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THE U.S. HOT DRY ROCK PROJECT

Robert H. Hendron

Los Aamos National Laboratory
P.O. Box 1663, Mail Stop J979
Los Alamos, New Mexico 87545

ABSTRACT

The Hot Dry Rock geothermal energy project began in the early 1970's with the objective of developing a technology to make economically available the large ubiquitous thermal energy of the upper earth crust. The program has been funded by the Department of Energy (and its predecessors) and for a few years with participation by West Germany and Japan. An energy reservoir was accessed by drilling and hydraulically fracturing in the precambrian basement rock outside the Valles Caldera of north-central New Mexico. Water was circulated through the reservoir (Phase I, 1978-1980) producing up to 5 MWt at 132°C. A second (Phase II) reservoir has been established with a deeper pair of holes and an initial flow test completed producing about 10 MWt at 190°C. These accomplishments have been supported and paralleled by developments in drilling, well completion and instrumentation hardware. Acoustic or microseismic fracture mapping and geochemistry studies in addition to hydraulic and thermal data contribute to reservoir analyses. Studies of some of the estimated 430,000 quads of HDR resources in the United States have been made with special attention focused on sites most advantageous for early development.

INTRODUCTION

The primary objective of the U.S. Hot Dry Rock Program is to develop and demonstrate an economical, commercially usable technology for recovering thermal energy from naturally heated rock at accessible depths in the earth's crust. While other methods are possible in different geologic environments, the Program has so far concentrated on hot crystalline rock of low initial permeability; the use of fluid pressure (hydraulic fracturing) to create flow passages and heat-transfer surface in that rock; and operation of a closed, recirculating, pressurized-water loop to extract heat from the rock and transport it to the earth's surface. Large-scale field experiments are conducted at Fenton Hill in the Jemez Mountains of northern New Mexico, and supporting activities are primarily at Los Alamos National Laboratory. The latter include development of new or improved downhole equipment and instruments, field and laboratory experimental and observational techniques, and analytical and numerical data analyses and modeling procedures. Many of these developments have been found useful in other experimental programs and in a variety of industrial applications.

The technical issues faced in HDR development are challenging. Wells must be drilled to depths where temperatures range from 200 to 350°C, suitable for electricity generation. In regions with favorable geothermal gradients such temperatures are found at depths, of 3 to 5 km, where the minimum component of the in-situ earth stress is likely to be 35 to 100 MPa. One must then fracture the rock formation, and open the fractures so that the permeability remains high and flow resistance is low. Furthermore, large areas of hot rock must be adequately bathed to result in high heat production. At the same time, since all water must be provided extraneously, one must avoid excessive water losses to the country rock surrounding the fractured reservoir. Furthermore, the technology development must assure that potentially damaging earthquakes will not be caused by down hole accumulation of this water. One must also avoid potential geochemical problems, such as scaling of surface equipment with precipitated products of aqueous rock dissolution and corrosion of surface and downhole piping.

The incentive for meeting these challenges is the enormous resource base that HDR energy provides. Unlike hydrothermal reservoirs, which are rarely found, potential HDR reservoirs underlie much of the world. Even if one considers just the high grade resources, i.e., regions with geothermal gradients greater than 40°C/km, the HDR resource base in the U.S. alone represents a thermal energy equivalent to nearly 100 million Megawatt-centuries, about ten times that of coal deposits.

An International Energy Agency Implementing Agreement adopted in 1979 provided for participation by other countries in the Fenton Hill Project of the U.S. Hot Dry Rock Geothermal Energy Development Program which, until then, had been sponsored solely by the U.S. Department of Energy and its predecessor agencies. Under the IEA Agreement, Kernforschungsanlage - Julich GmbH (representing the Federal Republic of Germany) and the New Energy Development Organization (representing the Government of Japan) have participated in the Project since 1980. Their participation included partial financial support of the Project, membership in its International Steering Committee, and assignment of scientists and engineers who worked as Staff Members at Los Alamos National Laboratory. German participation in the Fenton Hill Project ended in 1985 and Japanese participation ended in 1986. Informal cooperation as exchange of information continues.

