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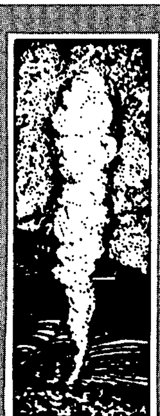

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DISCLAIMER

COMPARISON OF TWO HOT DRY ROCK GEOTHERMAL RESERVOIRS

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Two hot dry rock (HDR) geothermal energy reservoirs were created by hydraulic fracturing of granite at 2.7 to 3.0 km (9000 to 10 000 ft) at the Fenton Hill site, near the Valles Caldera in northern New Mexico. Both reservoirs are research reservoirs, in the sense that both are fairly small, generally yielding 5 MWt or less, and are intended to serve as the basic building blocks of commercial-sized reservoirs, consisting of 10 to 15 similar fractures that would yield approximately 35 MWt over a 10 to 20 yr period. Both research reservoirs were created in the same well-pair, with energy extraction well number 1 (EE-1) serving as the injection well, and geothermal test well number 2 (GT-2) serving as the extraction, or production, well. The first reservoir was created in the low permeability host rock by fracturing EE-1 at a depth of 2.75 km (9020 ft) where the indigenous temperature was 185°C (364°F). Reservoir performance was evaluated by a 75-day long period of closed-loop operation from January 28 to April 13, 1978. Hot water from the production well was directed to a water-to-air heat exchanger where the water was cooled to 25°C before reinjection. The relatively low power produced did not economically justify the conversion of the geoheat to beneficial usage, so it was simply dissipated to the atmosphere by this heat exchanger. The cooled water, in addition to the makeup water that was required to replace downhole losses to the rock surrounding the fracture, was then pumped down the injection well and then through the fracture system. Heat was transferred to the water by means of conduction within the nearly impervious rock contiguous to the fracture surfaces and the heated water was withdrawn by means of the production well. Results of the 75-day assessment of the first reservoir were presented by Murphy et al. (1978), Tester and Albright (1979), and Murphy and Tester (1979) but are summarized for comparison with the second reservoir below.

A second, larger reservoir was formed by extending a small, existing fracture at 2.93 km (9620 ft) in the injection well about 100 m deeper and 10°C hotter than the first reservoir. The resulting large fracture propagated upward to about 2.6 km (8600 ft) and appeared to have an inlet-to-outlet spacing of 300 m (1000 ft), more than three times that of the first fracture. Comparisons are made with the first reservoir in Table 1. Evaluation of the new reservoir was accomplished in two steps: (1) with a 23-day heat extraction experiment that began October 23, 1979, the results of which are described by Murphy (1980), and (2) a second, longer-term heat extraction experiment still in progress, which as of November 25, 1980 has been in effect for 260 days. The results of this current experiment are compared with earlier experiments below.

TABLE 1.

CHARACTERISTICS OF RESERVOIR SYSTEMS STUDIED
WITH FIRST PAIR OF WELLS

Characteristic	First Reservoir May 1977 - Jan. 1979	Second Reservoir Jan. 1979 - Present
EE-1 injection hole condition	Before recementing	After recementing
Main injection zone location in EE-1	2.75 km (9020 ft)	2.93 km (9620 ft)
Main production zone locations in GT-2	2.6 - 2.7 km (8600 - 8850 ft)	2.6 - 2.7 km (8600 - 8850 ft)
Average wellbore separation between EE-1 and GT-2 in the production interval	100 m (300 ft)	300 m (900 ft)

RESERVOIR GEOMETRIES AND FLOW PATHS

Figure 1 shows the inferred geometry of both fractures. The first fracture, whose origin was at 2.75 km in EE-1, is shown as the small vertical fracture and the new fracture is shown to the left as the larger one. Both fractures are shown as nearly vertical because the planes of hydraulic fractures are orthogonal to the minimum (least

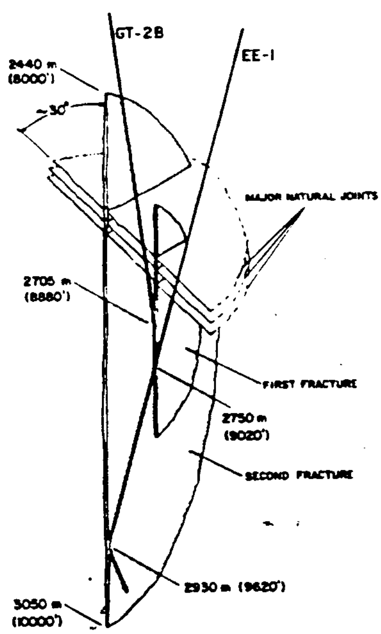

Fig. 1. Inferred reservoir geometry.

