THERMAL DEPLETION OF LIQUID-DOMINATED GEOTHERMAL RESERVOIRS WITH FRACTURE AND PORE PERMEABILITY

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The lifetime of a geothermal power plant is strongly dependent on the fracture spacing and fracture permeability of the geothermal reservoir. This conclusion is based on solution of three coupled linear rate equations for the time dependence of the average temperature of the rock, pore fluid and fracture fluid. By averaging temperature over the entire reservoir and assuming all the fluid is reinjected, effects such as drawdown are ignored, and an upper bound for the reservoir heat content and average wellbore temperature is determined as a function of time. Heat transfer from the rock to the fluid by conduction both in fractures and in pores and by the flow of fluid through the pores is accounted for in this model.

Several approaches to the problem of thermal depletion of a geothermal reservoir are possible. A volumetric estimate of heat in place may be based on an estimate of the volume of fluid available (Towse, 1975). Heat obtained from the rock may be estimated and included in the thermal resource estimate. An estimate for the resource lifetime is then made by assuming some fraction of the thermal resource is recoverable (White and Williams, 1975). A complete numerical simulation of the coupled heat-flow and mass-flow equations for specified well and reservoir geometries can be attempted. Numerical simulations are complex and often involve so many adjustable parameters that it is often difficult to gain insight into a problem from such a solution. Our approach is to idealize the problem (see e.g., Bodvarsson, 1972) and consider only the essential aspects of the heat and mass transport as discussed below. In this way, a model is obta ned which involves a small number of parameters and provides insight into the reservoir behavior during production.

The specific questions of interest are: 1) how much heat can be extracted from the reservoir rocks when reservoir fluid is produced with complete reinjection; and 2) how will the reservoir heat extraction be affected by the presence of fractures?

For a porous reservoir, essentially all of the heat above the re-injection fluid temperature can be removed from the rock. If fractures are present in the reservoir, they may short-circuit the injection-production process and cause a rapid temperature decline.

Our model of the system is represented by Fig. 1. The resource consists of three components: rock matrix, fluid in interstitial pore space, and fluid in the fractures (fissures, faults, etc.). The two fluids are represented by the single box in Fig. 1. Three coupled differential equations represent the idealized model. In defining the equations, we do not need to give the number or distribution pattern of the individual

geothermal wells.   Rather, it is assumed that a system of production and injection wells exists which can accommodate the required flow rates for a specified level of power extraction from the fluid.   In this summary, we consider only the case of fractures which are perpendicular to the wellbores of the production and injection wells.   For vertical wells the fractures are assumed to be horizontal.   If inclined (or horizontal) wells are drilled, the fractures are again perpendicular to the flow in the well system.

The fractures are modeled by a series of channels between parallel plates, as shown in Fig. 2.   Two parameters are used to specify the fracture distribution, w, the aperture or opening of the fracture, and D, the distance between fractures.

The ratio of fracture fluid to pore fluid flowing into the production well is calculated from the assumed permeability of the porous slabs and the calculated permeability due to the fractures.   The heat transfer from rock to pore fluid is given by the steady-state conduction equation.   An exact calculation of the heat exchange from rock to fracture fluid is too difficult, because it would depend on the entire temperature history of the fluid passing the rock.   We estimate that heat transfer term at any time from the instantaneous average temperature difference between the rock and the fracture fluid.   This approximation is tested in results to be shown later (Fig. 5).

Calculated upper bound curves for the average temperature of a reservoir are shown in Fig. 3.   The reservoir has the volume estimated for the Salton Sea KGRA (Towse, 1975).   The flow rate from the production wells is sufficient to produce 1000 MW of electric power, assuming that 16% of the energy coming from the reservoir is converted to useful power.

If no fractures are present, the temperatures of the fluid and rock remain equa? and the heat content decays exponentially.   The time constant of the decay can be calculated from the total thermal mass of the rock and fluid.   The top line in Fig. 3 represents the exponential decay, but the scale is expanded so that the line looks almost straight.

