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PROGRESS IN MAKING HOT DRY ROCK GEOTHERMAL ENERGY A VIABLE RENEWABLE ENERGY RESOURCE FOR AMERICA IN THE 21ST CENTURY

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ABSTRACT

An enormous geothermal energy resource exists in the form of rock at depth that is hot but essentially dry. For more than two decades, work has been underway at the Los Alamos National Laboratory to develop and demonstrate the technology to transport the energy in hot dry rock (HDR) to the surface for practical use. An HDR heat mine is developed by applying hydraulic stimulation techniques to open pre-existing joints in hot, crystalline rock and thereby create a fully-engineered geothermal reservoir. In operation, pressurized water is injected into the opened joints and is heated by contact with the reservoir rock. Upon reaching a production well, located at some distance from the point of injection, the water returns to the surface where its useful thermal energy is extracted. The same water can then be recirculated to mine more heat. In this closed-loop system, the sole motive force is a high-pressure pump located directly upstream from the injection wellhead.

During the 1980's, the world's largest, deepest and hottest HDR reservoir was created at the Fenton Hill HDR test facility in northern New Mexico. The reservoir is centered in rock at a temperature of about 460°F at a depth of about 11,400 ft. After mating the reservoir to a fully automated surface plant, heat was mined at Fenton Hill for a total period of almost a year in a series of flow tests conducted between 1992 and 1995. These tests addressed the major questions regarding the viability of long-term energy extraction from HDR.

In all of the flow testing operations, water was circulated through the reservoir at rates of 100-150 gpm and consistently returned to the surface at temperatures in excess of 360°F. The produced heat was released to the atmosphere via an air-cooled heat exchanger, and the cooled water was then returned to the injection pump to be recirculated through the reservoir. Auxiliary feed pumps provided makeup water to this closed-loop system to replace the water lost in the circulation process.

No thermal drawdown of the HDR resource was observed over the course of the testing. In fact, tracer testing indicated that new flow paths through the reservoir were continually developing and that the contact area between the circulating water and the hot reservoir rock increased as testing proceeded. The fraction of the injected water lost during circulation through the reservoir decreased with time, eventually declining to about 7%. Geochemical measurements indicated persistently low levels of dissolved solids and gases in the circulating fluid. Because the entire system was pressurized, nothing except waste heat was released to the atmosphere during the closed-loop testing.

The steady-state flow tests at Fenton Hill showed that energy can be produced from an HDR reservoir on a routine basis and that there are no major technical obstacles to implementation of this heat mining technology. Additional brief special flow tests also demonstrated that the energy output from HDR systems can be rapidly increased in a controlled manner to meet sudden changes in power demand.

Because they are fully engineered, HDR reservoirs can be well-characterized and optimized for each individual application. The confined nature of HDR reservoirs and the ability to rapidly recharge and discharge them provides a high level of operational flexibility. Finally, HDR reservoirs may be able to accept a feedstock consisting of a fluid such as treated sewage or industrial waste and convert it to high-quality water while producing electricity at the same time. These unique characteristics of HDR energy systems should enable HDR technology to play a significant role in the clean energy world of the 21st century.

INTRODUCTION

An abundant supply of energy exists virtually everywhere in the world in the form of geothermal heat in rock at depth. In a relatively few locations, mobile fluid naturally in contact with hot rock can be tapped to bring geothermal energy to the surface. Such hydrothermal resources are used to generate electric power at about 20 sites in the western United States and at a number of other locations around the world. More than 5,000 MW of geothermal electricity-generating capacity is in place today, and power production from geothermal energy is increasing rapidly in countries such as The Philippines and Indonesia. By far the largest amount of geothermal energy is found, however, in rock that is hot but is not in contact with the mobile fluid needed to bring its thermal energy to the surface.