compressive) component of the tectonic earth stress. In tectonically relaxed geological settings this stress is expected to be a horizontal one at depths greater than about 1 km and, in fact, it has been shown [Murphy et al., 1977] that the minimum horizontal stress at the Fenton Hill site is only one-half the vertical overburden stress at a depth of 2.7 km. The granitic rock in which these fractures were created is fairly homogeneous and unstratified, so it is assumed that all the fractures discussed here are approximately circular in shape, rather than rectangular as is usually assumed for oil and gas reservoirs in sedimentary formations. All fracturing operations were performed with water alone; no viscosity increasing agents, loss-of-fluid agents, or proppants were added. Subsequent pumping tests suggested that, upon depressurization, the induced fractures remained partially open due to the "self-propping" of the misaligned rough surfaces produced during fracturing. The second reservoir was created by injecting a total of 1360 m^3 (48 000 ft^3) of water, raising the downhole pressure by 200 bars (3000 psi) above the hydrostatic level.

The manner in which the fractures are connected with the production well, GT-2, is complex and was studied with temperature drawdown and recovery measurements, wellbore flow rate measurements, visible dye and radioactive NH_4Br^{82} tracer measurements, and other logging methods. This connectivity apparently consists of a set of nonvertical natural fractures or joints with a dip of approximately 60° that intersect both the vertical fractures and the GT-2 wellbore. These joints appear to be extensions of the same ones that formed the connections between the first fracture and GT-2. The downhole temperatures and velocities of the water in the connecting joints were measured at the joint/well intersections with a combined temperature (thermistor) probe and flow rate (spinner) logging tool, which was used to determine temperature and flow rate profiles in the open hole region of GT-2. Both profiles were used to infer the depth of the connecting joints and also the relative flow rate contributions communicated by each joint.

THERMAL DRAWDOWN

During heat extraction tests of both reservoirs, the downhole temperature and flow rate tool, when not actually logging the well, was positioned at a depth of 2.6 km (8500 ft) in the production well, just above all the known producing joints that intersect the production well. In this manner the mixed mean outlet temperature of the production flow rates converging upon GT-2 was nearly continuously measured. Figure 2 shows the temporal decline of this temperature. The abrupt change in curvature for the first reservoir that occurs at day 25 is due to the doubling of the production flow rate at that time from 6 to 13 ℓ/s (100 to 220 gpm). Despite the thermal drawdown this increase in flow rate resulted in a roughly constant power level after the first 25 days. Peak power was 5.1 MWt and the average power was about 4 MWt. The thermal decline of the first reservoir was 100°C in 75 days.

In comparison, as of November 25, 1980 the mean outlet temperature of the second reservoir had drawdown only 5°C after 260 days of heat extraction at a flow rate of 6 ℓ/s. The initial temperature of the second reservoir was 157°C, 17°C cooler than that of the first

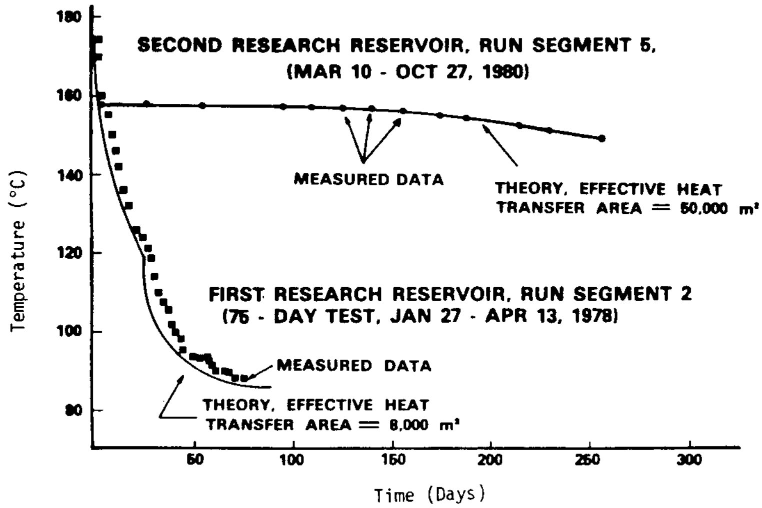

Fig. 2. Comparison of thermal drawdowns, 1st and 2nd reservoirs.

reservoir. This difference in initial temperature is due to the thermal interaction between the closely spaced reservoirs (Figure 1). As a consequence of the drawdown and subsequent thermal recovery of the first reservoir, it is estimated that the temperature of the second reservoir was disturbed by 15 to 20°C. These data, in concert with the thermal drawdown analysis models of Harlow and Pracht (1972) and McFarland and Murphy (1976), result in estimates of 8000 and 50 000 m² (86 000 and 540 000 ft²) respectively, for the effective heat transfer areas of the two reservoirs.

