NOV 05 1987

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LA-UR--87-3388

DE88 001838

TITLE HOT DRY ROCK RESERVOIR ENGINEERING

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SUBMITTED TO
Proceedings of NATO Adv. Study Institute
on Geothermal Reservoir Engineering,
July 1 - 10, 1987, Antalya, Turkey**DISCLAIMER**

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HOT DRY ROCK RESERVOIR ENGINEERING

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1. INTRODUCTION

The development of geothermal energy has been limited historically to the use of natural hot water and steam contained in what are referred to as hydrothermal geothermal reservoirs. However, as indicated by Roland Horne elsewhere in these proceedings, probably less than 5% of the energy in a hydrothermal reservoir is contained in the extractable fluid. What about the 95% remaining?

Most of the heat is in rocks some distance away from permeable fracture systems filled with water. In such rocks, cooling is by conduction, an extremely slow process. Even if the temperature is not maintained or increased by further injection of magma, it may take several million years for the rock to cool to ambient temperatures. The vast, hot rock thermal resources at many volcanic fields in the world, as well as more widespread, but cooler, resources of thermal anomalies not associated with volcanic fields, could be exploited by means of man-made geothermal systems. One such system is being developed at the Los Alamos National Laboratory in New Mexico.

The Hot Dry Rock (HDR) concept is a simple one (Heiken et al., 1981). Two nearly parallel wells are drilled, and hydraulic fractures are then formed to hydraulically connect the wells (Figure 1). Water pumped down the injection well and through the fracture system is heated by contact with the hot rock and rises to the production well. This hot fluid is passed through a heat exchanger at the surface and the extracted heat is used for direct heating or electricity generation. The cooled production fluid is then reinjected, thereby setting up a circulation loop. The idea, although simple in theory, is difficult to implement. To pursue and

develop it, a geothermal energy group was established at Los Alamos in 1973. Since then the technical feasibility of the method has been demonstrated in several successful heat extraction tests, and the project has grown into an international program underwritten by the governments of the Federal Republic of Germany, France, United Kingdom and the United States. Interest in Hot Dry Rock is so high because, in principle, HDR potential can be found anywhere in the world simply by drilling deep enough to encounter hot rock. This differs substantially from hydrothermal resources, where one requires not just the hot rock, but also the simultaneous (and increasingly rarely found) discovery of sufficient porosity within that rock, which is already filled with hot water or steam, so that large amounts of water or steam can be easily extracted. In HDR, the permeability must be man-made, and the water is provided from the surface, rather than required to be present in situ. Because in situ water, often heavily laden with minerals and silts, is avoided, HDR results in fewer environmental problems. Potential resources are much greater as shown in Figure 2, because it is easily found. A comparison of HDR and hydrothermal reservoirs is provided in Figure 3. Figure 4 is a photo of Fenton Hill, New Mexico, site of U.S. HDR reservoir experiments.

2. HDR RESERVOIR FUNDAMENTALS

Figure 5 indicates the fundamental relationship between the expected thermal power of an injection/production well pair and the required volumetric flow rate, $\dot{Q}$, when the reservoir temperature, θ_r , is 240°C, a typical temperature for producing electricity. Because HDR wells are not artesian, pumping is required, and it is desired to hold the pumping power to a small value, say 15%, of the net electric power to be produced from the well pair. As is indicated, this requirement means that the pressure drop through the reservoir is limited to 10 MPa, which corresponds to a limit on reservoir impedance (pressure drop per unit flow rate) of 0.2 GPa s/m³. To be compared with this requirement are measured values which vary from 0.05 to 1 based upon Fenton Hill reservoir experiments.