When fractures are present, the depletion curves are calculated by keeping the pore fluid and rock in equilibrium.   We assume that the fractures communicate between injection and production wells.   The fluid produced is a mixture of fracture fluid, which cools rapidly, and pore fluid, which cools slowly.   The rapid decay of average temperature for the mixture is apparent in Fig. 3.

Although this very simple calculation leads to an appreciation of the effects of fractures on field lifetime, it does not represent a good upper bound for the useful lifetime of a geothermal reservoir because regions of cool re njected fluid are averaged with regions of hot fluid near production wells.

Fig. 4 shows how we estimate the temperature profile between the product on and injection wells.   The reservoir is represented by several volumes in series.   Each volume may have a very complicated shape and is not necessarily singly connected.   The fluid is assumed to move through the reservoir with no mixing, i.e., the first volume fills completely with

reinjection fluid before any reinjection fluid reaches the second volume. We choose a time-step sufficient to exchange fluid in one volume, solve for the temperature decline in each volume independently using the method described above, and then move the fluid to the next volume. In several steps, we can calculate the temperature decline at the last volume, which represents the region nearest the production well.

The most important assumption we have made is that the fluid moves without mixing, which is consistent with our desire to find an upper bound. To test our method, and our approximation of the heat-transfer between rock and pore fluid, we compared our calculations to the numerical results of Gringarten, et al. (1975), for hot dry rock with multiple fractures. As shown in Fig. 5, the two numerical methods agreed closely.

Fig. 6 shows our calculated wellbore temperatures for a resource with the volume of the Salton Sea Geothermal Field (SSGF) (Towse, 1975), and an effective power production of 400 MW. Power could be produced at that level for 20 years from the hot fluid alone. Our calculations for a porous medium with no fractures indicate a lifetime of up to 3.3 times as long, because of heat extraction from the rock.

Fractures cause a more rapid decline of production temperature. The calculated temperature drop after 20 years is used as a measure of the effect of fractures. In Fig. 7, that temperature drop is contoured for a variety of values of w and D. The dashed lines indicate different ratios of pore fluid and fracture fluid in the production well.

For small w or D, the depletion is the same as if fractures were absent. If more than 10% of the flow occurs in widely separated fractures, the wellbore temperature declines more rapidly. The depletion increases when

$$D > 50 \text{ m and } \frac{w^3}{D} > 2. \times 10^{-12} \ (m^2).$$

In summary, resource estimates should consider the heat in the rock matrix in addition to that in the geothermal fluid. Fractures may cause a significantly greater temperature decline than would be predicted from estimates based on porous flow alone. This result is very important for the design and production of a liquid-dominated hydrothermal system, because wells are targeted on fractures whenever possible, in order to increase the flow rate per well. Our results emphasize that if reinjection wells and production wells intersect the same fracture system, the useful lifetime of the production wells may be dramatically reduced.

References

G. Bodvarsson, "Thermal Problems in the Siting of Reinjection Wells," Geothermics, Vol. 1, No. 2 (1972).

D. Towse, "An Estimate of the Geothermal Energy Resource in the Salton Trough, California," UCRL-51851 (June 18, 1975).

D. F. White, D. L. Williams eds., "Assessment of Geothermal Resources of the United States - 1975," U.S. Geological Survey Circular 726.

