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HOT DRY ROCK GEOTHERMAL ENERGY: IMPORTANT LESSONS FROM FENTON HILL

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ABSTRACT

The concept of Hot Dry Rock (HDR) geothermal energy originated at Los Alamos National Laboratory in the early 1970s, to exploit the heat contained in those vast regions of the earth's crust that contain no fluids in place—by far more widespread than natural hydrothermal resources.

Two separate HDR reservoirs were created in deep, hot crystalline rock, at the Fenton Hill HDR Test site about 40 miles west of Los Alamos. These reservoirs, at depths of 2800 m and 3500 m and temperatures of 195°C and 235°C respectively, were created with technology that was rapidly evolving at the time. They were flow-tested for a period of almost a year each. Thermal power production ranged from 4 MW for extended routine production intervals to as high as 10 MW for a 30-day period. The testing proved beyond a doubt that it is technically feasible to recover useful amounts of thermal energy from HDR.

From tracer testing of the deeper reservoir, it was found that the flow patterns became more diffuse with time, suggesting that more of the reservoir was being accessed as flow continued—with flow definitely not tending toward short-circuiting, which had been a worry.

The major finding of the work at Fenton Hill is that an HDR reservoir should first be created from the initial borehole, and then accessed by two production boreholes. It is almost impossible to create an effective system by drilling the boreholes first and then trying to connect them by hydraulic pressurization.

INTRODUCTION

In the early 1970s, a small group of researchers at Los Alamos National Laboratory invented, and then patented, the new idea of Hot Dry Rock (HDR) geothermal energy. As defined by these early researchers, the practical HDR resource is the heat contained in those vast regions of the earth's crust that contain no fluids in place—the situation characterizing by far the largest part of the earth's drilling-accessible geothermal resource.

What is a true HDR geothermal energy reservoir?

1) It is an *engineered* reservoir, created within a previously impermeable body of hot crystalline basement rock.
2) It is created by hydraulic pressurization of a selected portion of this deep, multiply jointed—but re-sealed—rock mass.
3) As such, it is *totally* confined, and enclosed within a “stress cage” reflecting the earth's elastic response to the pressure-dilated HDR reservoir.

Because it is a man-made geothermal system, one can control

1) production temperature, by selecting the drilling depth;
2) size of the reservoir, by the amount of fluid injected (Figure 1 shows a plot of seismic volume vs fluid injected for the Massive Hydraulic Fracturing [MHF] Test, as determined by Bob Potter, one of the inventors of HDR).

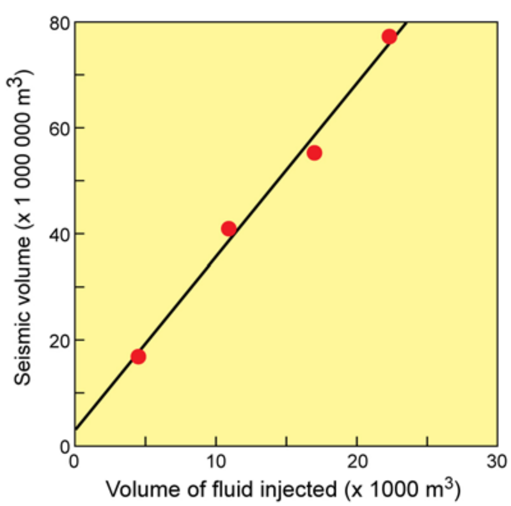

Fig. 1: Linear relationship between seismic reservoir volume and volume of injected fluid, as determined from microseismic event location data during the MHF Test. Source: Brown, 1995 [Fig. 3].

3) injection conditions of pressure and flow rate, as primarily dictated by the jointed reservoir flow situation and the near-wellbore outlet impedance;
4) amount of reservoir growth (if any) allowed during operation, by specifying the degree of reservoir over-pressure (above the joint-extension pressure);
5) production well backpressure (which "modulates" the outlet impedance);
6) number and placement of production wells for optimum productivity. (Figure 2 shows a plan view of reservoir growth during the ICFT, suggesting that a second production well could beneficially be used to access the southern—stagnant—portion of the reservoir, and prevent reservoir growth at the higher ICFT injection pressure of 31.5 MPa.)

