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STATUS AND PROSPECTS FOR HDR IN THE UNITED STATES

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ABSTRACT

The vast majority of accessible geothermal energy exists in the form of heat stored in dry rock at depth. For nearly the last two decades, the Los Alamos National Laboratory has been engaged in a program to develop the technology to mine the thermal energy in this hot dry rock (HDR). The world's first heat mine was developed and operated at Fenton Hill, NM in the 1970's by using drilling and hydraulic fracturing techniques to create an artificial reservoir in hot rock and subsequently circulating water through this reservoir to mine the heat from the rock. Over the last ten years, a much larger, deeper, and hotter heat mine has been constructed at Fenton Hill and a permanent energy extraction plant has been built on the surface.

A long-term testing program has recently begun to evaluate the potential for sustained energy extraction from the large Fenton Hill heat mine. This paper summarizes the history of HDR research and development at Los Alamos, reports the initial results of the long-term testing program at Fenton Hill, and discusses the possible future course of HDR technology.

Introduction

Geothermal energy from natural steam and hot water sources is a significant factor in the energy supply picture of the western United States. Electric power is produced at a number of locations in California and Nevada, and geothermal waters are employed for direct thermal applications such as municipal heating, greenhouses, and fish farms in a number of states.

Only a minute fraction of the geothermal energy potential of the earth will ever be realized by relying on open fracture systems in the earth's crust and naturally occurring fluids as the transport medium, however. Such natural hydrothermal resources are very limited in distribution and are often found in locations where their surface manifestations make them more valuable as tourist attractions than as energy sources, or are too far removed from transmission capabilities or the potential energy users to warrant their development.

The vast majority of accessible geothermal energy exists almost everywhere beneath the surface of the earth in the form of hot dry rock (HDR). While the exploitation of hydrothermal resources is fairly straightforward, the technology to extract the energy from HDR is more complicated and, as yet, has not been developed to the point of commercial application.

There is no question, however, that it is possible to mine the energy from HDR. The feasibility of heat mining was demonstrated more than a decade ago and there are presently a number of projects around the world dedicated to research and development aimed at demonstrating that HDR heat mining is a practical method for meeting the worldwide demand for clean and abundant energy. This paper will discuss the current status of HDR research, development, and testing in the United States and the prospect it has for becoming an important factor in the geothermal energy market of the future.

History

The Emergence of the HDR Idea

Mining the heat contained in dry rock at depth was first proposed early in this century (Armstead and Tester, 1987) but all the recent work in HDR springs from the basic concept outlined in a patent issued in 1974 (Potter, Robinson, and Smith, 1974) and assigned to the Los Alamos National Laboratory. That patent describes a heat mining system in which an artificial reservoir, consisting of a relatively small amount of water dispersed in a large volume of hot rock, is created by hydraulic fracturing in a deep well. A second well penetrates the reservoir at some distance. In operation, water is pumped through the reservoir from one well to the other, absorbing heat from the rock in the process. After the water is returned to the surface, its thermal energy is extracted for useful purposes and the water is then recycled to mine more heat.

Experimental work began at the Los Alamos National Laboratory in the early 1970's. This was followed by a large HDR effort in England beginning in 1978 and, subsequently, by projects in Japan, western Europe, and the former Soviet Union in the 1980's. The number of HDR experimental projects has grown to the point that today there are more than half a dozen active HDR sites around the world. At about half of these, work has advanced to the stage of reservoir development and characterization or beyond.

The Los Alamos HDR Program

The Program run by the Los Alamos National Laboratory at Fenton Hill, NM is the oldest and most advanced HDR effort in the world. The project can be divided into 4 stages. The early work (stage 1) was concerned with simply developing a small (Phase I) HDR reservoir and demonstrating that the extraction of energy from HDR was possible. This was done during the decade of the 1970's. A series of flow tests in 1978-1980 demonstrated the possibility of operating HDR to produce useful energy (Dash, Murphy, and Cremer, 1981).

Stage 2, which began in 1980, entailed the creation of a larger, deeper, and hotter (Phase II) HDR system capable of sustained operation. This task began with a series of rather simple assumptions about HDR based on the easy successes of Stage 1. The work conducted during this stage was fraught with difficulty and yielded surprising results. New information was generated and lessons were learned at an astounding rate. By the time the Phase II reservoir was completed in 1985, a large body of new theories, understanding, techniques, and tools had been developed to guide the future expansion of HDR technology(Brown, 1990; Dennis, 1990).

