of about 4 MW in two test phases lasting 112 and 55 days, respectively, and intermittently for a period of 7 1/2 months between the continuous test segments. Temperature measurements at the surface and at depth indicated no decline in the average discharge temperature of water from the reservoir over the span of the test. In fact, tracer testing indicated that access of the circulating water to the hot reservoir rock improved as the test proceeded.

Other observations during the test were equally encouraging from the standpoint of the practicality of the technology: Water losses in circulation through the underground reservoir declined steadily throughout the test, reaching a level of only 7% of the injected volume by the time the test was terminated. Measurements showed that significantly more energy was extracted from the HDR reservoir than was required to operate the Fenton Hill circulation system and its supporting equipment. There were no atmospheric emissions during normal operations except waste heat. Dissolved gases and solids remained at low and essentially constant levels. Finally, with the exception of a major pump failure for reasons unrelated to HDR technology, the plant operated in a highly reliable manner.

The promising results of the recent flow testing program have set the stage for the further development of HDR technology toward the point of commercial implementation. The United States Department of Energy is seeking industry participation in a joint venture to construct a facility to produce and market electricity generated from HDR energy. This pre-commercial plant would generate revenue for its operator and at the same time convincingly demonstrate that HDR can be a clean, practical energy source. The stage would then be set for HDR to play a major role in supplying clean energy to America and the world in the 21st century.

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