MODEL FOR RESERVOIR HEAT DEPLETION CALCULATION

Power production

Injection wells

Production wells

Reservoir

Rock

Fluid-rock
heat
transfer
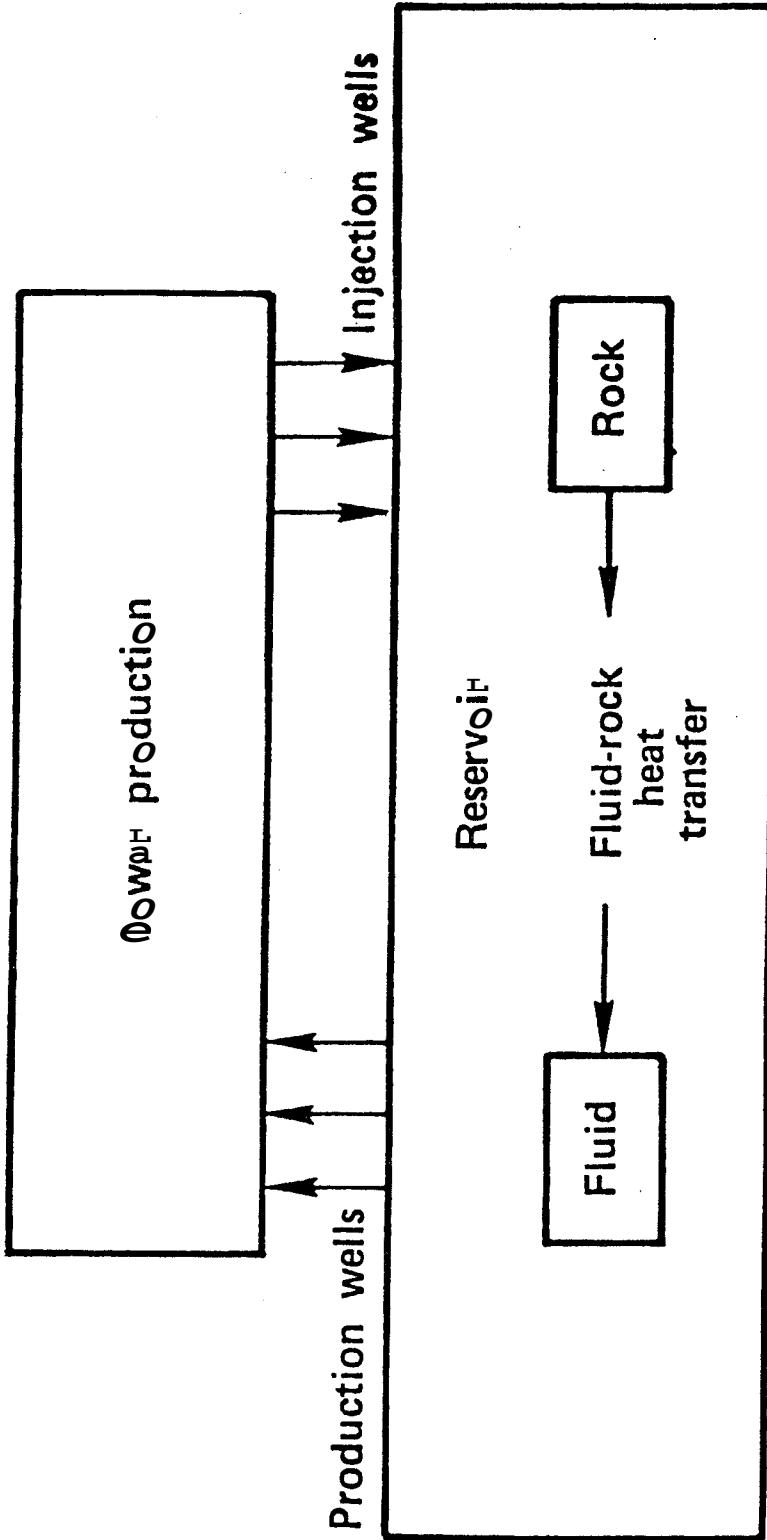
Fluid

Assume

- Constant reservoir mass
