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PRELIMINARY ASSESSMENT OF A HOT DRY ROCK GEOTHERMAL ENERGY RESERVOIR FORMED BY HYDRAULIC FRACTURING

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If a mass of relatively impermeable hot rock can be hydraulically fractured and if a heat extraction fluid can be circulated through the fracture and recovered, appreciable amounts of energy can be extracted from the rock. The Los Alamos Hot Dry Rock Geothermal Energy Project is designed to investigate and demonstrate this concept. A series of field experiments have been carried out at a site called Fenton Hill, located on the west flank of the Valles Caldera in the Jemez mountains of northern New Mexico.

In December, 1974, the first deep borehole, GT-2 was completed to a depth of 2.929 km (9609) ft) in granite, where the temperature was 197°C (386°F). A hydraulic fracture was then created near the bottom of this borehole, and a second borehole, EE-1, was drilled to complete the circulation loop, but it failed to intersect the fracture by about 8 m (26 ft). Communication between the wellbores was established by initiating a fracture from EE-1. This paper discusses some aspects of what has been learned about this dual fracture system by subsequent experiments.

Permeation Studies and Minimum Earth Stress

By assuming constant, one-dimensional, permeable flow into a homogeneous porous media with constant properties, and by also assuming that the hydraulic conductivity of the fracture is very large compared to that of the rock, it can be shown that if water is injected into a fracture at a constant rate, q, the change in fracture pressure, P, is[1]:

$$P = \frac{2\mu q}{kA}\sqrt{\frac{\kappa t}{\pi}} \quad \ldots\ldots\ldots\ldots \quad (1)$$

Because the hydraulic diffusivity, κ, is

$$\kappa = k/\mu \bar{\beta} \quad \ldots\ldots\ldots\ldots \quad (2)$$

the product of the fracture area times the square root of permeability, $A\sqrt{k}$, is given by rewriting Eq 1.

$$A\sqrt{k} = 2\sqrt{\frac{\mu}{\pi\bar{\beta}}}\ \frac{q\sqrt{t}}{P} \quad \ldots\ldots\ldots\ldots \quad (3)$$

Typical data for the EE-1 fracture are presented in Fig. 1. The experiment was conducted by pumping into the EE-1 wellbore at a constant rate of 2.1 ℓ/s (34 gal/min), corrected to downhole conditions. A good linear fit to the data is obtained on P versus $\sqrt{t}$ coordinates. Deviation of the later time data from the linear fit is thought to be due to pressure dependent permeability, or a "leak" from the EE-1 fracture to the GT-2 fracture via a flow connection, as will be discussed.

Since the porosity of the granite is less than 1%, the mean compressibility, $\bar{\beta}$, is essentially that of the rock which, based upon the results of sonic velocity logs, is estimated to be 2.7×10^{-6} bar^{-1} (1.9×10^{-7}psi^{-1}; 1 bar = 10^5 N/m^2 = 14.5 psi). Using available properties of water at 200°C,[2] and the above values of $\bar{\beta}$ and q, it can be shown that the $A\sqrt{k}$ value for the EE-1 fracture at the time this experiment was conducted was 2.2×10^{-5}m^3 (7.8×10^{-4}cu ft). Since this result was obtained with an initial pore pressure of zero (taking hydrostatic pressure as the baseline), the $A\sqrt{k}$ derived is more properly designated as $(A\sqrt{k})_o$, where the subscript represents the change in the initial pore pressure.

It is found that values of $(A\sqrt{k})_o$ are most useful when they are interpreted as a parameter which characterizes a fracture. Changes in $(A\sqrt{k})_o$ indicate irreversible changes in a fracture, examples being fracture extension due to pressurization or changes in k due to potential geochemical effects such as the formation and precipitation of rock-water interaction products or the dissolution of rock mineral components, particularly silica (SiO_2).