EARLY ACCOMPLISHMENTS

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 operated successfully for more than a year. It was constructed by drilling a hole from the surface to a depth of approximately 3000 m, into granitic rock at about 185°C; producing large hydraulic fractures centered at about 2600 m depth; and directionally redrilling to intersect those fractures. 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, system was initiated at Fenton Hill in 1979. This is often referred to as our Phase II system. Two new holes, about 50 m apart at the surface, were drilled directionally, the deeper one to a vertical depth of 4.66 km -- where the rock temperature was 327°C. As was the case in the shallower system described above, it was expected that planar hydraulic fractures produced from these holes 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 35° from the vertical. Figure 1 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 1 is a Phase I reservoir well which contains a geophone sonde. This sonde, and similar seismic sensors emplaced in other boreholes, detect and locate the microearthquakes triggered during hydraulic fracturing (House, Keppler and Kaieda, 1985).

FRACTURING THE NEW RESERVOIR

In 1982, hydraulic fracturing experiments were conducted at the deepest depths in the two new wells. Unexpectedly, the stimulated zones produced were three-dimensional rather than planar, inclined rather than vertical, according to location of microseismic events, and did not meet each other or connect the two wells hydraulically. The unexpected non-vertical inclination of the microseismic zone is believed to be related to the presence of a cooling magma body beneath a volcanic

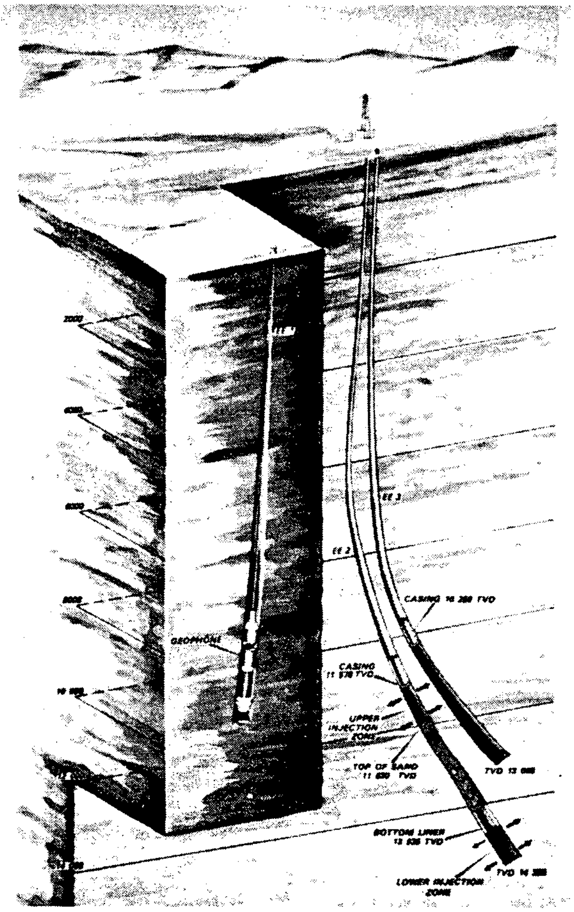

Figure 1. Perspective view of Phase II boreholes and geophone emplaced for microearthquake monitoring during fracturing.