RESERVOIR TESTING AT FENTON HILL

The Los Alamos HDR Geothermal Energy Project lasted about 25 years, ending in 1995. During this time, two separate, confined HDR reservoirs were created in deep, hot crystalline rock, and then interrogated and flow-tested for almost a year each. To the author's knowledge, these are still the only true, confined HDR reservoirs created in the world. This testing was conducted at the Fenton Hill HDR Test Site in the Jemez Mountains of north-central NM, about 40 miles west of Los Alamos.

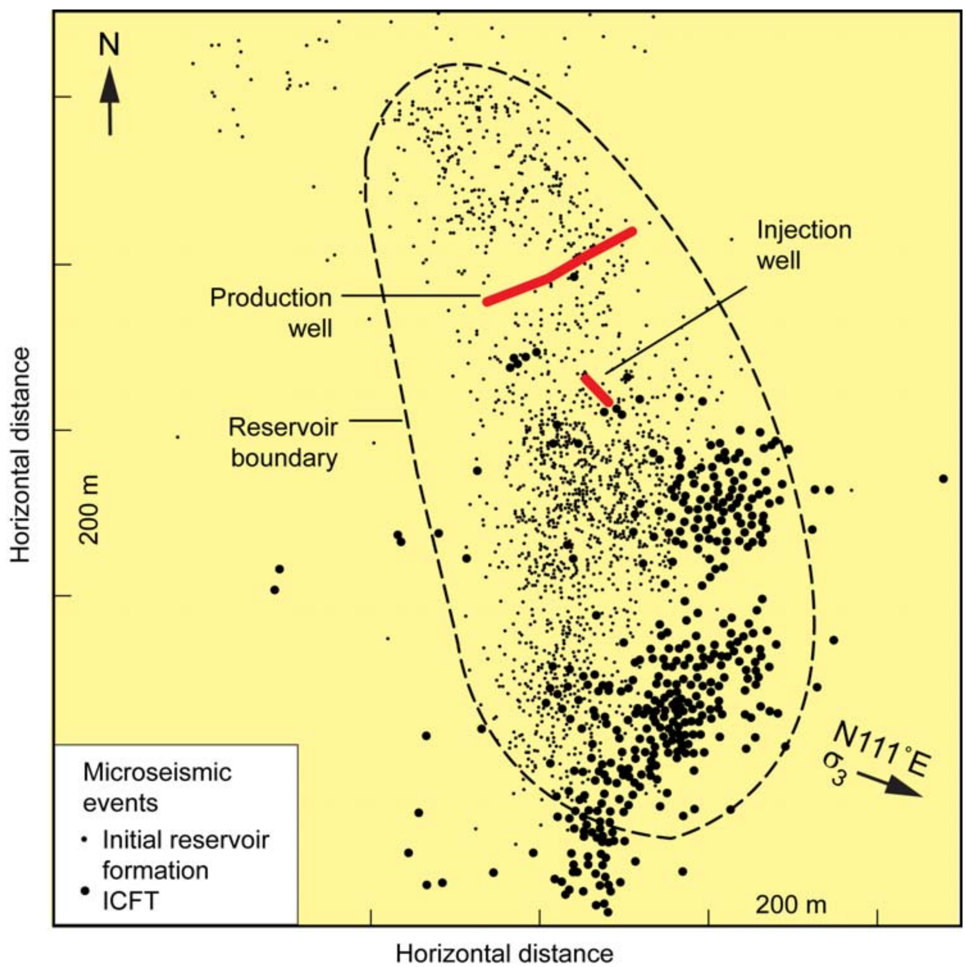

Fig. 2: Distributions of seismic events during the MHF test and during the ICFT. The direction of the least principal earth stress (σ_3) is also shown.
Source: Brown, 1995 [Fig. 2]

The Shallower (Phase I) Reservoir

This first reservoir was created at a depth of about 2800 m (9200 ft), in jointed granitic rock at a mean temperature of 195°C. The operating parameters varied as the reservoir was enlarged during the extensive testing. The seismic volume (the envelope containing the majority of the microseismic events) was increased in steps to a final volume of 10×10^6 m^3. Table 1 summarizes the operating conditions for the final phase of flow testing.