The second stage of HDR development closed with a brief (30-day) flow test of the Phase II reservoir in 1986(Dash, 1989). Results are summarized in Table 1.

The production temperatures reached were sufficient to make this resource practical for the production of electricity if sustained production at useful rates could be demonstrated. The reservoir was operated during this test at such a high pressure that active reservoir expansion occurred with resultant high water consumption.

Table 1. Operating conditions at the close of the 30-day flow test (May-June, 1986).

Injection Conditions	
Pressure, psi	4570
Flow Rate, gpm	290
Temperature, °C	16
Production Conditions	
Backpressure, psi	500
Flow Rate, gpm	214
Temperature, °C	190
Thermal Power, MW	9.8
Derived Conditions	
Water Loss, gpm (%)	76 (26)
Impedance, psi/gpm	19.6

This test was run with improvised surface facilities and rented equipment. In addition, the massive fracturing operations of the previous few years had damaged one of the wells. Because the existing surface system and particularly the damaged well were not suitable for extended operations, it was necessary to first carry out repairs to this well and then design and build a permanent surface plant in order to conduct a sustained test of the reservoir.

The third stage of HDR development at Los Alamos was dominated by engineering work. During 1987-1988, repairs to the underground system which, as mentioned above, had been damaged due to the extensive experimental work of the previous 6 years, were completed(Dreesen, et al, 1989). This was followed by construction of a surface plant to power industry standards. Due in part to budgetary limitations, design, construction, and commissioning of the facility took somewhat over three years (Ponden, 1991). It was built with commercially available equipment or materials and components already on hand to the degree this was practical, and with provisions for operational flexibility to permit a valid evaluation of the Phase II HDR reservoir under a variety of operating scenarios. Figure 1 is a schematic drawing of the surface plant.

While the surface facility was being constructed, extended static pressure testing of the Phase II reservoir was carried out (Brown, 1991). This effort consisted of simply injecting water as needed to maintain the reservoir at an elevated pressure and then measuring the quantity of water required to accomplish this. In practice, the test consisted of a series of pressure plateaus interspersed with periods when the system pressure was being increased or allowed to decay. The course of the experiment is illustrated graphically in Figure 2.

The most important information generated by this extended

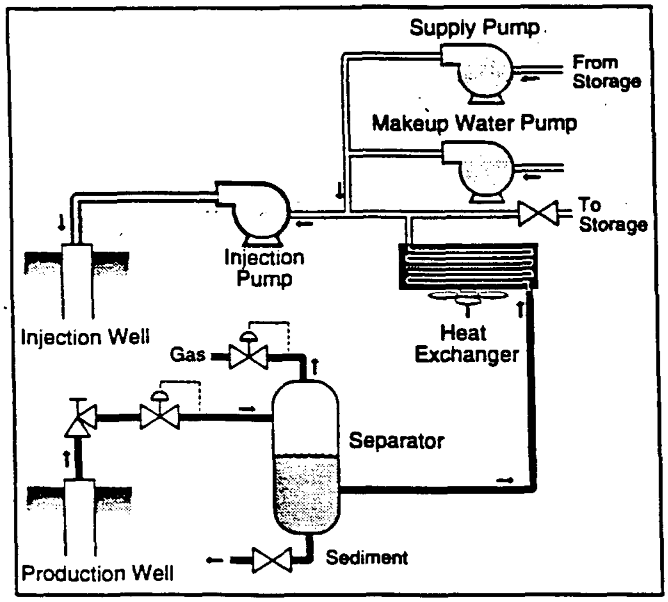

Figure 1. Schematic drawing of the Fenton Hill HDR surface plant.

test was a picture of declining water consumption as the system approached an elevated equilibrium pressure. Table 2, for example, shows the water requirements at the close of each of the 5 periods when the pressure was held at 2175 psi and the two times when the pressure was held at 2755 psi.

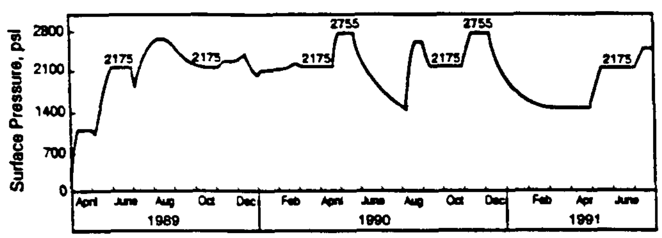

Figure 2. Phase II reservoir pressure profile over the course of the extended static pressure experiment.