Attempts to recover useful amounts of energy from this large HDR resource, that comprises more than 99% of the geothermal energy at attainable depths in the earth's crust, have been underway in the United States and elsewhere for more than 20 years. Remarkable progress has been made in bringing HDR technology from the raw concept described in a patent issued to the Los Alamos National Laboratory in 1974 (Potter, et al) to the stage of practical demonstration. The major technical issues have been resolved. The remaining barriers to widespread implementation of HDR technology for energy production are primarily economic and financial. In the face of low domestic energy prices, it has not been possible so far to offset, with the promise of a sufficient financial reward, the risks inherent in implementing this promising technology in today's highly competitive energy market.

THE HDR PROCESS

Advanced HDR research and development programs are now underway in the United States, Japan, and the European Community. A number of other nations such as Australia and Mexico are in the process of developing HDR projects or assessing their HDR resources. All modern HDR work is based on the relatively simple concept described in the Los Alamos patent: Formation of a fully-engineered geothermal reservoir in hot, crystalline rock by the application of hydraulic fracturing techniques, and the subsequent circulation of water through that engineered reservoir to mine the thermal energy from the hot rock.

To develop an HDR reservoir, a well is first drilled into hot, crystalline rock. Water is then injected at pressures high enough to open the natural joints in the rock. The water flows into the open joints and an engineered geothermal reservoir is thereby created. The reservoir consists of a relatively small amount of water dispersed in a large volume of hot rock. The dimensions and orientation of the reservoir are determined by the local geologic conditions, while its ultimate volume is a function of the injection pressures applied and the duration of the hydraulic fracturing procedure employed to create it. Seismic techniques are used to follow the growth of the reservoir and to assess its location and approximate dimensions (House, 1987). Using the seismic data as a guide, one or more additional wells are subsequently drilled into the engineered reservoir at some distance from the first well. In a properly engineered HDR reservoir, there are a number of fluid-flow pathways between the injection and production wellbores.

Operation of an HDR heat mine is extremely simple: A high-pressure injection pump is used to circulate water through the engineered reservoir in a closed loop as shown in Figure 1.

The injection pump provides the sole motive force for moving the water continuously around the loop to collect energy from the reservoir and deliver it to a power plant on the surface. The hydraulic pressure applied via the injection pump

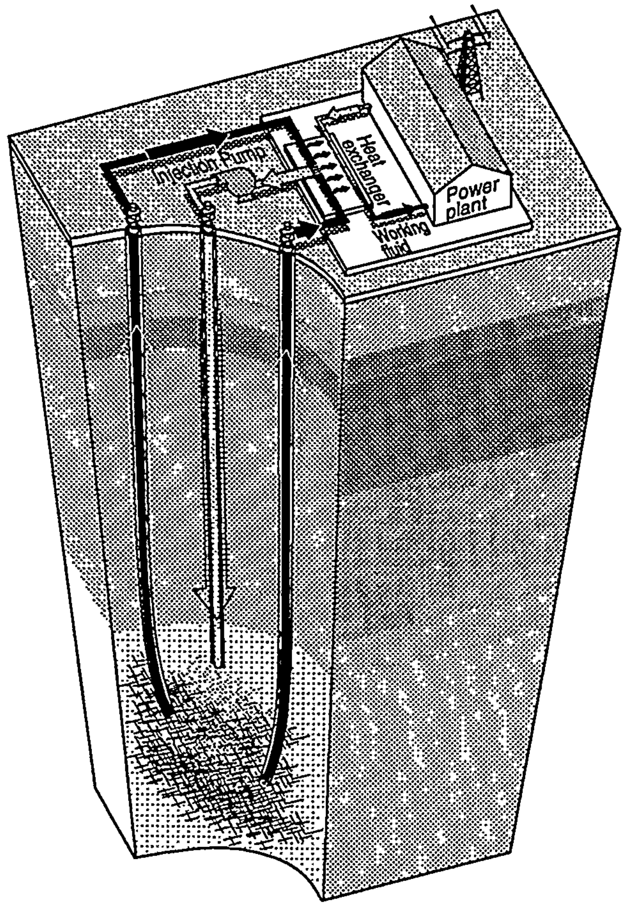

FIGURE 1. WATER IS CIRCULATED THROUGH AN HDR HEAT MINE IN A CLOSED LOOP

also serves to keep the joints within the reservoir propped open. The operating parameters applied to the injection pump thus greatly affect both the flow rate through the reservoir and its instantaneous fluid capacity. By using a combination of injection and production control measures, an almost limitless variety of operating scenarios may be employed to mine the heat from an HDR reservoir.

