The US Hot Dry Rock Program --
20 Years of Experience in Reservoir Testing

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Abstract

During 25 years of research on Hot Dry Rock (HDR) geothermal energy at Los Alamos National Laboratory, no obstacle has yet been found that would preclude its ultimate development into a major new energy source for mankind. Techniques for efficiently extracting the thermal energy contained in the vast worldwide resource of deep, hot crystalline rock have been under investigation since 1973 at the Laboratory's Fenton Hill HDR test site in north-central New Mexico. From the engineering and flow testing of two successive deep HDR reservoirs, we have gained a clear understanding of how to create such man-made geothermal systems. Also, we have learned a great deal about the rock mass deformation and joint flow within the pressure-dilated region comprising the HDR reservoir at pressures well in excess of the minimum earth stress. The principal remaining task is that of increasing the productivity of these man-made reservoirs through engineered solutions.

Introduction

Actual construction of the world's first HDR geothermal reservoir (referred to as the Phase I reservoir) was begun at Fenton Hill in 1974, with major flow testing, including a 9-month continuous circulation test, occurring during the period from 1978 through 1980 (Dash et al., 1981). Then, beginning in 1980, a deeper and hotter reservoir was constructed at the same site. This second HDR reservoir, referred to as the Phase II reservoir, has been under development and testing since 1983, with the most recent period of flow testing having occurred from April 1992 through May 1993 (referred to as the Long-Term Flow Test). The current reservoir -- with which most of this paper will be concerned -- is situated at a depth of about 3500 m in highly jointed Precambrian granitic rock with a mean temperature of 240°C.

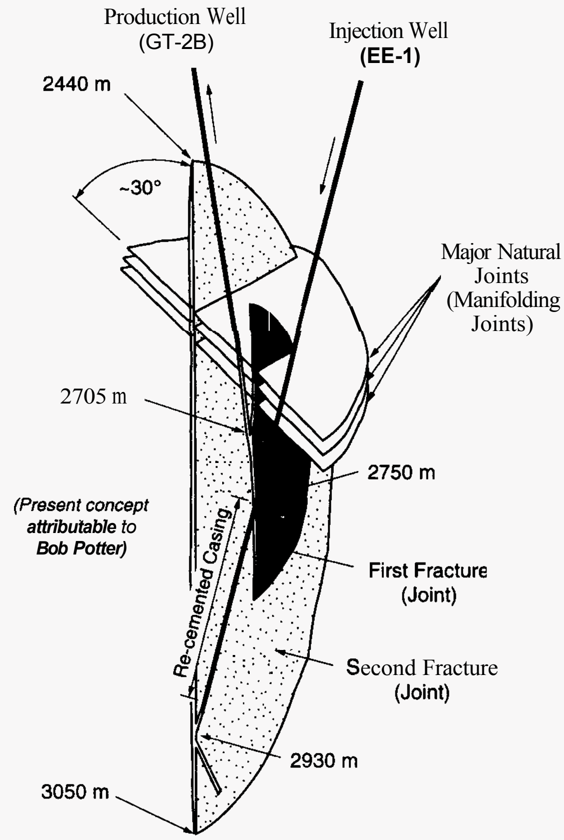

Figure 1: Concept of the Phase I Reservoir following re-cementing of the production well to close off the upper fracture connection at 2750 m.

This paper deals primarily with the knowledge we have gained from extensive reservoir flow and pressure testing over the years, and does not consider other areas of effort such as packer design, drilling, high-temperature completions, or diagnostic tool development.

Background

The principal difference between the larger Phase II reservoir and the earlier, somewhat shallower Phase I reservoir, as discussed in more detail later, is in the associated joint structure. In the Phase I reservoir shown schematically in Figure 1, the continuous joints were vertical, and oriented almost orthogonal to the direction of the least principal earth stress (σ_3, at a depth of 3000 m at Fenton Hill, is about 10 MPa above hydrostatic and essentially horizontal in roughly a N60°E direction). However, from wellbore observations, the manifolding joints connecting these continuous vertical joints were inclined about 30" from the vertical.