Table 2. Water consumption at the close of static pressurization stages.

2175 psi Pressurization Plateau	
Period 1	8.23 gpm
Period 2	4.78 gpm
Period 3	3.24 gpm
Period 4	2.63 gpm
Period 5	2.57 gpm
2755 psi Pressurization Plateau	
Period 1	8.30 gpm
Period 2	7.41 gpm

The decline in water consumption with time is consistent and obvious. The practical implication is that any HDR reservoir will require a considerable portion of makeup water at first, but water consumption will decline significantly in the long-term as the system continues to operate under steady-state conditions. Of course, if the reservoir region intercepts an open fault, a leakage path may be established which will continue to drain away water indefinitely. It is thus important to create reservoirs in rock masses which are as naturally "tight" as possible, and away from active fault systems.

The program has now entered the fourth stage which is dedicated to extended testing of the Phase II reservoir to demonstrate that energy from an HDR reservoir can be delivered over the long-term. The success of this stage is very dependent on the work done in stages 2 and 3 of the project. The underground reservoir and wellbores constructed during stages 2 and 3 will now be required to deliver hot fluid to the surface, and the plant built during stage 3 will be required to process that fluid, measure and dissipate the energy, and recirculate the water to mine heat over an extended time period.

Long Term Flow Testing at Fenton Hill

The central feature of the demonstration stage of the Fenton Hill HDR Project is the long-term flow test (LTFT). It is conceived as an extended test, with operations on a 24-hour a day basis for a period of a year or more. In accordance with the advice of our industrial advisors, this test is presently being conducted at the highest injection pressure which does not cause the reservoir to grow. Such growth would be evidenced by seismic events detected at subsurface stations in the area and by excessive water consumption.

The primary goal of the LTFT is to demonstrate that the HDR reservoir at Fenton Hill can deliver practical amounts of energy on a sustained basis. The second most important goal of this test is to determine water requirements for operation of the Fenton Hill facility over an extended flow period and relate these to the water needs of a practical HDR plant.

Other objectives are related to these two and include the documentation of operational and maintenance factors, measurements of parasitic power consumption, and evaluation of environmental effects. In an effort to advance the state of the art of HDR science and engineering, tracers will be developed and employed, reservoir performance parameters will be carefully measured and used to test and modify models, and extensive seismic monitoring will be conducted during any periods of active reservoir growth.

Preliminary Tests

The long-term testing effort began in December 1991 with a sequence of three 3-day flow tests which continued through February 1992. These were followed by a 10-day flow test in March. These preliminary flow tests served as commissioning trials of the surface plant. Deficiencies were identified and corrected, and then the modified plant was evaluated in the subsequent test. In addition, they served to train the plant crews and give them hands-on experience with operations under a variety of production and injection conditions. Finally, these tests demonstrated the conditions under which the reservoir could be operated during extended production including potential flow rates and anticipated water consumption. They thus formed the basis for determining the steady-state conditions under which the LTFT would be conducted.

For about a day preceding each of these preliminary flow tests, the reservoir was inflated to a pressure of about 3100 psi above hydrostatic. Since the backpressure imposed on the production well was in all cases lower than the reservoir inflation pressure, it was necessary to initially vent the reservoir through the production well for a period of time regardless of the injection conditions. As a consequence, for each test, the reservoir production flow approached equilibrium "from above," with the flow rate *decreasing* with time as it approached steady-state. However, the time required for establishing flow equilibrium depended to a considerable extent on the level of controlled backpressure relative to the reservoir pre-production pressure level of 3100 psi.

The final operating conditions for the first two of the 3-day flow tests in this testing sequence are given in Table 3.

Table 3. Operating conditions during preliminary flow testing (after 3 days of continuous circulation).

Dates (1991 and 1992)	Test 1 12/4-12/7	Test 2 2/4-2/7
Injection Conditions		
Pressure, psi	3700	3865
Flow Rate, gpm	85.8	114.4
Temperature, °C	18	18
Production Conditions		
Backpressure, psi	2210	1510
Flow Rate, gpm	74.1	100.7
Temperature, °C	154	177
Thermal Power, MW	2.7	4.2
Derived Conditions		
Water Loss, gpm (%)	9.7 (11.3)	11.5 (10.0)
Effective Flow Impedance, psi/gpm	20.1	23.4

The 23°C increase in production temperature between Tests 1 and 2 is primarily due to the 36% increase in production flow rate for Test 2. This increase is in turn a result of increasing the injection pressure by 165 psi and reducing the backpressure by 700 psi, and is achieved at the expense of a 16% increase in effective flow impedance.