- Injection mass equals production mass
- No heat exchange with rock or fluid outside the reservoir
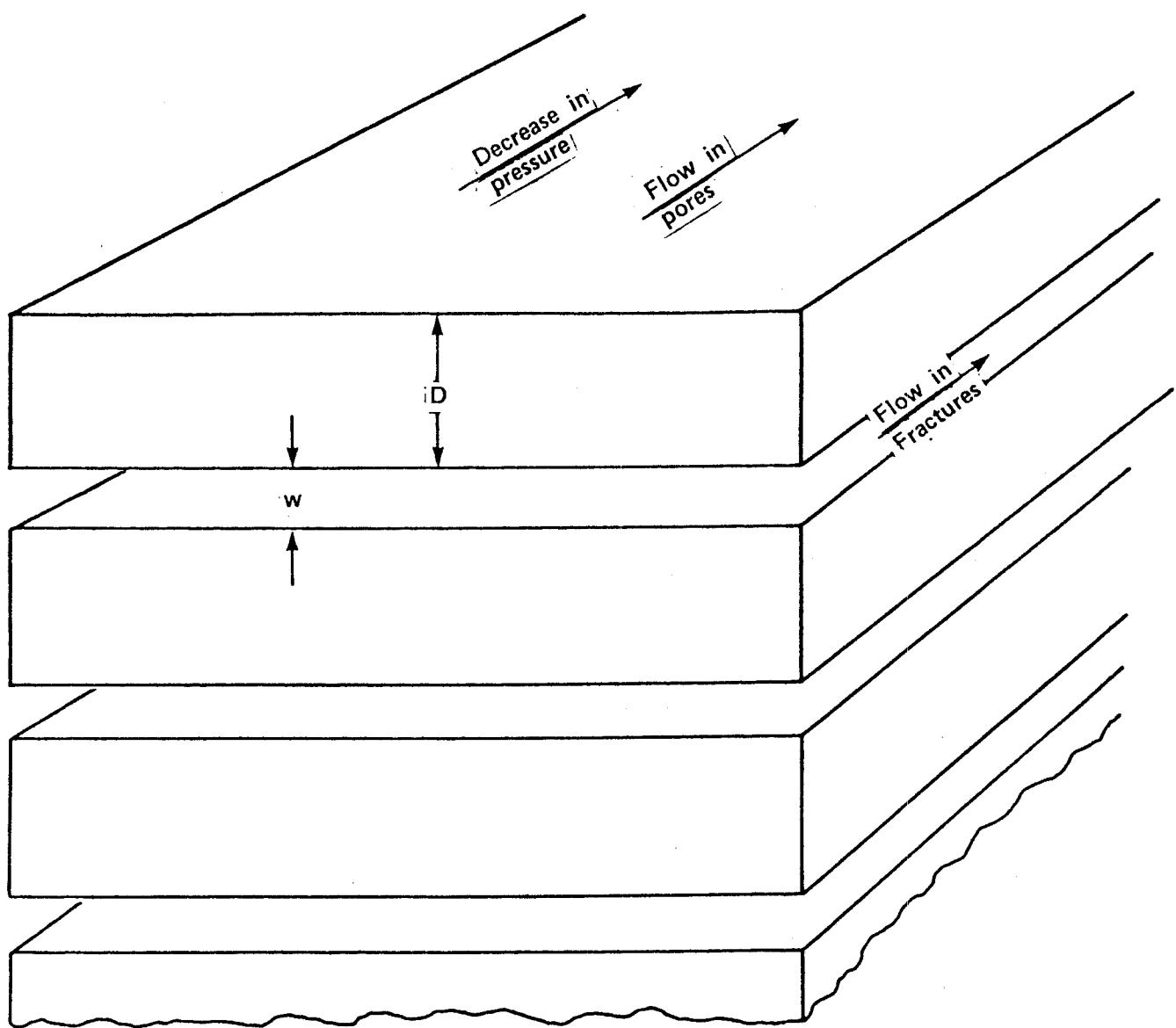- Fluid consists of pore fluid and fracture fluid

FIGURE 1.

FIGURE 2.