A historical summary of the $(A\sqrt{k})_o$ for both fractures is presented in Fig. 2. At the top of this figure are identified the various flow experiments, while near the bottom, the maximum EE-1 wellhead pressure achieved during each experiment is indicated. Since the creation of the EE-1 fracture in October, 1975, its $(A\sqrt{k})_o$ has increased during several of these flow experiments. Furthermore, these increases have been observed only when the EE-1 pressure has exceeded 90 to 94 bars (1300 to 1360 psi). Thus, it is believed that these increases in $(A\sqrt{k})_o$ are due to increases in A (fracture extensions) and that the fracture extension pressure, P_e, is approximately 92 bars (1330 psi) above hydrostatic. Since its creation, $(A\sqrt{k})_o$ of the GT-2 fracture has not changed significantly. The maximum sustained pressure ever reached at the GT-2 wellhead was 91 bars (1320 psi), i.e., below P_e. The permeability of the rock surrounding the GT-2 fracture has apparently not changed, in spite of the potential geochemical effects cited above.

If it is assumed that the fracture extension pressure for large fractures is approximately equal to the minimum earth stress less hydrostatic pressure, the value of the minimum earth stress, S_3, in the EE-1 and GT-2 fractures is approximately 375 bars (5440 psi) or 50% of the overburden pressure, S_1.

Pore Pressure Dependent Permeability

The effects of pore pressure upon $A\sqrt{k}$ are indicated in Fig. 3. The results were obtained from an experiment in which the sequence of operations was to first inject water into the EE-1 fracture at a constant rate until a pressure of 28 bars (400 psi) above hydrostatic was reached, and then adjust the flow rate such that this pressure was maintained constant for two hours. In such a manner a new pore pressure was established in the rock adjacent to the fracture face. Following the two-hour "soak" the procedure was repeated at the additional pressure levels shown on the figure. The start of each new change in pressure level was taken as a new zero time and the results, when plotted versus $\sqrt{t}$, yielded straight lines as shown. Using a modified principle of superposition, the $A\sqrt{k}$ for each increment of pressure can be calculated and the results are indicated on the figure. As can be seen, increasing the pore pressure from 0 to 69 bars (1000 psi) above hydrostatic resulted in a factor of 3.8 increase in $A\sqrt{k}$. Since A did not change (pressure levels were below the fracture extension pressure) the permeability apparently increased by a factor of 15.

Additional results, obtained from another flow experiment, indicate that the permeability increases even more sharply (up to a factor of 80!) as the pore pressure increases to 83 bars (1200 psi) above hydrostatic. These results are qualitatively similar to those of Brace, et al.[3] for westerly granite and to those of Potter, et al.[4] for GT-2 core specimens. If one interprets the "effective" stress holding microcracks closed as simply the difference between the earth stress and the pore pressure, then Brace, et al.[3] have shown that reducing the effective stress by increasing the pore pressure tends to open the microcracks, leading to large changes in the effective permeability of the rock.

Fig. 4 presents a summary of all the data we have measured pertaining to pore-pressure-dependent permeability. Included are data from the EE-1 fracture, the present GT-2 fracture (roughly centered at 2.81 km) and an early, now-inactive fracture in GT-2. Empirically we have found that the square root of the ratio of the permeability at zero wellhead pressure to the permeability at elevated pressured, $\sqrt{k_o/k}$, is reasonably linear with pressure as shown. A value of zero for the ratio $\sqrt{k_o/k}$ at the intercept with the abscissa mathematically implies infinite permeability at the face of the fracture plane. A reasonable interpretation would be that when the pressure approaches the maximum horizontal component of earth stress, S_2, (the intermediate earth stress, aligned horizontally and parallel to the fracture plane) the effective stress in the S_2 direction approaches zero with concomitant opening of microfractures. The least squares line using the entire data set has the equation:

$$\frac{k_o}{k} = 1.00 - 0.0098\ P(\text{Bars}) \quad \ldots\ldots\ldots\ldots \quad (4)$$

and the extrapolated pressure, at $\sqrt{k_o/k} = 0$, of 102 bars (1480 psi) above hydrostatic is believed to be an estimate of S_2. Thus the absolute value of S_2 is about 390 bars (5660 psi), or only 15 bars above S_3.

References

1 Gringarten, A. C., Ramey, H. J., Jr., and Raghavan, R. "Unsteady-state pressure distribution created by a well with a single infinite-conductivity vertical fracture," Soc. Petr. Engr. Jour. (Aug 1974), 347.

2 ASME Steam Tables (1967)

3 Brace, W. F., Walsh, J. B., and Frangos, W. T. "Permeability of granite under high pressure," J. Geophys. Res. (1968) 73, 2225-2236.