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 21,000 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 Dreesen and Nicholson (1985), and House, Keppler and Kaieda (1985). Figure 2 shows the locations of the microearthquakes induced. The sensitivity of the downhole seismic sensors enabled detection of events with body wave magnitudes as low as -5, on an extrapolation of the relative Richter scale, but Figure 2 shows only 850 high quality events with magnitudes from -3 to 0. Note that seismicity is induced over a rock volume that is about 0.8 km high, 0.8 km wide in the N-S direction, and about 0.15 km thick, or about 0.05 km^3 of stimulated rock volume. This rock volume is 3000 times greater than the water volume injected. House et al. (1985) concluded that:

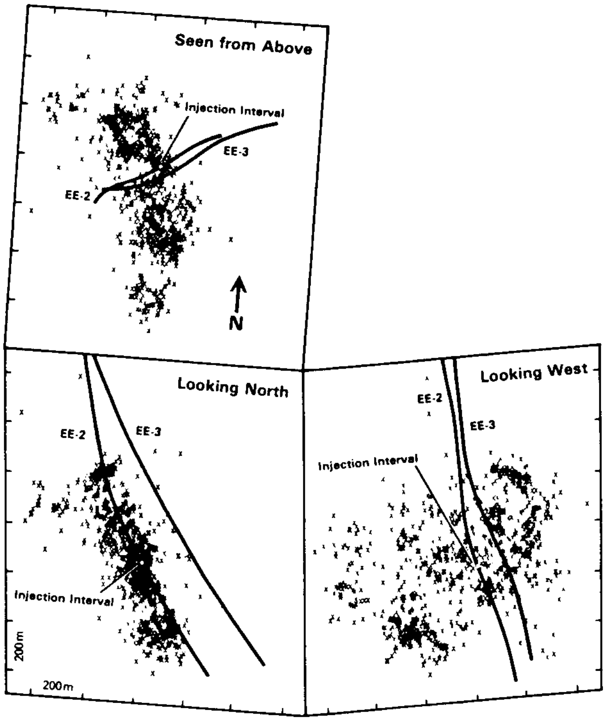

Figure 2. Hypocentral locations of microearthquakes induced by massive hydraulic fracturing in injection well EE-2

1. First motions of the microearthquakes and the fault plane solutions determined from the surface array of seismometers indicated a shear-slip motion, probably along existing rock joints. This suggests that any tensile or oscillatory source mechanism may generate only very weak seismic signals.

2. The finite thickness, 0.15 km, of the zone of seismicity and its spatial growth imply the creation of a zone of joint stimulation, rather than a single fracture.

Fehler (1984) performed spectral analysis of many of the microearthquake coda, and found power spectral densities consistent with usual earthquake mechanics, i.e., shear slippage. Corner frequencies were of the order of 300 Hz, and based upon the work of Brune (1970), Fehler found that the characteristic dimension of the rock surface mobilized for each shear-slip event was of the order of 10 m, comparable to the spacing of the major joints observed in well surveys.

The above results indicate a fracturing mechanism which is inconsistent with conventional theories of hydraulic fracturing (Hubbert and Willis, 1957; Daneshy, 1973) which predict the propagation of a single fracture caused by tensile failure of the rock. However, the HDR results are consistent with Lockner and Byerlee (1977), who observed a transition from tensile to shear fracturing when low flow rates were injected into laboratory rock specimens; and our observations were confirmed at the British Hot Dry Rock reservoir in Cornwall where it was observed (Pine and Batchelor, 1984) that fracturing occurred as a zone of multiple fractures, and that shear slippage along existing joints was the dominant mechanism. Because these joints are pre-existing natural fractures, it is perhaps inappropriate to refer to the process of forcing water into them as "fracturing;" "stimulation" is used instead in the remainder of this report.

The stimulation results just discussed, and the important role played by shear, rather than tension, have important implications not only for HDR programs, but also for stimulation of oil and gas reservoirs. So important is "shear stimulation" that it is a key research issue in the U.S. and HDR projects, and serves as an important basis for collaborative research. For example, the FRIP code (Fluid Rock Interaction Program), developed for the British HDR project by Peter Cundall, is also used at Los Alamos, and recent improvements have been cost-shared by both HDR projects.

ACHIEVING HYDRAULIC COMMUNICATION

Despite the huge volume of water injected in the lower well during the 1983 massive hydraulic fracturing, the stimulated zone did not propagate into the vicinity of the upper well, as shown in Figure 2, 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 as shown in Figure 3 through the fracture zone associated with the lower well. This redrilled well is referred to as EE-3A.