A COMPARISON OF FRACTURE APERTURE FOR THE
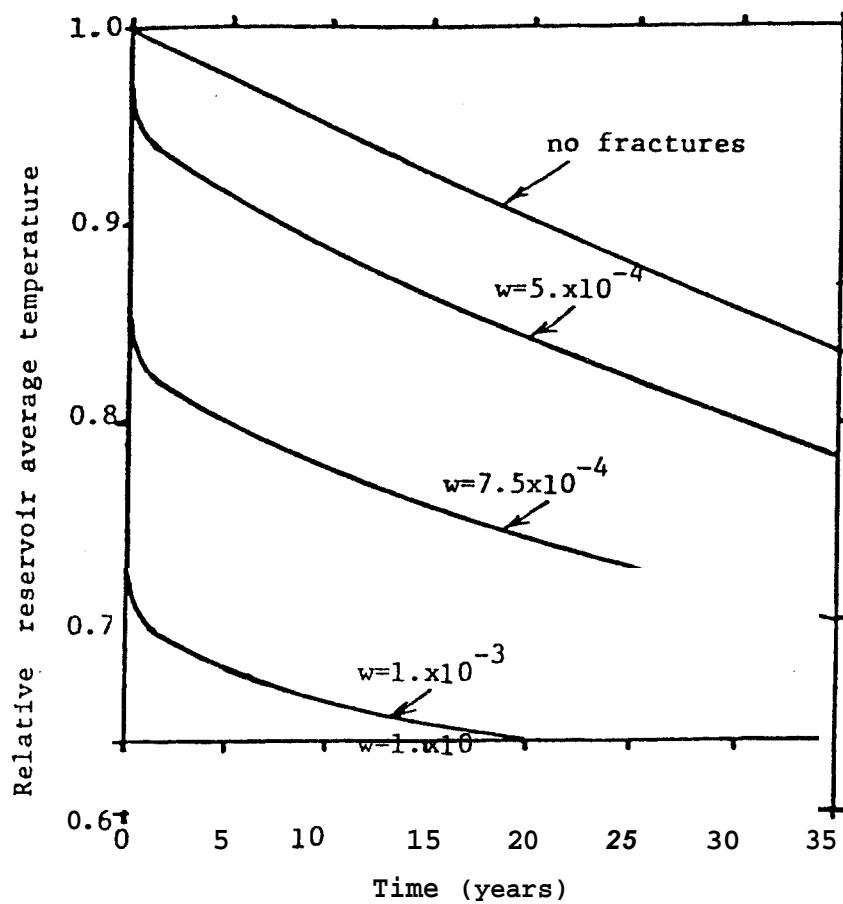SALTON SEA KGRA, 1000MWe, 1500 m FRACTURE
SPACING.

FIGURE 3.