For the somewhat deeper Phase II reservoir, the continuous joints are almost north-south in orientation, but inclined to the east at from 15° to 30° from the vertical (listed in Table I as planes IA, IB, II, 2A, 2B, and 2C), whereas the manifolding joints (listed in Table I as planes 1A and 1B) are also inclined to the east, but rotated farther toward the second principal stress. The inclination of the Phase II manifolding joints with respect to both the overburden (maximum) and the second (horizontal) principal stresses accounts for the significantly higher surface injection pressures required to initiate high rates of reservoir inflow -- about 15 MPa for the Phase I reservoir and about 37 MPa for the Phase II reservoir. However, the Phase II reservoir is vertically separated from the overlying Phase I reservoir by only about 300 m. Between these two reservoir regions is a near-horizontal microbrecciated shear zone (Levy, 1995) that apparently stops the upward extension of pressure-dilating joints into the lower-pressure Phase I reservoir region.

Table 1. Orientation of the Predominant Joints Stimulated During the Massive Hydraulic Fracturing (MHF) Test in December 1983 (all angles in degrees)

Plane'	Strike	Dip
IA	N4W	74E
IB	N2W	75E
II	N3E	61E
1A	N29W	76E
1B	N29W	76E
2A	N6E	67E
2B	N5E	64E
2C	N8E	67E

'Letters indicate separate, but parallel, planes. Roman numerals refer to the major joints stimulated during the first 10 hours of seismic activity, as determined from the re-analysis of a much larger microseismic data set. Arabic numerals represent the analysis of the initial microseismic data set for the full duration of the **MHF** test.

WHAT WE HAVE LEARNED

The Deep Precambrian Basement at Fenton Hill

The deep Precambrian basement at Fenton Hill, and by inference at many other locations in the U.S. and elsewhere, is highly jointed. At Fenton Hill, the age of the intrusive granodiorite is 1.5 billion years and that of the host metamorphic complex is 1.62 billion years. As might be expected considering the age of the rock mass and previous episodes of deformation, the preexisting joint systems in these ancient rocks generally are not now aligned with the contemporary stress field.

Based on the results of extensive pumping tests at Fenton Hill, the joint systems in these rocks now appear to be completely sealed at depths below those corresponding to crustal temperatures of about 200°C. This sealing, from core and drill cuttings analyses (Levy, 1995), is typically from secondary mineralization, probably resulting from a slowly diminishing convective flow of hot, mineral-laden connate fluids over a very long period of time. These large-scale field observations have been recently supported by laboratory experiments on granite samples. Moore et al. (1994) report that the addition of hydrothermal fluids to heated, intact granite leads to significant permeability reductions in the temperature range of 300° to 500°C. In addition, they observed that the flow rate through an artificially created, throughgoing fracture eventually drops to the level of intact granite.

When such a jointed rock mass is internally pressurized by pumping from the surface, one or more of the joints favorably oriented with respect to the least principal earth stress will open. The joints intersecting the wellbore injection interval, which represent planes of weakness and are probably also slightly more permeable than the surrounding country rock, would be expected to fail in tension before. the country rock hydraulically fractures as the wellbore pressure is increased. These joints would then progressively open, extend, and intersect, expanding the dilated reservoir region as high-pressure injection continues. However, the rock mass beyond the slowly expanding periphery of the pressurized region would remain tightly sealed, as our very low overall fluid loss measurements have shown.

The Formation of Hot Dry Rock Reservoirs

At Fenton Hill, we have demonstrated that at appropriate temperatures and depths in the earth's crust (at least 200°C at 3 to 5 km), large HDR reservoirs can be created in regions of previously impermeable crystalline rock. Specifically, the present Phase II reservoir has a stimulated volume of about 130 million m3, and would be capable of a thermal power production level of about 20 MW for a period of at least 15 years (Brown, 1994b). We have repeatedly shown that water under high pressure can be used to open and then extend (i.e., hydraulically fracture) preexisting -- but sealed -- joint systems, creating a network of interconnected flow passages. This dilated region of hot, jointed crystalline rock is referred to as the HDR geothermal reservoir. The nature of the pressurized deformation of this dilated region is mostly controlled by the orientations of the joint sets within it relative to the contemporary stress field. Conversely, the deformation of the reservoir region is only minimally influenced by the mechanical characteristics of the rock blocks themselves, which appear to be very stiff (with a very high bulk modulus) and to compress in a linearly elastic fashion.