Precursor signs of an impending connection were observed when water flowed into the redrilled well when the other well was pressurized to 12 MPa. It was decided to improve the hydraulic communication quality of joints near 3.6 km by stimulating them with high pressure. This was accomplished by setting a specially developed, high temperature packer (Dreesen and Miller, 1985) at a depth of 3.52 km, where the drill hole was reasonably smooth, and then pumping water into the entire open hole interval between the packer and the bottom of the hole, which was located at 3.72 km at this time. The physical situation is depicted in Figure 3. A volume of 1,670 m^3 was injected, primarily at rates of 15 to 27 l/s, and at downhole pressures ranging from 66 to 75 MPa. A rapid rise in pressure occurred at EE-2, and two hours after the commencement of pumping in EE-3A, EE-2 was put on

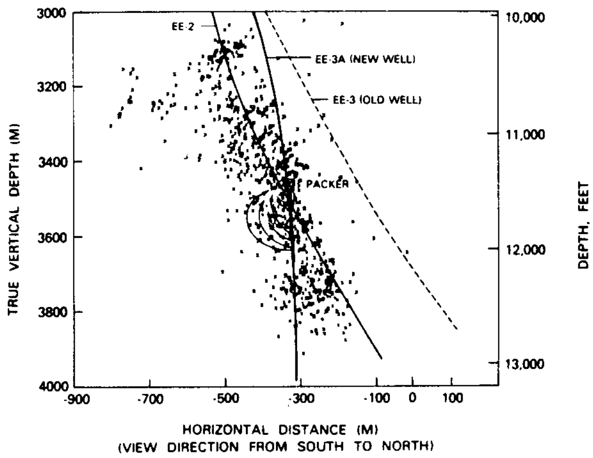

Figure 3. Elevation view of reservoir, looking North. Packer shown allowed supplementary stimulation of EE-3A, which resulted in low flow resistance connection between EE-2 and EE-3A. The flow paths indicated are inferred from joint locations determined from a temperature survey in EE-3A.

production and water flowed out. At first the outflow rate was small, but by repetitively surging the well i.e., by shutting it in for a while, then quickly venting it, the outflow rate was steadily increased, and at the end of the test it attained a value of 10 l/s. A post-connection temperature survey taken in EE-3A on May 30 showed that several new joints had been stimulated which served as flow entries from EE-3A to the reservoir. Figure 3 portrays the potential flow paths, which appear short in this elevation view, but bear in mind that EE-2 and EE-3A are horizontally separated by 150 m at the depth at which the two wells appear to intersect.

Following this successful connection the redrilling continued and three additional stimulations were conducted with open hole packers. The second stimulation was conducted very deep, at 3.83 km, and failed to result in additional hydraulic communication and with flow indicated going down from the bottom of the borehole. The third stimulation occurred at 3.65 km, a depth about midway between the successful and unsuccessful ones, and another hydraulic connection was achieved. In February 1986 the final stimulation was attempted, at 3.76 km, but little evidence of hydraulic communication was observed.

In summary, the two shallower, and successful, stimulations were more centrally located within the zone of seismicity induced during the 1983 massive stimulation of EE-2. The injection depths of the two deeper, unsuccessful, stimulations were still within, but closer to the perimeter of, the 1983 seismic zone. While the seismic zone induced by these two unsuccessful stimulations tended to grow down and away from the 1983 seismic zone, nevertheless there was sufficient overlap of the zones that hydraulic connection of the wells would have been expected. This illustrates the complex nature of stimulation of jointed rock - one cannot expect to encounter high permeability stimulated rock everywhere in the seismic zone. Instead, discrete, and often well spaced, natural joints are stimulated. Hence, one needs to examine carefully the complete three dimensional nature of the seismic zone, and track its development with time. Of particular promise are the recent developments at both the British and US HDR programs of techniques for detecting lineaments in the seismic zones which may reveal the presence of those natural fractures most successfully stimulated.