Because of the higher production backpressure for Test 1, the reservoir appears to have almost stabilized in only 3 days, while during Test 2, it was still quite transient after an equivalent period of time.

The final operating conditions for the 10-day test are shown in Table 4.

Table 4. Operating conditions during the 10-day flow test (March 3-13, 1992).

Injection Conditions	
Pressure, psi	3750
Flow Rate, gpm	108.7
Temperature, °C	21.6
Production Conditions	
Backpressure, psi	1501
Flow Rate, gpm	95.1
Temperature, °C	180.1
Thermal Power, MW	3.97
Derived Conditions	
Water Loss, gpm (%)	10.5 (9.7)
Effective Flow Impedance, psi/gpm	23.6

From Tables 3 and 4, it is apparent that the operating conditions for Test 2 and the 10-day flow test are quite similar with regard to the injection and production pressures. However, the production flow rate is higher and the production temperature is lower for Test 2. A more thorough analysis shows that Test 2 essentially represents the first 3 days of the 10-day flow test, with the reservoir still approaching equilibrium after 3 days. As the pressure field in the reservoir continued to come into balance during the 10-day flow test, the production flow rate slowly decreased while the production temperature continued to rise. At the injection well, the pumping pressure continued to slowly drop as the joints connecting the wellbore to the reservoir cooled and thermally dilated. It appears that the conditions at the end of the 10-day flow test were close to those which Test 2 would have reached had it been continued for an additional week.

Initial Results from the Long-Term Flow Test

The Long-Term Flow Test began on April 8, 1992. As of this writing (5/27/92), it has been in operation for just over 7 weeks under aseismic (nonextensional) injection conditions. The first 9 days were devoted to investigating an "off-design" production well backpressure condition of 2000 psi, to provide additional data for reservoir model verification. Since that time, with a few minor exceptions, the reservoir has been operated at more nearly optimum aseismic conditions and appears to have finally reached a true state of equilibrium. Table 5 summarizes the two steady-state operating conditions that have been investigated to date.

Table 5. Phase II reservoir steady-state operating conditions during the first phase of the LTFT.

Measured Performance as of:	April 17	May 22
Injection Conditions		
Pressure, psi	3555	3896
Flow Rate, gpm	90.7	116.2
Temperature, °C	24	16
Production Conditions		
Backpressure, psi	2011	1410
Flow Rate, gpm	74.7	98.9
Temperature, °C	167	183
Thermal Power, MW	2.8	4.4
Derived Conditions		
Water Loss, gpm (%)	12.5 (13.8)	13.3 (11.4)
Effective Flow Impedance, psi/gpm	20.7	25.1

Recently a considerable upset to the flow test occurred as a result of a two-hour loss of site electrical power. The main injection pump was shut down, and both wellheads shut in, resulting in a rapid equilibration of reservoir pressure from the previously established flowing pressure gradient between wellbores. After a reservoir shutin period of about 140 minutes, the main injection pump was restarted, but production flow was not initiated for another three hours due to a coincident mechanical problem.

By the following day, near steady-state operating conditions had been re-established but at a production backpressure of 1600 psi rather than 1400 psi. All the other reservoir operating parameters appeared to be about the same as before the power failure, however. The injection pressure was still 3900 psi, while the production flow rate was slightly higher at 100 gpm but was slowly decreasing. This decrease was primarily a function of a reservoir relaxation back toward equilibrium after the 3-hour period of reservoir inflation without production flow. In effect, the reservoir was again approaching steady state "from above."

Since the only reservoir performance changes appeared to be minor, the flow test has been continued at the higher production backpressure of 1600 psi over the short term to determine the true effect, if any, of this 200 psi increase in production backpressure. Table 6 summarizes the significant reservoir parameters just before the system upset on May 23, and those existing on the morning of May 27.

Table 6. Reservoir parameters at 1400 psi and 1600 psi production well backpressure.