In cooler regions of the earth's crust where the preexisting joints and faults are either open or only partially filled with secondary minerals; or in hotter, but tectonically active areas containing recent joints or faults (e.g., the Japanese HDR site at Ogachi), the necessary requirement of an essentially impermeable rock mass to contain the HDR reservoir may not be satisfied. In these cases, one is left with a situation intermediate between a true hot *dry* rock environment and a hydrothermal environment, where the rock mass is leaky but does not contain sufficient mobile fluid to be commercial. The Japanese have proposed exploiting such marginal hydrothermal systems using modified HDR reservoir stimulation and injection techniques, and refer to these intermediate systems as Hot Wet Rock geothermal reservoirs (Abe and Hayashi, 1992).

Figure 2 shows a plan view of the Phase II HDR reservoir at Fenton Hill, New Mexico. The majority of this reservoir was initially formed at an average injection pressure of 48 MPa during the massive hydraulic fracturing (MHF) test in December 1983, and then extended to the south and east at injection pressures up to 32 MPa during the initial 30-day flow test in mid-1986 (Dash, 1989). The volume of the stimulated region, as determined from the envelope of microseismic events defining the pressure-stimulated reservoir (the ***seismic*** volume), is about 130 million m^3. However, the adequately flow-connected portion of the reservoir, at lower circulating or testing pressures of from 10 to 27 MPa, appears to be only about 16 million

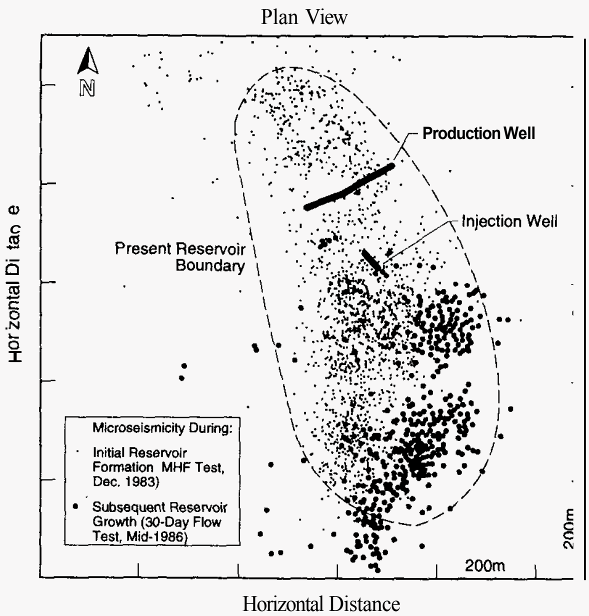

Figure 2: Plan view of the Phase II HDR Reservoir at Fenton Hill showing microseismic event locations.

m³. As can be seen in the plan view of Figure 2, the reservoir is elongate in the north-south direction with a length of about 1000 m and a width of about 350 m. The corresponding height (not shown) is 650 m. Figure 3 shows the correlation between the seismic volume of the expanding reservoir and the volume of injected fluid during the MHF test, the initial phase of pressure stimulation. It can be inferred from Figure 3 that to create even larger HDR reservoirs, one need only pump at high pressure for longer periods of time, since the reservoir volume is directly proportional to the amount of water injected. However, this is definitely not the case for corresponding hydraulically fractured sedimentary formations in the oil industry. There, the rock is typically moderately permeable, and fluid leakoff at the boundaries ultimately limits the size of the stimulated region.