TESTING THE NEW RESERVOIR

In March and April of 1986 the new reservoir was readied for preliminary testing by cementing-in a liner in well EE-3A; finishing the surface piping system; readying the water-to-air heat exchanger used previously for the Phase I reservoir; and hiring a service company to pump water (injection capability of 30 l/s and 35 MPa).

The Initial Closed-loop flow test was begun May 19, 1986 and completed June 18, 1986. Cold water was injected into EE-3A, and hot water produced from EE-2. The hot water was cooled to 20°C in the heat exchanger before being reinjected. Major flow parameters are presented in Table I, and these are compared with values measured in the enlarged, earlier Phase I reservoir and the British program.

COMPARISON OF THREE HDR RESERVOIRS AFTER ONE MONTH OF OPERATION

	FENTON HILL		
	ENLARGED PHASE I RESERVOIR	CURRENT PHASE II RESERVOIR	ROSEMANOWES CORNWALL, U K.
DEPTH OF RESERVOIR (m)	2,800	3,550	2,400
TEMPERATURE OF RESERVOIR (°C)	195	240	85
MODAL VOLUME (m^3)	160	350	270
SURFACE TEMPERATURE (°C)	135	191	76
THERMAL POWER (MW)	3	9	1
PRODUCTION FLOW RATE (l/s)	7	13	4
INJECTION WELL PRESSURE (MPa)	10	30	4
CORRECTED IMPEDANCE (GPa s/m^3)	1.7	2.2	1.0
WATER LOSS RATE AT 30 DAYS (l/s)	1.1 (16%)	6.0 (33%)	0.4 (10%)

During the course of the 30 day test the flow impedance of the reservoir declined, and at the end was about half its initial value.

Furthermore, the final impedance was nearly equal to that measured in the Phase I reservoir after a comparable period of time, despite the fact that, on average, the effective confining stress acting to close joints is over three times higher in the new reservoir. Two tracer experiments were conducted during the 30 days, and the modal volume, a Table I characteristic measure of the void volume of major fractures and joints, increased from 270 to 350 m^3. This is quite promising, as a reduction of impedance could be the result of flow channeling, i.e., the tendency for the water to sweep through fewer fractures of larger aperture, resulting in smaller modal volumes and heat production, rather than the increased modal volume actually observed.

The water loss rate, expressed as a fraction of the injected flow rate, was higher than the Phase I value after a comparable period, but this may be an artifact of our constant experimentation during the 30 days of testing. Many shut-in experiments were conducted, as well as changes of injection flow rate and production well pressure, thus precluding the attainment of quasi-steady state water losses. In addition we attribute this short-term loss rate to the large highly fractured volume of the several fracture and stimulation efforts and the increasing volume due to high injection pressures maintained and evidenced by microseismic activity.

Seismicity during this experiment was quite low, and the largest event registered about 0.4 on the extrapolated Richter body wave scale. Observation of coupon test specimens indicate very low corrosion (15 mils per year or 0.38 mm/yr). Finally, this short test was designed to measure hydrological and volume properties, and so was never intended to be run long enough to measure potential thermal drawdown. A test of about one year duration is presently scheduled to begin in 1988.

SUPPORTING ACTIVITIES

In addition to the drilling and stimulation activities described above, the following activities have continued. These activities are expected to have significant impact on the continuing development of HDR technology.

1. In a cooperative program with Westfalische Berggewerkschaftskasse of Bochum, FRG, a high-temperature borehole acoustic televiewer has been designed and fabricated, and will be field tested at the end of February 1987. A televiewer measures the travel time of ultrasonic pulses reflected from the borehole wall to map irregularities in the reflecting surface -- such as natural or hydraulic fractures -- with a high degree of resolution. In addition to a number of acoustic and thermal design improvements, this new instrument is of modular construction to facilitate field assembly and maintenance, and incorporates a downhole microprocessor to control data collection and produce a digital signal for transmission to the surface.