To develop insight into heat extraction in HDR reservoirs, consider the single hydraulic fracture shown in Figure 6. For mathematical purpose this fracture is assumed to be rectangular, and also assumed to be embedded in rock of infinite extent. In reality, such fractures can be spaced as close together as 50 meters without invalidating the results to follow. As

shown, the decline in the temperature of the water exiting the fracture, also known as thermal drawdown, is given by the complementary error function of an expression involving mass flow rate, $\dot{m}$, fracture heat transfer area A , rock conductivity and diffusivity, λ and α , and time, t . Figure 7 graphs the thermal drawdown and indicates that if a well pair is to produce 35 MW of thermal power, which will yield about 5 MW of electric power, and is to do so for 10 years with a thermal drawdown limited to only 20% (so turbine/generator performance will not be adversely affected) then a heat transfer area of 1 square kilometer is required.

3. CREATING HEAT TRANSFER AREA

Can the large areas required for economic heat extraction be created by fracturing? Figure 8 illustrates that the requisite area can be made with a single large fracture, or several smaller, but still discrete fractures, or by a system of closely spaced fractures created by a single hydraulic fracturing treatment. The latter concept, often called "volumetric fracturing", because it results in a fully fractured, three dimensional zone, is the observed result when a low viscosity fluid like water is injected into granitic rock which contains natural fractures, or joints. These joints are tightly closed to begin with, and perhaps filled with geochemical deposits, but the squeezing of water along these joints (which, although nearly closed, still provide a better flow path than the nearly impervious blocks of rock) raises the pressure in the joint sufficiently to lower the effective closure stresses holding the joint surface in tight contact. As shown in Figure 9, this effective stress reduction results in shearing, but is not sufficient to yield conventional fracturing (termed "jacking" in Figure 9). This unconventional stimulation, due to shear, results in volumetric fracturing (Pine and Batchelor, 1984; Murphy and Fehler, 1986) and Figure 10 shows the fracturing pattern revealed by mapping the acoustic emissions, or microearthquakes, that accompany fracturing.

4. RESERVOIR OPERATING EXPERIENCE

The world's first hot dry rock geothermal energy system was completed at Fenton Hill in 1977; enlarged in 1979 by additional hydraulic fracturing; and then operated successfully for more than a year. It was created by drilling a hole from the surface to a depth of approximately

3000 m, into granitic rock at about 185°C; producing hydraulic fractures centered at about 2600 m depth; then directionally drilling a second hole from the surface to intersect those fractures. Water was produced from the man-made reservoir at temperatures and thermal power rates as high as 175°C and 5 MW_t. The produced water contained less than 4000 ppm of dissolved solids and caused no corrosion or scaling problems. Water losses due to saturation of the rock surrounding the fractures diminished to less than 10% of the water injected. Additional results of reservoir testing are provided by Dash et al. (1983).

To extend the technology to the temperatures and rates of heat production required to support a commercial power plant, construction of a larger, hotter, hot dry rock system was initiated at Fenton Hill in 1979. This is often referred to as the Phase II system. Two new holes, were drilled directionally, the deeper one to a vertical depth of 4.66 km -- where the rock temperature was 327°C. Based upon experience in the shallower system described above, it was expected that hydraulic fractures produced from the new wells would be substantially vertical, with an approximately north-northwest strike. To provide the horizontal separation required to thermally isolate a series of such fractures, the bottom 1000 m of each hole was drilled toward the east-northeast and inclined at 35° to the vertical. Figure 11 shows a perspective view. The upper well, EE-3, lies 300 m above the lower well, EE-2, in the slanted interval. Also shown in Figure 11 is the Phase I reservoir well EE-1 which contains a geophone sonde. This sonde, and similar seismic sensors placed in other boreholes, detect and locate the microearthquakes triggered during hydraulic fracturing (House et al., 1985).

In 1982, hydraulic fracturing experiments were conducted near the bottoms of both new wells. As related above, the fracture zones produced were three-dimensionally distributed networks of stimulated natural joints, rather than single planar fractures. Furthermore the fracture zones were inclined rather than vertical, and did not connect the two wells hydraulically. The unexpected non-vertical inclination may be related to the presence of a cooling magma body beneath a volcanic caldera a few kilometers east of Fenton Hill which altered the earth stresses.