MODEL FOR CALCULATING TEMPERATURE DISTRIBUTION WITHIN
RESERVOIR

Production fluid

Power production
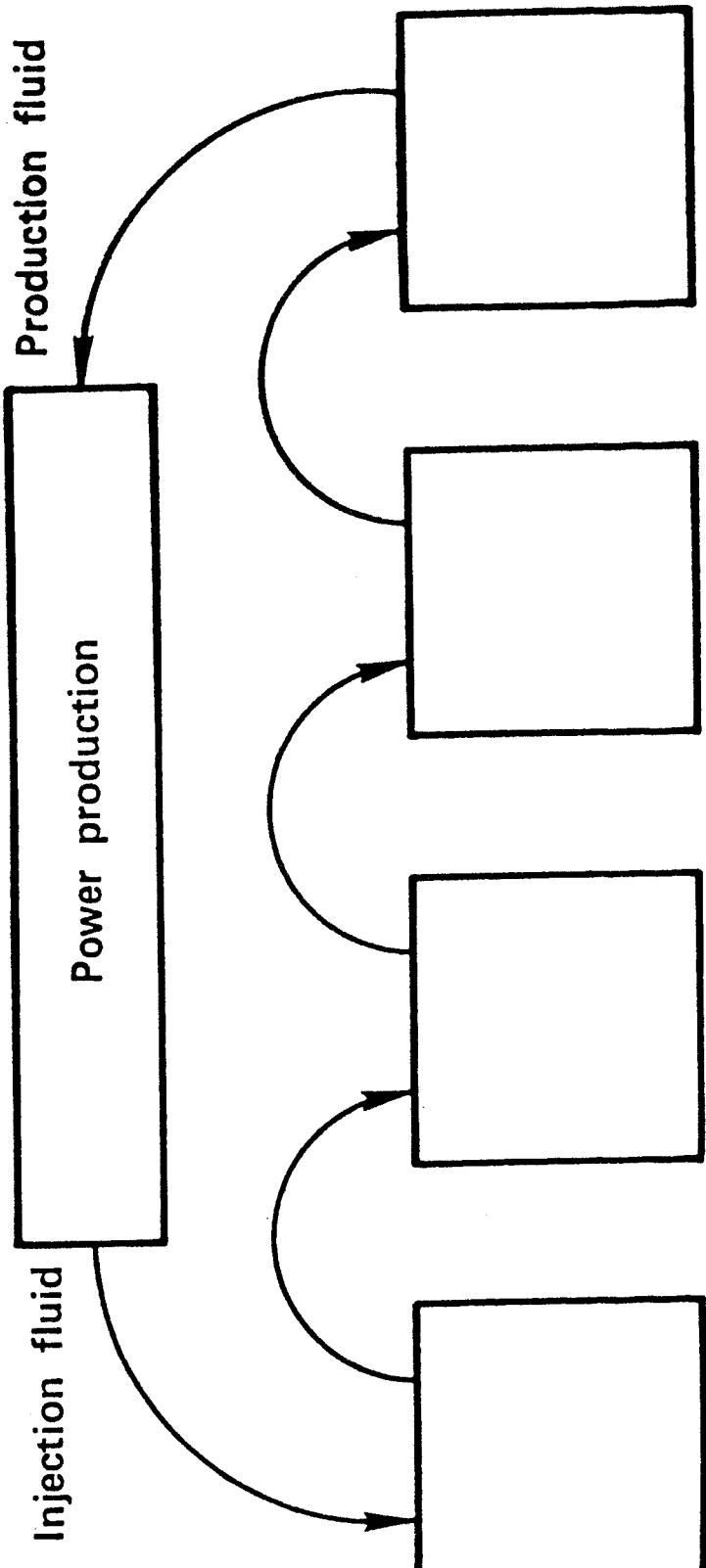
Injection fluid

FIGURE 4.