THE UNITED STATES HDR PROGRAM

The First HDR Heat Mine

In the United States, field work on HDR technology has been concentrated at the Fenton Hill HDR Pilot Facility in the Jemez Mountains, about 90 miles northwest of Albuquerque, NM. Between 1974 and 1978, the world's first HDR reservoir, centered in rock at a depth of about 9,850 ft with an initial temperature of about 365°F, was created at Fenton Hill. After a production well was connected to the fractured reservoir, water was circulated through the reservoir in a number of flow tests conducted from 1978-1980. The water was typically returned to the surface under pressure at temperatures of 275°-285°F (Dash et al., 1981).

The volume of this Phase I reservoir was estimated at about 3.5 million cubic feet, far too small for practical, long-term operation. Thermal drawdown was observed early in the flow-test series and persisted in spite of several attempts to enlarge the heat-transfer surface of the reservoir. Although experiments with this initial HDR reservoir provided scientific proof that engineered geothermal reservoirs could be created and exploited, it was clear that a much larger reservoir would be needed in order to demonstrate the kind of long-term, steady-state energy production that would be required for practical applications.

Development of the Current HDR System

In 1980, under an International Energy Agency agreement, scientists and engineers from the United States, Japan, and Germany began working together to design and construct a second HDR reservoir at Fenton Hill. Experience with the Phase I system had led to a consensus that hydraulic stimulation in crystalline rock would create vertical, disk shaped fractures. Based on this hypothesis, two wellbores were drilled, with the final 3,280 ft of each wellbore trajectory inclined at an angle of 35° to the vertical, and a vertical separation of somewhat more than 1,000 ft between the angled portions of the wellbores. The deeper well penetrated into rock 14,400 ft below the surface at a temperature of about 620°F.

Hydraulic stimulation experiments began in 1982, by pumping water under high pressure into isolated portions of the lower wellbore. The intent was to create a number of artificial fractures connecting the lower wellbore to the upper wellbore. The combined surface area of the multiple of fractures would then provide enough contact area between the reservoir rock and the circulating water to assure a long reservoir thermal lifetime. Numerous stimulation experiments were conducted in the lower wellbore over the next two years, but no fluid was produced from the upper wellbore.

Analyses of the microearthquakes caused by the stimulation experiments indicated that it was, in fact, unlikely that continued hydraulic stimulation would ever lead to a connection between the two wellbores. The locations of the microearthquakes showed that a 3-dimensional reservoir zone was being developed along the approximate orientation of the lower wellbore. This observation led to a complete revision of the concept of engineered geothermal reservoir creation and growth. Rather than creating artificial, vertical fractures, it became clear that hydraulic stimulation simply caused preexisting natural joints to open. The growth of the engineered reservoir was therefore governed by the earth stresses and the orientations of the natural rock joints in the stimulated region. With this idea in mind, the upper wellbore was partially sanded-up and then redrilled on a trajectory which seismic information indicated would penetrate the major reservoir zone. When this was done, a flow connection was rapidly established. A 30-day flow test in 1986 verified that continuous production of energy from the deeper (Phase II) reservoir was feasible. The bottom of the lower wellbore, which had been damaged during the extensive fracture operations, was then sanded-up and redrilled nearby to complete the underground system utilized in all subsequent testing.

The present Phase II HDR system consists of two wellbores penetrating an elongated reservoir with its major axis tilted approximately 30° to the vertical. The reservoir is located at an approximate depth of 11,000-12,000 ft in rock at a temperature of 440-460°F. Both wellbores are uncased below 10,800 ft where they penetrate the reservoir. On average, the open-hole portions of the wellbores are about 360 ft apart. Simple geometric calculations, seismic analyses, and tracer and hydro-mechanical testing indicate that the effective volume of the Phase II reservoir is about 750 million cubic feet.