Table 1
PHASE I RESERVOIR TESTING
(March–December, 1980)

PARAMETER	VALUE	COMMENTS
Injection Pressure, MPa (psi)	9.7 (1400)	Declined near end of test
Injection Flow, L/s (gpm) Production Flow, L/s (gpm)	6.3 (100) 5.9 (93)	Final Final
Thermal Power, MW	3	Average
Backpressure, MPa (psi)	1.4 (200)	Average
Production Temp., °C	158	Average
Flow Impedance, psi/gpm	13	Average
Water Loss, L/s (gpm)	0.2 (2)	Final

The Deeper (Phase II) Reservoir

The second reservoir was created at a depth of about 3500 m, again in jointed granitic rock, at a mean temperature of 235°C. Within a previously tight body of crystalline rock, an interconnected array of pressure-stimulated flow paths was formed using hydraulic stimulation. The reservoir was flow-tested during two periods: the Initial Closed-Loop Flow Test (ICFT) in 1986, and the Long-Term Flow Test (LTFT) from 1992 through 1995. The seismic volume for the initial reservoir created during the MHF Test, at a joint extension pressure of about 38 MPa (5500 psi), was 1/3 km^3. However, as shown in Figure 2, there was considerable additional seismic growth to the south during the ICFT.

The diffusional water loss from the boundaries of this totally confined reservoir was only about 0.15 L/s after 1 1/2 years of pressurization at 15 MPa above hydrostatic (about the flow from a garden hose).

Table 2 summarizes the typical operating conditions for the Phase II reservoir.

Table 2
PHASE II RESERVOIR TESTING
(1986–1995)

PARAMETER	VALUE	COMMENTS
Injection Pressure, MPa (psi)	26.9 (3900) 31.5 (4570)	LTFT ICFT
Injection Flow, L/s (gpm)	6.3 (100)	LTFT
Production Flow, L/s (gpm)	13.5 (214) 5.9 (93)	ICFT LTFT
Thermal Power, MW	10 4	ICFT LTFT
Backpressure, MPa (psi)	3.3 (1400)	LTFT
Production Temp., °C	190	ICFT
Flow Impedance, psi/gpm	19	ICFT
Water Loss, L/s (gpm)	0.15 (2)	Pre LTFT at 15 MPa

Based on closed-loop circulation testing, it was found that the flow impedance of the Phase II reservoir was concentrated near the exit wellbore—the near-wellbore outlet impedance. Less than 10% of the overall flow impedance was in the body of the reservoir because the flowing joints were being held open (pressure-propped) by a mean pressure of about 26 MPa, about 16 MPa above the least principal earth stress. On the other hand, less than 1% of the overall impedance occurred near the reservoir entrance—since, after about 2 weeks of cold water injection, thermal dilation had opened the inlets of the joints connected to the reservoir.

A NOT-OFTEN-ACKNOWLEDGED FACT: AN HDR RESERVOIR IS *CONFINED* (OTHERWISE, IT IS AN *OPEN* HYDROTHERMAL SYSTEM)

Both of the HDR reservoirs produced at Fenton Hill were confined. Although obvious, the single necessary requirement to demonstrate confinement is that the reservoir be pressure-tight. That is, the reservoir can be maintained at an elevated pressure with only a small—and declining—injection flow, to satisfy the diffusional water loss at the reservoir boundaries.

Figure 3 shows the rate of water loss from the Phase II reservoir during a 17-month period of shut-in testing. During this time, the daily amount of pressurized injection needed to maintain the reservoir pressure level at 15 MPa (2280 psi) was measured. At the end of the shut-in period, the water loss rate from this very large reservoir was only 0.15 L/s (2 gpm)! The corresponding loss rate from the Phase I reservoir after 5 months of flow testing was 0.4 L/s (7 gpm).