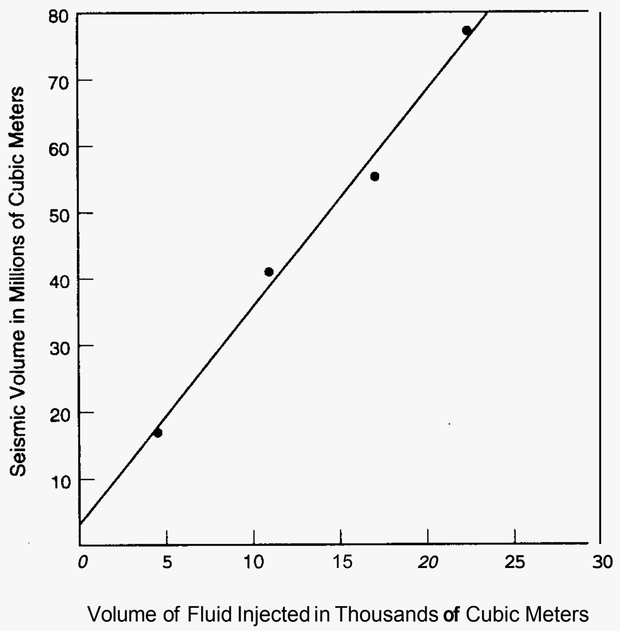

Figure 3: Linear relationship between reservoir volume and volume of injected fluid as determined from the microseismic event location data from the Massive Hydraulic Fracturing Test in December **1983.**

The 3-Dimensional Nature of HDR Reservoirs and Implications Regarding the Resulting Flow Patterns

With the possible exception of the major portion of the HDR reservoir at Hijiori, Japan (Yamaguchi, 1993), all HDR reservoirs tested to date worldwide are three-dimensional in nature, which implies that when each of these reservoirs was created, at least two interconnected joint sets were simultaneously opened. This accounts for the observed 3-dimensional nature of HDR reservoirs. For example, the Phase II reservoir at Fenton Hill, as shown in Figure 2, has a thickness of about 350 m in the third dimension, implying axial (north-south) as well as transverse (east-west) flow.

From our experience with multiply jointed reservoirs at Fenton Hill, it is quite apparent that the highest-opening-pressure joints which are required to establish a circulating system (i.e., the manifolding joints), also provide the principal reservoir paths for transverse flow from the injection well to the production well. Otherwise, we would have observed good flow communication at lower injection pressures, where other joints were already open. In fact, if good flow communication at lower pressures had been established, as we experienced in the Phase I reservoir at 15 MPa, we could never have achieved an injection pressure high enough to open the manifolding set of joints in the Phase II reservoir which appear to open at about 27.5 MPa above hydrostatic -- 17.5 MPa *above* the least principal earth stress. This is not to imply that some of the lower-opening-pressure joints are not extensive, but simply that the flow ***must*** traverse across one or more of the highest-opening-pressure manifolding joints in flowing from the injection well to the production well.

A corollary to the above assertion is that if, in developing the Phase II reservoir, we had opened one or more direct flow connections between the injection and production wells via lower-opening-pressure joints, we would have achieved a lower impedance flow system, but may have also suffered a direct flow short circuit across the reservoir. In fact, this exact situation occurred while testing the precursor to the older Phase I reservoir during the high backpressure experiment in 1978 (Dash et al., 1981). During this test, water flowed between the injection and production wells primarily across one fairly small near-vertical joint (labeled as the "first fracture" in Figure 1). It was only after having re-cemented the bottom 180 m of the casing in the injection well which shifted the injection point deeper and to the west (i.e., to one side) to a second, and apparently larger, north-south trending vertical joint (labeled as the "second fracture" in Figure 1), that we were able to obtain a much larger, but also a more highly flow impeded (by almost a factor of 10), 3-dimensional HDR reservoir (Dash et al., 1981). The Japanese had apparently also developed a 3-dimensional HDR reservoir with their initial 3-well HDR system at Hijiori in 1989, but the water losses were found to be excessive due to the more open nature of the joints and faults at a depth of only about 1800 m in the tectonically and volcanically active area inside the Hijiori Caldera where their reservoir is being developed.

As discussed previously, the highest-opening-pressure joints (i.e., the manifolding joints) account for the majority of the reservoir flow impedance but with very little associated fluid storage. Conversely, the lower-opening-pressure joints provide the majority of the fluid storage within the reservoir region but very little of the resistance to flow across the reservoir. Based on the steady-state data set obtained from reservoir flow testing in 1992 and 1993 (Brown, 1994a) and numerous previous injection tests, these highest-opening-pressure joints, which have experienced considerable shear displacement as evidenced by the pronounced shear wave arrivals in the microseismic data, open at a surface injection pressure of about 27.5 MPa. However, the lower-opening-pressure joint sets, which are by inference oriented more orthogonal to the least principal earth stress, would have been expected to have experienced significantly less shear displacement, and would therefore have been less obvious in the microseismic data set. The more continuous of the lower-opening-pressure joint sets appears to open at a surface injection pressure of about 22.4 MPa (Brown, 1989).