Between 1987 and 1991, an automated surface plant, built to power plant standards, was constructed at Fenton Hill and mated to the underground system (Ponden, 1991). With this plant in place, the HDR system can be operated routinely as a closed, energy extraction loop. A high-pressure injection pump provides the sole motive power for fluid circulation. The injection pressure must be high enough to hold open the joints that allow flow through the reservoir, but not so high as to cause additional joints to open at the periphery of the reservoir, since the latter condition leads to uncontrolled reservoir growth as indicated by seismic activity and excessive water consumption. Water is typically injected into the Fenton Hill system at surface pressures of about 3,960 psi, and returned to the surface with an applied backpressure on the production wellhead of 1,400-2,200 psi. At the surface, the pressure is reduced to about 700 psi. The fluid is passed through a particle/gas separator and an air-cooled heat exchanger that wastes the extracted geothermal energy to the atmosphere. Makeup water is then added to the main circulation loop to replace the water lost in transit through the underground reservoir, as the fluid flows back to the inlet of the injection pump.

Fenton Hill Flow Testing Results

A series of flow tests of the Phase II HDR reservoir were conducted between 1992 and 1995. Three of those tests entailed steady-state operation of the reservoir on an around-the-clock basis for periods ranging from 56 to 112 days. During these periods the plant was operated in a fully automated mode with provision for automatic shutdown in the event of malfunction of key components. Personnel were on site during normal working hours and for brief periods on weekends, but much of the time the plant operated completely unattended except for a security guard who was present to deter vandalism. Although, brief system shutdowns were scheduled for system maintenance or resulted from inadvertent occurrences such as weather-induced power failures, the Fenton Hill plant was on line for more than 95% of the time during all of the steady-state tests. As shown by the data of Table 1, the steady-state test results were remarkably consistent.

The flow tests of 1992-1995 demonstrated the extremely reliable performance obtained during routine operation of the large Fenton Hill HDR system. Fluid production levels were stable, there was no decline in the production temperature, and the dissolved species in the circulating fluid rapidly reached equilibrium concentrations at a total dissolved solids level approximately one-tenth that of seawater. Almost no suspended solids were brought to the surface. Tracer analyses conducted periodically during all three flow tests revealed the dynamic nature of the flow paths within the reservoir. Some flow paths closed while others opened as circulation proceeded, with overall fluid access to the hot reservoir rock increasing with time.

Table 1: HDR Flow Test Data

Test Dates	Apr-July 1992	Feb-Apr 1993	May-July 1995
Period of Continuous Flow	112 Days	56 Days	65 Days
Typical Production Conditions			
Flow Rate, gpm	90	93	104
Temperature, °F	361	363	365
Dissolved Solids, ppm	3600	3400	3700
Dissolved Gases, ppm	2800	2400	2400
Water Loss Data			
Loss, as % of Injected Volume	12	7	14
After Continuous Flow, mo.	3.5	1.5	1.2
After Continuous Pressurization, mo	6	15	2

Two different reservoir management strategies were employed during the periods between the steady-state tests. For the six months between the first and second tests shown in Table 1, the reservoir was pressurized continuously, but circulation was maintained only about 50% of the time on a highly intermittent basis. In contrast, the pressure on the reservoir was allowed to decline by about 2,200 psi over the two years between the second and third tests. The data indicate that, at least for these two situations, extended periods of dormancy have no deleterious consequences on the productivity of HDR reservoirs.