2. In addition to conventional analyses of microseismic data collected during pressurization tests, special studies have been made of low-frequency, long-period events that occur early in pressurization, which may represent tensile fractures. Downhole-tool coupling phenomena are being investigated to improve design of geophone sondes. There has been further improvement of the hodogram technique of seismic-event location, and software has been developed for a Masscomp computer that has greatly increased the speed and accuracy of on-line event location during stimulation and flow experiments. This system will be employed for a more comprehensive look at earlier data. Good progress has been made in correlating fault-plane solutions with the locations of seismic events.

3. An active seismic interrogation method has been developed that uses an acoustic source transmitter that "scans" a section of one wellbore, while a receiver is stationed in the adjacent wellbore. The transmitter houses a 3J magnetostrictive source that operates at the frequency of 8.5 kHz. The transmitter can be triggered at rates of up to 5 pulses per second. An accelerometer, mounted coaxially with the magnetostrictive source, provides a zero time for each pulse. The receiver consists of a piezoelectric transducer that is tuned for maximum response at the transmission frequency. The receiver gain can be controlled automatically downhole or manually from the surface control unit. The characteristics of the medium through which the acoustic vibrations pass are deduced from the character of the received signals and from their arrival times at the detector. The distance between two boreholes can be measured with considerable accuracy, and the presence of fluid-filled fractures in the formation can be determined.

4. Recent reservoir-engineering activities have included numerical and analytical studies of fluid flow in deformable joints; estimations of fracture apertures from hydraulic data and of fractured-reservoir size from the results of hydraulic-fracturing experiments; and modeling of thermal effects during a variety of pressure-transient tests.

5. Geochemical studies have included investigations of the degradation of sepiolite drilling muds at high temperatures, corrosion and calcite deposition in surface-system components, a variety of chemically reactive tracers, and the adsorption of such tracers on rock surfaces. The reactive tracer technique will use the extreme temperature dependence of chemical reaction rates to map the progress of the thermal front in an HDR reservoir during long term energy extraction. Derivatives of bromobenzene are excellent candidates for re-

active tracers in high temperature geothermal reservoirs from 200-300°C.

6. Corrosion resistance of the logging cable accounts for many of the limitations to work in geothermal boreholes. Tests are in progress to determine effects of brines where sulfides and chlorides are present. Tests are also planned to determine work hardening of tubular cores used in available magnesium oxide-insulated cables. More studies are needed to determine cooling methods when retrieving cables from very hot wellbores. In addition, development of high-temperature electronics using special devices such as integrated thermionic circuits will contribute to reliable operation of logging tools up to temperatures of 500°C.

7. The Electric Power Research Institute has undertaken an independent study of the economic potential of commercial hot dry rock energy systems.

CONCLUSIONS

Seismic monitoring provides a view of fracture systems which is unobtainable by any other means at the depths of interest here. These seismic observations, supported by results in Britain as well as from the rock mechanics lab, indicate that injecting low viscosity fluid, like water, into jointed rock results in multiple joint stimulation caused by shear-slippage, not the single tensile fracture of conventional theory. Guided by microearthquake maps, an existing well was sidetracked and redrilled into the 0.05 km^3 stimulated zone created by earlier massive hydraulic injections at EE-2. The redrilled well encountered zones of permeability induced by the early stimulation but it required supplementary stimulation before good flow communication could be established between the two wells. Two of the four supplementary stimulations were successful in making hydraulic connections, and the new reservoir appears promising. In May and June of 1986 we completed an initial closed-loop flow test to acquire preliminary information on reservoir behavior, and as shown in Table I, the new reservoir represents a considerable improvement over the old Phase I reservoir. A long term test is planned. Armed with these results, as well as complementary results in Europe and Japan, the stage should be set for successful commercial adaptation of HDR technology.

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