In December 1983 a massive hydraulic fracturing operation was conducted in which 21,600 cubic meters of water were injected at 3.5 km in the lower well at downhole pressure and average flow rate of 83 MPa and 100 l/s.

Details are provided by Dash et al. (1985) and House et al., (1985). The locations of the microearthquakes induced were shown earlier in Figure 10. The downhole seismic sensors are extraordinarily sensitive, enabling detection of events with extrapolated Richter body wave magnitudes as low as -5, but Figure 10 shows only the 850 high quality events with magnitudes from -3 to 0. Note that seismicity is induced over a rock volume that is about 800 m high, 800 m wide in the N-S direction, and about 150 m thick, or about 50,000,000 m³ of stimulated rock volume. This rock volume is 2500 times that of the volume of injected water.

Despite its huge volume the stimulated zone did not propagate into the vicinity of the upper well, as shown in Figure 10, and no hydraulic communication between the two wells was observed. Another large fracturing operation was conducted, this time in the upper well, but the two stimulated zones did not overlap and again no communication was observed. Consequently, in March of 1985 the upper well was sidetracked at a depth of 2.9 km, and directionally drilled through the fracture zone created from the lower well, and hydraulic communication was established between the two wells.

In March and April of 1986 the newly connected reservoir was readied for preliminary testing by installing a temporary surface piping system; refurbishing the water-to-air heat exchanger used previously for the Phase I reservoir; and temporarily renting pumps to inject water. The purpose of this initial test was to inexpensively define reservoir operating characteristics so equipment for the more ambitious Long Term Flow Test (LTFT) could be designed. The Initial Closed Loop Flow Test (ICFT) was begun May 19, 1986 and completed on June 18, 1986. Cold water was injected into EE-3A, and water was produced from EE-2 as hot as 192°C, and producing up to 10 MW_T. The hot water was cooled to 20°C in the heat exchanger before being reinjected.

5. REMAINING PROGRAM OBJECTIVES

The work of the Fenton Hill project to date has shown that the HDR geothermal energy concept is technically feasible. The program goal is to develop the technology to a level that will confirm economic viability, demonstrate environmental acceptability, and confirm the national resource. Operation of the Long Term Flow Test of the Fenton Hill reservoir will provide the test sequence for the objectives listed below. Figure 12 is a

simplified diagram of the surface plant required to conduct the LTFT. The hot water from the production well, EE-2, will be cooled from temperatures as high as 230°C down to about 30°C with water-to-air heat exchangers which were used earlier for the Phase I reservoir test. After cooling, the water will be recirculated through the reservoir by pumping it down injection well EE-3A. The test is planned for about one year of operation, which should suffice to observe thermal drawdown and measure long term characteristics of the reservoir. The test will also provide operation and maintenance experience of an HDR system, thus contributing to future engineering and economic decisions.

ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy. It is a pleasure to acknowledge the work of Ada DeAguiro and Jean Butler in preparing the manuscript.

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FIGURE CAPTIONS

Figure 1. Hot Dry Rock Concept.

Figure 2. Comparison of energy resources.

Figure 3. Hot dry rock compared to hydrothermal.

Figure 4. The Fenton Hill, New Mexico HDR Site.

Figure 5. Fundamental calculations.

Figure 6. Heat transfer for "ideal" fracture.

Figure 7. Thermal drawdown illustration.

Figure 8. Creating heat transfer area.

Figure 9. Fracturing in jointed crystalline rock.

Figure 10. Hypocentral locations of microearthquakes induced by massive hydraulic fracturing in injection well EE-2. Left hand side presents elevation view, looking north, while right hand side is plan view looking down. Note volumetric distribution of fracturing.

Figure 11. Perspective view of Phase II boreholes and geophone sonde emplaced for microearthquake monitoring during fracturing.

Figure 12. Diagram of surface loop for Long Term Flow Test.