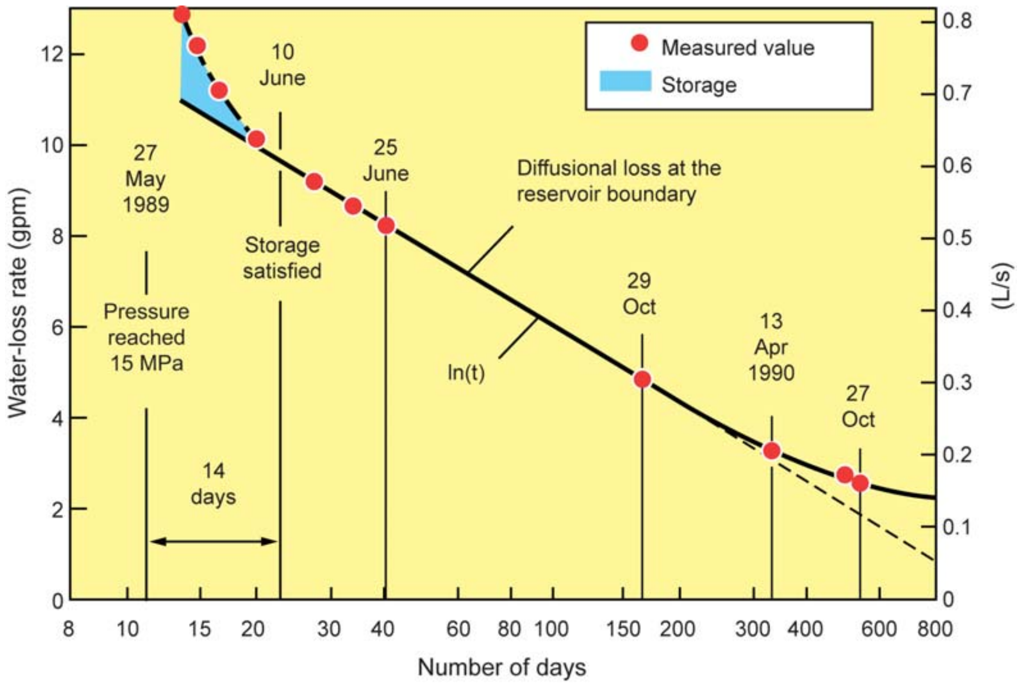

Fig. 3: The Phase II Fenton Hill reservoir: water loss rate vs the logarithm of time at a reservoir surface pressure of 15 MPa.
Source: Brown, 1995 [Fig. 4]

SIGNIFICANT OBSERVATIONS AND CONCLUSIONS

The most profound lesson from the Laboratory's HDR work is that to create an effective HDR geothermal system, the stimulated region should first be created from the initial borehole, and then accessed by two production wellbores drilled to near the elongated boundaries of the seismically determined, ellipsoidal reservoir region. To first drill two boreholes, and then try to connect them by hydraulic pressurization, is almost impossible. (The reason for two production wellbores is twofold: First, to double the productivity; and second, to permit even higher reservoir pressures to further dilate the flowing joints and reduce the body impedance, while constraining additional reservoir growth.)

Reservoir productivity is the most critical remaining issue related to HDR technology development, and this is inexorably linked to the near-wellbore outlet impedance. This impedance can be significantly reduced by operating the production wells at elevated pressure, which tends to dilate these otherwise tightly closed flow outlets (held closed by the wellbore stress concentration and the decreasing differential pressure holding the joints open as the flow converges to the production wellbore).

A major observation from our Fenton Hill HDR reservoir testing and development is that the characteristics of the jointed rock mass are variable, and unpredictable. For example, the joint-extension pressure in the Phase I reservoir was only about 2000 psi, whereas the corresponding joint-extension pressure for the Phase II reservoir was 5500 psi, a remarkable difference. This pressure is controlled by the interconnected joint structure—something that cannot be discerned from borehole observations (as yet) nor, assuredly, from the surface!

Although microseismic observations are essential to understanding HDR reservoir development, there is much more to do in this field—particularly in understanding/discerning that portion of the induced seismicity that is really related to the opening of the joints providing the principal flow paths.

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