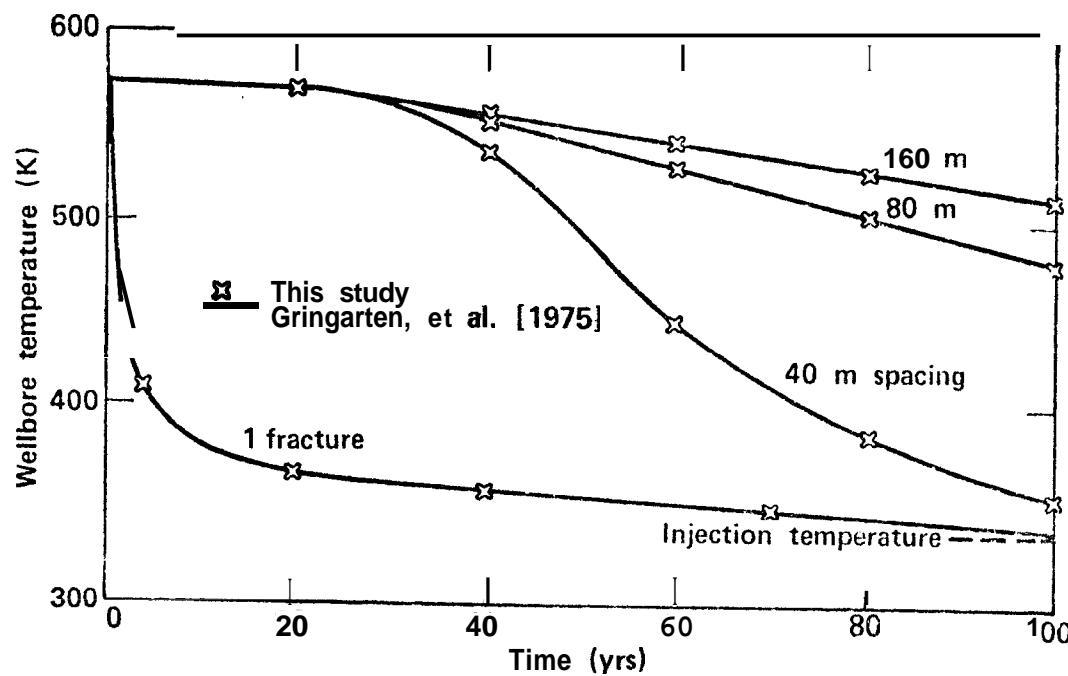## HOT DRY ROCK WITH MULTIPLE FRACTURES RESULTS FROM TWO NUMERICAL METHODS

FIGURE 5.

WELLBORE TEMPERATURE vs. TIME
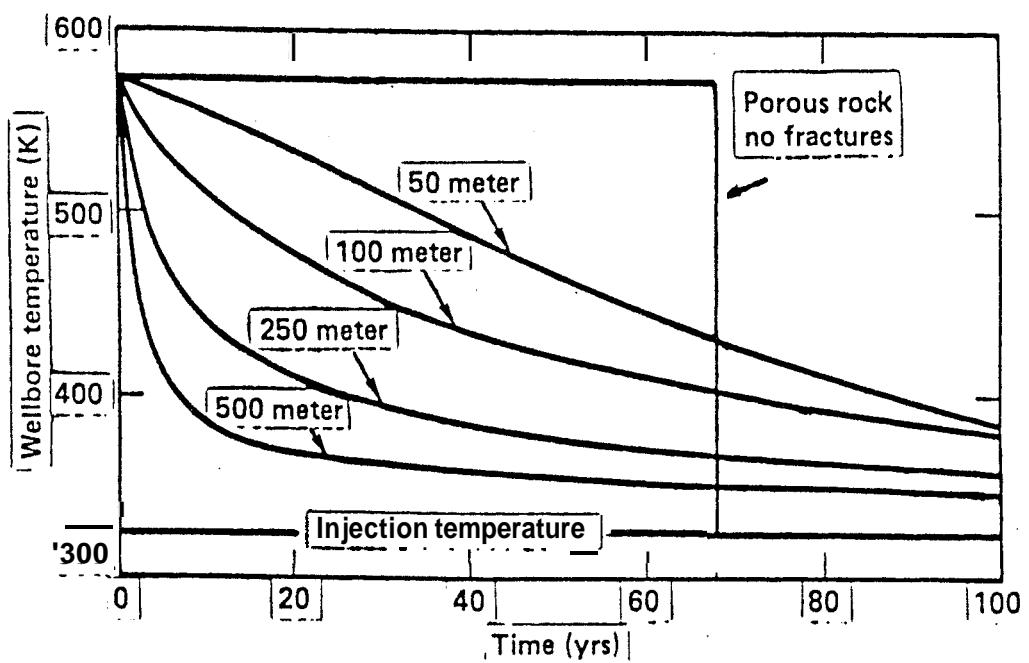SSGF 400 megawatts initial power extracted (with fractures)

FIGURE 6.