FIGURE 1

FIGURE 2

Hot Dry Rock Compared to Hydrothermal

Advantages

- Huge Resource Base
- Easier to Site Near Energy Needs
- Fewer Environmental Problems
- Less Scaling, Corrosion
- Simpler Drilling

Disadvantages

- Reinjection Pumping Required
- Usually More Expensive
- Still Being Developed

FIGURE 3

FIGURE 4

FUNDAMENTAL CALCULATIONS

"TYPICAL" WELL PRODUCES 5MW_e
OR ABOUT 35MW_t

$$\text{THERMAL POWER} = \dot{m} c [T_{\text{out}} - T_{\text{in}}]$$

$$35 \times 10^6 = \dot{m} \cdot 4200 [220 - 50]$$

$$\dot{m} = 45 \text{ kg/s} = 160 \text{ Tons/hr}$$

$$\text{OR } \dot{Q} = \dot{m} / \rho = 45/1000 = 0.045 \text{ m}^3/\text{s}$$

$$\text{PUMPING POWER} = \dot{Q} \Delta P / \eta_p \eta_m$$

$$15\% \text{ OF ELECTRIC: } 0.75 \times 10^6 = 0.045 \Delta P / 0.8 \times 0.8$$

$$\Delta P = 10 \text{ MPa} \approx 1500 \text{ psi}$$

$$\text{DEFINE FLOW IMPEDANCE} \equiv \Delta P / \dot{Q} = 10 / 0.045 = 0.2 \text{ GPa} \cdot \text{s} / \text{m}^3$$

FIGURE 5

HEAT TRANSFER FOR "IDEAL" FRACTURE

(Carslaw & Jaeger, 2nd Ed. p396)

FLUID ENERGY:

$$\dot{m} c \frac{\partial T}{\partial y} = 2W\lambda \left(\frac{\partial \theta}{\partial z} \right)_0$$

SPEC. HEAT WATER TEMP. ROCK THERMAL COND. ROCK TEMP.

ROCK CONDUCTION: $\lambda \frac{\partial^2 \theta}{\partial z^2} = (\rho c)_r \frac{\partial \theta}{\partial t}$

OR: $a \frac{\partial^2 \theta}{\partial z^2} = \frac{\partial \theta}{\partial t}$

BC's + IC's $\theta(z=0, y, t) = T(y, t)$ INIT. TEMP.
 $\theta(z \rightarrow \infty, y, t) = \theta_r$ ROCK TEMP.
 $T(z=0, t) = T_{in}$

SOLUTION (By Laplace Trans.) IS: $\frac{\theta_r - T_{out}}{\theta_r - T_{in}} = \text{erfc} \left[\frac{\lambda A}{\dot{m} c \sqrt{at}} \right]$

FIGURE 6

RECALL THAT FOR "TYPICAL" WELL, PRODUCING 35MWt, $\dot{m} = 45\text{kg/s}$

FOR CRYSTALLINE ROCK, $\lambda = 3\text{W/m}^\circ\text{C}$, $a = 10^{-6}\text{m}^2/\text{s}$

FOR THERMAL DRAWDOWN OF 20%, THEN 45kg/s REQUIRES

$A = 1.0(\text{km})^2$ FOR 10 YEAR LIFETIME

$A = 1.7(\text{km})^2$ FOR 30 YEAR LIFETIME

FIGURE 7

**SUFFICIENT HDR RESERVOIR LIFETIME & CAPACITY
MAY BE ACHIEVED WITH A NUMBER OF CONCEPTS
FOR LOW PERMEABILITY FORMATIONS**

1. LARGE SINGLE FRACTURES

**2. SMALLER MULTIPLE
PARALLEL FRACTURES**

3. FULLY FRACTURED REGIONS

FIGURE 8

FRACTURING IN JOINTED CRYSTALLINE ROCK

1. "JACKING"

2. SHEARING

FIGURE 9

FIGURE 10

FIGURE 11

Los Alamos National Laboratory
Hot Dry Rock Energy Test
Simplified Flow Diagram

FIGURE 12