Measured Performance as of:	May 23	May 27
Injection Conditions		
Pressure, psi	3899	3906
Flow Rate, gpm	117.0	116.9
Production Conditions		
Backpressure, psi	1402	1601
Flow Rate, gpm	99.5	98.5
Temperature, °C	183	184

One significant feature of this comparison is not shown in Table 6 explicitly. Before the system upset at a backpressure of 1400 psi, the production flow rate had been very slowly *increasing*, while four days later at a backpressure of 1600 psi, the production flow rate was *steady and lower* by about 1 gpm. The unmistakable conclusion is that under present aseismic reservoir operating conditions, an increase in production backpressure results in a finite, but small, *decrease* in production flow rate. Therefore, the optimum backpressure under current conditions is at or somewhat below 1400 psi. Future changes in the backpressure imposed on the production wellhead will be in the direction of lower rather than higher values.

Our goal has been to conduct the LTFT continuously for a period of a year or more in order to clearly demonstrate sustainability of the resource Whether we can do this or not will depend largely on the funding the program receives. We are working with the US Dept of Energy to obtain the supplementary funds required for sustained operations throughout the year.

During this time we will meet periodically with our industrial advisory committee to decide whether to maintain a steady course or to make relatively minor course corrections to increase the value of the data being generated. Such decisions can only be made on a real time basis and in view of data which is not yet in hand.

Other Findings of the LTFT

Several important systematic findings have arisen in our short experience with the LTFT. First, we have found that it is possible to shut down the injection system for a few hours periodically while still producing the system (the produced fluid is temporarily stored on the surface during this time). One might say that the reservoir actually performs like the storage system which its name indicates. From the standpoint of commercial production of energy from HDR, this means that small upsets in the operation of the injection system need not be a concern to an operator from a power delivery standpoint. The production half of the loop, of course, operates in a manner similar to a hydrothermal plant and the reliability of these has been well established through years of operation.

Operating experience together with the results of a tracer test conducted in early March at the end of the 10 day segment have indicated that in spite of the fact that the system has lain dormant or been pressurized but not flowed for a number of years, the general condition of the reservoir has not changed. Within the limits that we have explored, backpressure imposed on the production well also appears to have little effect on flowpaths within the reservoir. These are important clues to long-term physical stability of the underground system. Indeed, these early operational observations clearly bode well for the adaptability of commercial HDR systems.

After the Long Term Flow Test

At the close of the LTFT, sufficient information should be in hand to support the construction of a second HDR site. This facility must be situated where its energy output can be produced and sold at competitive prices. The second HDR facility should set the technology on a path toward general application in a variety of geological and geographical settings.

The fate of the Fenton Hill test facility after the LTFT can take one of several courses. The site may be used for general experimental work to broaden the base of HDR knowledge. Such activities could include the drilling of a second production well to access a greater portion of the reservoir and test theories that this will greatly increase system productivity or, an in-depth evaluation of the ramifications of cyclic operations of HDR systems which could supply valuable peaking power to utility systems. It might also be fruitful to adapt the Fenton Hill site to make and sell power. This could be done either before or after the construction of a three-well system dependent upon an economic analysis. Finally, it may be desirable to abandon the Fenton Hill site and move the entire HDR research and development effort to the second site. Such a move, however would seem to be like throwing away a valuable resource.

The Future of HDR in the United States

HDR today is a technology in its infancy. In its mature form, it will certainly serve as a source of energy. It has inherent advantages of abundance, widespread distribution, and environmental cleanness. It is potentially extremely competitive in cost with traditional energy sources. It may however find uses which today have only been dreamed of. This vast underground system may function to purify sewage water, treat industrial waste such as paper mill residues or to desalinate seawater for thirsty cities. Other as yet unthought of uses are sure to develop for this vast resource. The key to all these applications, however, is seeing this project through the growing pains to its full potential as one of the cornerstones of a 21st century society. Only if it receives support and nourishment will the domestic HDR industry develop and grow.

Summary

Hot Dry rock technology has grown from a demonstration of principle in the 1970's, through a period of rapid learning and development in the 1980's, to the point where today it is feasible to demonstrate that the technology has practical as well as scientific merit. The LTFT currently underway should show that HDR has the potential to deliver energy on a sustained basis with minimal water consumption. Subsequently, an effort will be needed by the private geothermal community in cooperation with the government to take this technology and make it work in a general fashion. If this effort is pursued with purpose and enthusiasm, HDR can become not only the geothermal energy supply of tomorrow, but a dominant factor in energy markets around the world.

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