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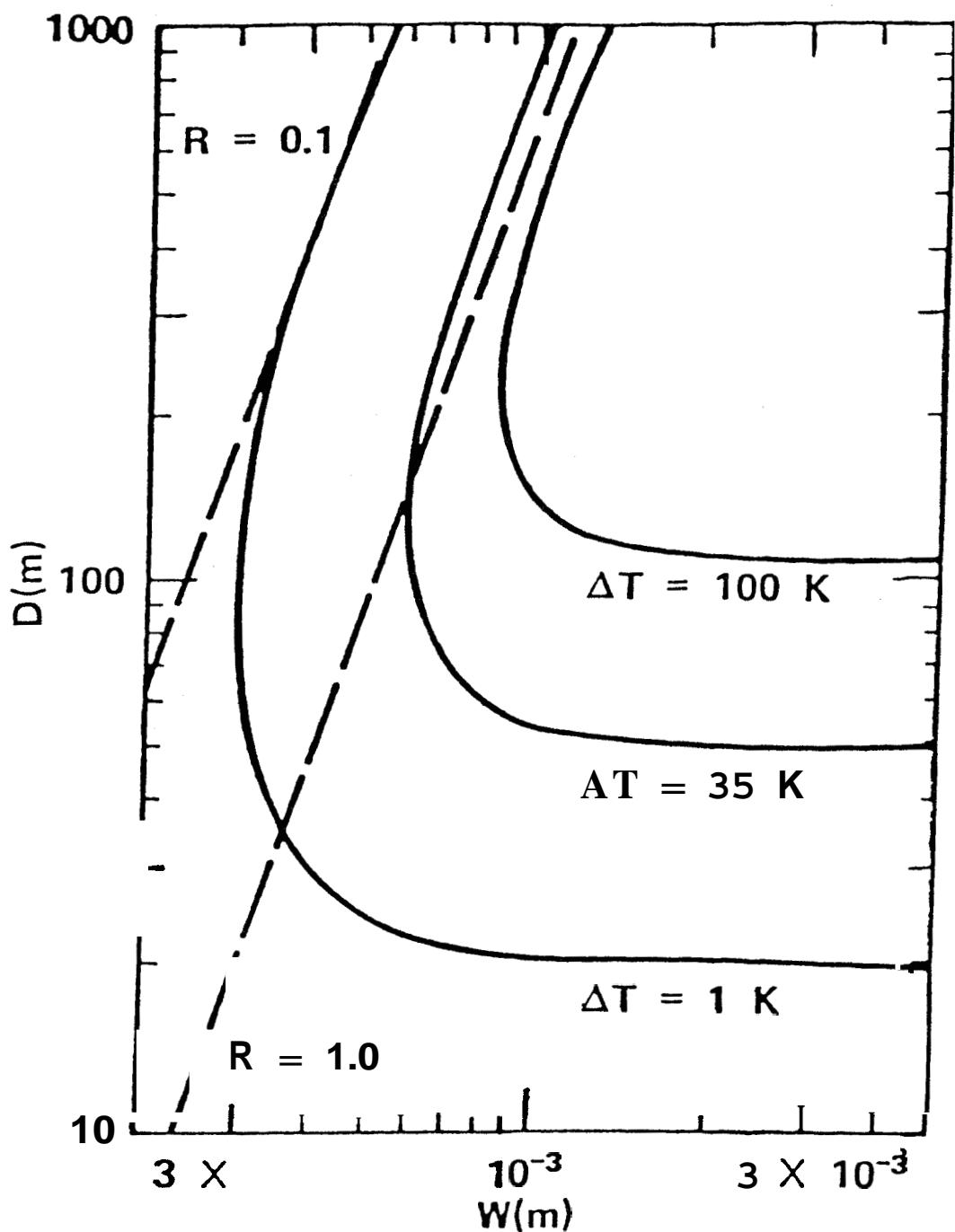# CONTOURS OF PRODUCTION FLUID TEMPERATURE DECLINE AFTER *20* YEARS, FOR DIFFERENT FRACTURE DISTRIBUTIONS (SSGF, 400MW)

FIGURE 7.