4 Potter, J. M., Balagna, J. R., and Charles, R. W.: "Permeability of granitic rock at elevated pressures and temperatures," Los Alamos Scientific Laboratory report (to be published).

Nomenclature

A = Area (both sides) of fracture
k = permeability of rock
P = pressure change in the fracture
P_e = fracture extension pressure
q = volumetric flow rate entering the fracture
S_1, S_2, S_3 = maximum, intermediate and minimum compressive earth stress
t = time
$\bar{\beta}$ = mean compressibility $(=\phi\beta_f + (1 - \phi)\beta_r)$
β_r = compressibility of rock
β_f = compressibility of water
κ = hydraulic diffusivity $(= k/\mu\bar{\beta})$
μ = viscosity of water
ϕ = porosity

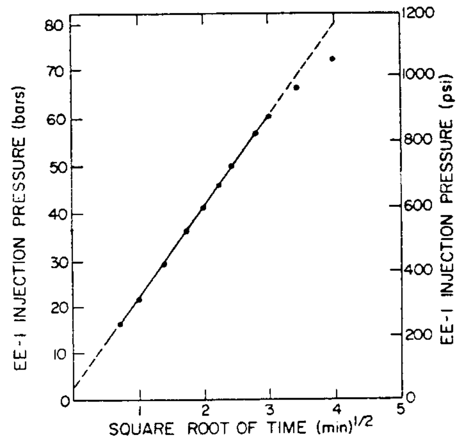

Fig. 1 - Transient increase in well-head pressure due to water injection.

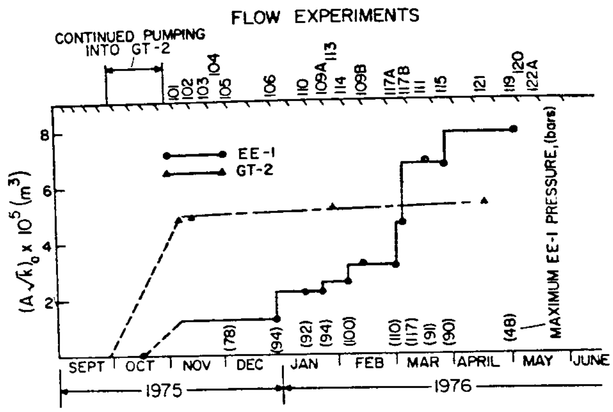

Fig. 2 - Variation of $(A\sqrt{k})_o$ product.

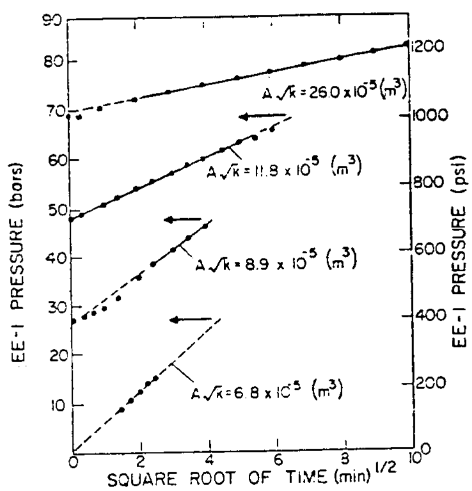

Fig. 3 - Transient pressure increases at elevated pore pressures.

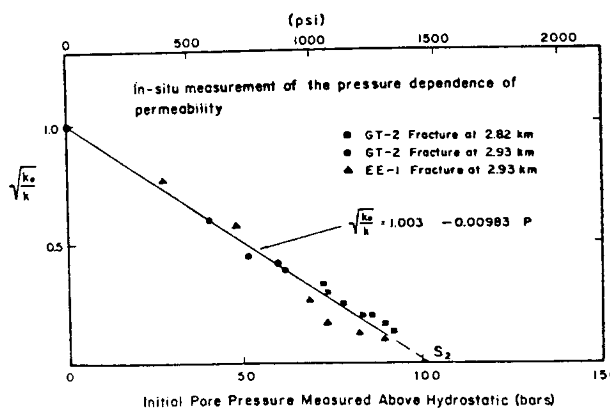

Fig. 4 - Summary of all pore pressure dependent permeability data and extrapolation to intermediate principal stress.