Based on analyses of a number of injection, pressure decay, and circulation tests performed at Fenton Hill over the past 12 years, it therefore appears that the Phase II reservoir is comprised of at least three separate sets of joints which have opening pressures of 15, 22.4, and 27.5 MPa, respectively. We have observed that as the pressure in the reservoir is slowly increased, the joints first start to pressure-dilate while most of the asperities are still in contact. Then, at the specified opening pressure, the joint surfaces actually separate. The same phenomenon occurs in reverse during slow reservoir pressure decay: the decay curves show inflection points at the respective joint-closing pressures (Brown, 1989). Careful stepwise reservoir inflation measurements indicate that there is a considerable amount of pressure-dependent fluid storage within the reservoir, even before the lowest-opening-pressure joints actually open. Therefore, the joint "opening pressure" is somewhat of a misnomer, since the joints are actually dilating and their mean apertures increasing as the reservoir pressure approaches the observed opening pressure -- only the rate of increase in the aperture with pressure changes at the opening pressure.

Peripheral Water Loss From Deep HDR Reservoirs

At Fenton Hill, for depths corresponding to rock temperatures at or above about 200°C, the joints in the Precambrian basement are initially tightly sealed with secondary minerals. **As** a consequence, the rate of water **loss** from the boundaries of the pressurized and dilated HDR reservoir through the surrounding undisturbed rock mass is very low. This diffusive outflow of water is primarily through the interconnected microcrack fabric of the surrounding **rock,** not through the very-low permeability joints that may be expected to be present. The rate of this diffusion is controlled by the level of reservoir pressurization relative to the earth stresses, and the nonlinear opening of the individual microcracks as a function of their spatial orientation and relative position along the pressure gradient from the boundary of the pressurized reservoir region to the far-field.

The results of extended static reservoir pressure testing have clearly shown that the rate of water **loss** from deep, pressure-dilated regions of hot crystalline rock can be very small. Figure 4 shows the rate of water **loss** from the Phase II HDR reservoir at Fenton Hill during 1-1/2 years of static testing at a surface pressure level of 15 MPa. Following the initial transient period of increased water storage within the body of the reservoir, a linear decline in the rate of water **loss** was observed when plotted vs. the natural logarithm of time, implying two-dimensional diffusion from the boundaries of the reservoir. However, beyond about 9 months, the rate of water **loss** appeared to be approaching a constant value of about 0.13 l/s, suggesting a transition to spherical diffusion from a point source for longer times.

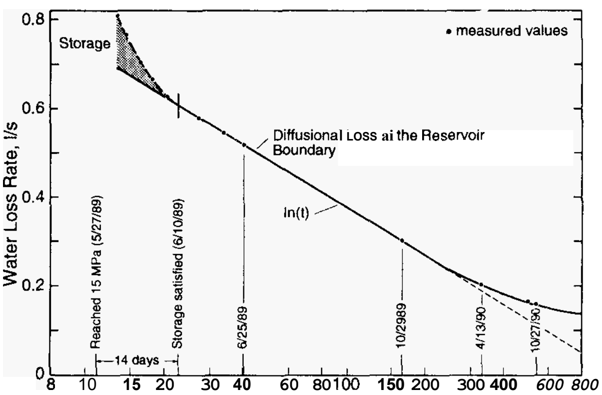

Figure **4:** Water **loss** rate versus ln(time) at a surface pressure of 15MPa for the Phase II Fenton Hill reservoir.