Apparent water losses in the Fenton Hill HDR reservoir have been shown to be primarily due to permeation of fluid from the pressurized joints into the sealed joints and rock at the periphery of the reservoir. The water-loss data of Table 1 reflect the fact that the rate of water consumption is much more dependent upon the pressure history of the reservoir than upon its flow history. The lowest rate of water-loss was observed during the second flow-test period when, even though circulation had been maintained for only a month and a half, the system had been under high pressure for more than a year. By comparison, after more than three months of circulation during the initial flow-test period, the water-loss rate had declined to only 12% because the system had been fully pressurized for only a total of six months. The water-loss data from the third test period provide further evidence of the direct link between pressure history and water consumption, showing a water-loss rate of 14% after two months of continuous pressurization.

In addition to the three steady-state flow tests, two important flow tests evaluated the potential for the operation of an HDR reservoir to meet time-variable energy demands (Brown, 1996). As illustrated in Figure 2, one of these tests showed that it is possible to increase the productivity of an HDR reservoir by more than 50% within a period of about two minutes and to maintain that elevated level of production for at least four hours before rapidly reducing output back to the baseline level. This important result demonstrates the high level of operational control that can be imposed on an engineered geothermal reservoir to provide a load-following power output.

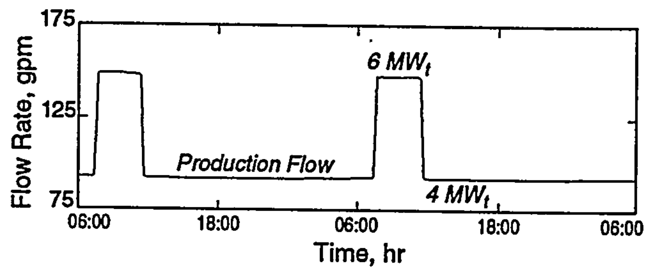

FIGURE 2. HDR RESERVOIR OUTPUT CAN BE RAPIDLY VARIED BETWEEN TWO STEADY-STATE LEVELS

UNIQUE CHARACTERISTICS OF HDR TECHNOLOGY

HDR reservoirs are fundamentally similar to natural hydrothermal reservoirs in that they consist of mobile fluid dispersed in a hot-rock matrix, but several aspects of HDR technology make it uniquely suited to meet the developing clean energy needs of the world: Unlike hydrothermal resources, the HDR resource is almost universally distributed, so there is a relatively wide choice in selecting the location of an HDR facility. Because they are fully-engineered, HDR reservoirs can be sized to fit the local energy requirements and they can be enlarged as needed. Seismic monitoring techniques make it possible to follow the growth of an HDR reservoir in real time and to obtain good knowledge of its shape and orientation as well as its size. The closed nature of HDR reservoirs makes it possible to discharge and recharge HDR systems rapidly thus permitting the kind of operational flexibility needed to meet peaking power demands efficiently. Finally, the closed nature and limited size of an HDR reservoir may eventually make it practical to use a wide variety of fluids as the heat transfer medium. For example, treated municipal wastes may feed an HDR reservoir located right at the site of a sewage treatment plant. Such a facility could produce both energy and purified water. Water-based industrial wastes from food-processing plants as well as lumber, paper, and textile mills might be utilized in the same manner. With provisions to extract the salt from the superheated fluid, even seawater might serve as an acceptable heat transfer fluid in an HDR system. Cogeneration of both energy and clean water may be the key to making HDR economically competitive by simultaneously addressing two of the most important problems in every area where human population is increasing.

CONCLUSIONS

The geothermal energy in HDR is a vast resource found almost everywhere in the world. Research and development work conducted by the Los Alamos National Laboratory at the Fenton Hill test site has taken the technology to extract HDR energy from the conceptual stage through a concrete demonstration that useful amounts of energy can be routinely produced. Flow testing during 1992-1995 has shown that HDR systems are reliable and resilient. HDR technology has a number of unique characteristics that make it particularly suited to the developing energy needs of the world. These include operational flexibility that can provide energy as needed to rapidly meet peaking or unanticipated power demands and the potential for cogeneration of both energy and clean water.

HDR technology has been shown to be practical and versatile. The next logical step in making HDR a viable energy resource is to develop an HDR system that will generate and market power, thereby providing the practical operating and economic data needed to promote the rapid commercial application of this unique energy technology.

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