FLOW CHARACTERISTICS

Residence Time Studies. Reservoir volumes and dispersion characteristics were measured by injecting tracers, either the visible dye Na-fluorescein, or radioactive NH_4Br^{82}, in the injection well and monitoring the concentration-time behavior at the production well [Tester, Potter and Bivins, 1979]. Four injections were conducted in each reservoir and the average modal volumes are presented in Table 2, accompanied by the earlier estimate of heat transfer areas, and the fracture aperture derived from the ratio of fracture volume and area. These fracture apertures are in accord with estimates based upon self-propping caused by misaligned fracture surface roughness. Profilometer measurements on core specimens taken at 2.7 km in GT-2, that were fractured after coring, showed that, on a very fine scale, roughness asperities of 0.2 mm, typical of the rock grain size, were spaced every 0.5 mm along the face; but on a larger scale the specimens had surface waves of the order of 1 mm on a 10 mm spacing. Agreement of measured and estimated self-propped apertures during these tests is expected because fracture fluid pressures were maintained at levels below the minimum earth stress.

Flow Impedance. Flow impedance is defined as the pressure drop through the fracture system connecting the two wells, divided by the production flow rate. As shown in Fig. 3 the impedance of the first reservoir declined nearly continuously and at the end of the experiment was less than one-fifth its initial value. Even impedances as

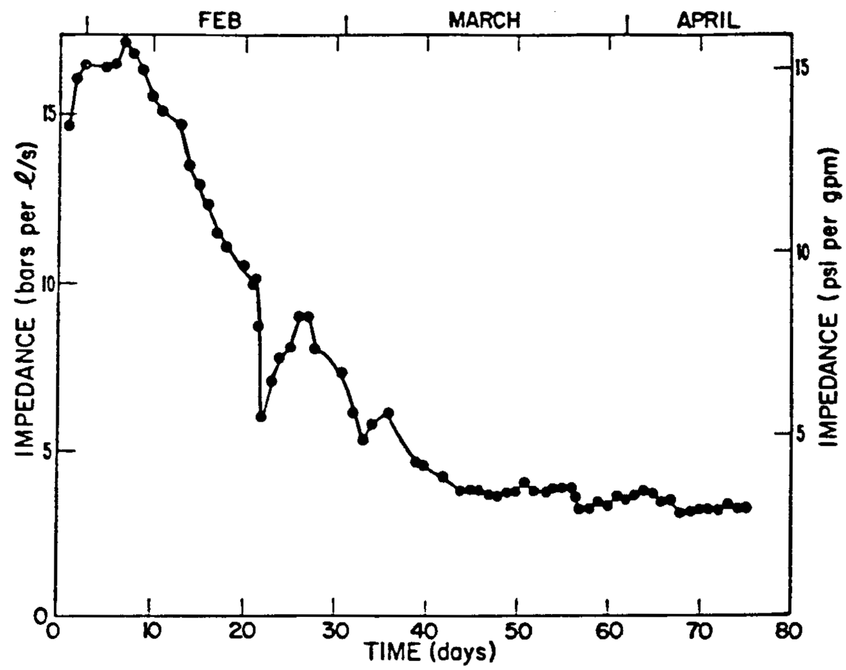

Fig. 3. Temporal variation of flow impedance, 1st reservoir.

high as the initial value, about 17 bars per ℓ/s (16 psi/gpm) are sufficiently low for individual fractures contained in larger multiple-fracture systems of commercial size. The trend of impedance reduction is well correlated with the thermal drawdown shown in Fig. 1 and is probably associated with the partial shrinkage of fracture faces away from each other caused by cooling. This effect is particularly important near the fracture outlets, where previous flow testing had identified localized impedances associated with the joints providing communication between GT-2 and the first hydraulic fracture. In fact, temperature surveys indicated that several closed or sealed joints eventually opened to the point where they began to produce fluid.