Determining the Size, Orientation, and Internal Structure of the Fenton Hill Reservoir

As an HDR reservoir is being formed and then extended by the injection of high-pressure water, microseismic signals are generated predominantly by shear slippage along joints that are not aligned with the contemporary **stress** field. These microearthquakes occur along all the joint sets with opening pressures **up** to and including that of the manifolding joints as discussed earlier. However, the strongest shear signals apparently are generated by slippage along the manifolding joints which have the highest opening pressure and which would therefore be expected to have the largest component of shear stress. The pressure-dilation and resulting slippage of the various joint sets microseismically defines the envelope and orientation of the evolving stimulated region as shown in Figure 2. In addition, as listed in Table I, the orientations of several of the predominant joint sets comprising the interconnected flow network within the reservoir can **be** determined from an analysis of the microseismic data. However. this in not to imply that there are no near-tensile-opening joints that are being pressurized aseismically within the pressure-stimulated region. Those joints within the stimulated region that are oriented close to orthogonal to the least principal earth stress should open with very little if any shear displacement, and would not be seen in the microseismic data because of the absence of clear shear-wave arrivals. ***It is our assertion that the absence of microearthquakes does not preclude the presence of flow paths for pressurized water.*** In fact, as a result of a 3200 m^3 reservoir stimulation at Fenton Hill that preceded the Massive Hydraulic Fracturing (MHF) test, it appears that the region around the injection wellbore was de-stressed from a shear displacement standpoint. On subsequent injection during the MHF test, this near-wellbore region was aseismic for approximately the first 10 hours of injection while the previously stimulated area was being re-inflated. Subsequently, the microseismic activity within the reservoir increased rapidly as the boundaries of the previously pressurized region were extended.

Self-Regulating Nature of HDR Reservoir Flow

The most significant observation that has been made during the recent Long-Term Flow Testing of the Phase II reservoir is the self-regulating nature of the flow through this pressure-dilated region of rock. With time, the flow tends to progressively concentrate in the more. indirect flow paths at the expense of the more direct flow paths. That is, the flow tends to become more distributed with time rather than becoming more concentrated in a few direct flow paths. This observation **is** based on both tracer and borehole temperature data (Brown. 1994a).

Figure 5 shows the dye tracer response for three times during the flow testing: Early and late during the first phase of the test and late during the second phase of the test. **As** shown, the first arrival of the tracer in April 1992 took about **3-1/2** hours. The delay in tracer arrival then increased in subsequent tests to a final value of about **5** hours. This suggests that the most direct flow paths were being somewhat closed off with time. A corollary observation is the peak in the tracer arrival, which was progressively delayed in time as the testing proceeded. This delay would imply that the flow was becoming more diffuse with time, with the flow tending to concentrate in the more indirect flow paths.

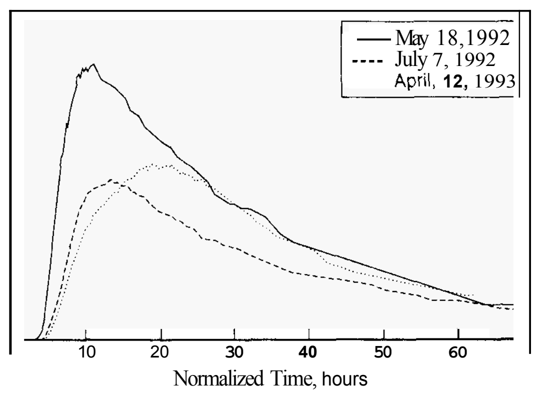

Figure 5. Recovery of Fluorescein Dye Tracer on Three Occasions During the LTFT.

Further, tracer testing (Rodrigues et al., 1993) has shown that, as the level of the reservoir pressure is increased, the flow paths for the circulating fluid tend to become more dispersed. **As** a consequence, by increasing the level of reservoir pressurization, the thermal sweep efficiency is improved, the tendency for flow to short-circuit is reduced, and the overall impedance to flow is reduced.

Conclusions

20 years of experience in HDR reservoir testing has resulted in:

- An understanding of many of the factors important in creating very large, fluid-accessible HDR reservoirs in deep regions of jointed crystalline rock,
- The development of techniques for determining the size and orientation of the pressure-stimulated region, as well as some of the details of the interconnected joint structure internal to the resulting HDR reservoir,
- An understanding of the nature of fluid flow through such deep, pressurized, multiply jointed regions of the earth, and particularly a recognition that the flow tends to become more distributed both with time and with increasing pressure level, and finally
- The observation that, at suitable depths and temperatures (3 to 5 km at temperatures above 200°C) in tectonically quiescent regions, the fluid permeation loss from the boundaries of such pressurized HDR reservoirs is extremely small.

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