In contrast the impedance of the second reservoir has remained essentially constant at 16 bar per ℓ/s during both heat extraction tests; no reduction with time has been observed as occurred in the first reservoir, presumably because the thermal drawdown of the second reservoir is negligible. This rough equivalence of impedance for the two reservoirs results despite the fact that the flow paths in the new reservoir are several times longer; the distance between the inlet and outlets is 3 times longer and the heat transfer area and volume are 6 and 10 times larger, respectively.

Water Losses. Of the 68 000 m^3 of water circulated during the 75-day test of the first reservoir, 1900 m^3 permeated into the surrounding formation. Initially the rate of loss was high but then it diminished, so that at the end of the test the rate was only 0.13 ℓ/s (2 gpm), or 1% of the produced flow rate. At the end of the 23-day test of the second reservoir the water loss rate once again declined, this time to a value of 1.3 ℓ/s (20 gpm) or 20% of the produced flow rate. For comparison purposes the loss rate from the first reservoir after 23 days was 0.7 ℓ/s (12 gpm). Therefore, the water loss rate from the second reservoir was only twice that of the first reservoir after an equivalent period of time, despite a 6-fold increase in reservoir area and a 10-fold increase in volume. Furthermore it is emphasized that these are short-term water losses; sustained heat extraction operations over a period of years would result in additional decline of loss rates as the porosity of the surrounding rock is satisfied, [Fisher, 1977], and in fact our current testing shows that the water loss rate for the second reservoir is only 0.4 ℓ/s (6 gpm) after 235 days.

TABLE 2

RESERVOIR SIZE ESTIMATES

Test	Effective Heat Transfer Area (m^2)	Average Modal Volume (m^3)	Average Aperture (mm)
First reservoir (75-day test)	8000	11.4	1.4
Second reservoir (23-day test)	50 000	111	2.0

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REFERENCES

1. H. D. Murphy, C. O Grigsby, J. W. Tester, and J. N. Albright, "Evaluation of the Fenton Hill Hot Dry Rock Geothermal Reservoir, Part I Heat Extraction Performance and Modeling," in Proc. of 4th Workshop on Geothermal Reservoir Engineering, Stanford Univ. December 13-15, 1978.

2. J. W. Tester and J. N. Albright, eds., "Hot Dry Rock Energy Extraction Field Test: 75 Days of Operation of a Prototype Reservoir at Fenton Hill," Los Alamos Scientific Laboratory report LA-7771-MS (1979).

3. H. D. Murphy and J. W. Tester, "Heat Production from the Geothermal Reservoir Formed by Hydraulic Fracturing--Comparison of Field and Theoretical Results," paper SPE 8265 presented at 54th Annual Mtg. of Soc. Petr. Engrs. of AIME, Las Vegas, Nevada, September 23-26, 1979.

4. H. D. Murphy, ed., "Preliminary Evaluation of the Second Hot Dry Rock Geothermal Energy Reservoir: Results of Phase I, Run Segment 4," Los Alamos Scientific Laboratory report LA-8354-MS (1980).

5. H. D. Murphy, R. G. Lawton, J. W. Tester, R. M. Potter, D. W. Brown, and R. L. Aamodt, "Preliminary Assessment of a Geothermal Energy Reservoir Formed by Hydraulic Fracturing," Soc. Petr. Engr. J. 17, 317-326 (1977).

6. F. H. Harlow and W. E. Pracht, "A Theoretical Study of Geothermal Energy Extraction," J. Geophys. Res. 77, 7038-7048 (1972).

7. R. D. McFarland and H. D. Murphy, "Extracting Energy from Hydraulically Fractured Geothermal Reservoir," in Proc. 11th Intersociety Energy Conversion Engineering Conference, State Line, Nevada, September 12-17, 1976.

8. J. W. Tester, R. M. Potter, and R. L. Bivins, "Interwell Tracer Analyses of a Hydrualically Fractured Granitic Geothermal Reservoir," paper SPE 8270 presented at 54th Annual Mtg. of Soc. Petr. Engrs. of AIME. Las Vegas, Nevada, September 23-26, 1979.

9. H. N. Fisher, "An Interpretation of the Pressure and Flow Data for the Two Fractures of the Los Alamos Hot Dry Rock (HDR) Geothermal System," in Proc. 18th U.S. Symp. on Rock Mechanics, Keystone, Colorado (1977).