APPLICATION OF THERMAL DEPLETION MODEL TO GEOTHERMAL RESERVOIRS WITH FRACTURE AND PORE PERMEABILITY

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The useful lifetime of a geothermal resource is usually calculated by assuming fluid will be produced from and reinjected into a uniform porous medium. However, most geothermal systems are found in fractured rock. If the reinjection and production wells intersect connected fractures, then reinjected fluid may cool the production wells much sooner than would be predicted from calculations of flow in a porous medium.

We have developed a "quick and dirty" method for calculating how much sooner that cooling will occur (Kasameyer and Schoeder, 1975, 1976). In this paper, we discuss the basic assumptions of the method, and show how it can be applied to the Salton Geothermal Field, the Raft River System, and to reinjection of supersaturated fluids.

Solution for Flow in a Porous Medium

We model a finite hot-water reservoir produced at a constant flow rate with fluid replenished either by reinjection or by cool recharge at the boundaries. We assume that an idealized well distribution can be found which allows a specified flow rate and which produces all of the original fluid from the reservoir before any reinjected fluid has been produced. Further, we assume there is no pressure drawdown or flashing, that the fluid moves with piston displacement through the pores, and that the pore fluid and matrix come to thermal equilibrium instantaneously. All these assumptions lead to an over-estimate of the production temperature.

An analytical solution for this idealized problem of heat transfer has been discussed by Bodvarsson (1974). A steep temperature front moves through the system with no change of shape with time, and with a slower velocity than the fluid front. Ahead of the temperature front, the reservoir retains its initial temperature. Behind the front, enough heat has been taken from the rocks to cool them to the reinjection temperature.

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Solution in the Presence of Fractures

A family of fractures is assumed to exist parallel to the direction of flow. The fractures are characterized by a permeability k_{fr} and a spacing D. (For the results presented here, the fractures are tight enough so that water storage in them is negligible.) The fractures are assumed to have no effect on the pressure field so that the flow stream lines are parallel in the porous rock and in the fractures, but the flow velocities are different.

The solution of a problem with two distinct velocities by a finite difference method (e.g., Kasameyer and Schroeder, 1975) is not efficient if the velocities are quite different. In that case, time steps must be determined by the most rapid velocity and calculations take a long time when fractures are important. An approximate solution requiring a few time steps has been developed. The reservoir is conceptually divided into 10 regions of equal volume. The boundaries of the regions coincide with flow fronts of the reinjected fluid so that the fluid in the pores and the fluid in the fractures both flow through the regions in series (see Figure 1). In each region, we write pairs of approximate equations relating the temperature of the fluid in the fractures averaged throughout the region, T_{fr}, to the average temperature of the saturating fluid, T_S. The 10 pairs of coupled first-order equations are solved analytically by assuming constant coefficients during time intervals which are much longer than those appropriate for the finite-difference method.

The equations for the i^{th} region are presented here in dimensionless form (see Kasameyer and Schroeder, 1976, for the derivations). The times have been multiplied by α = (thermal diffusivity)/$(D/2)^2$.

$$\frac{dT_{fr}}{dt} = \frac{-R_q(1+R_\mu)}{R_\mu(1+R_q)} \frac{M}{\tau^*} (T_{fr}-T_{fro}) + H$$

$$\frac{dT_s}{dt} = \frac{-(1+R_\mu)}{(1+R_q)} \frac{M}{\tau^*} (T_s-T_{so}) - R_\mu H$$

The equations depend only on three dimensionless constants

$$R_q = \frac{\text{Flow in Fractures}}{\text{Flow in pores}}$$

$\tau^* = \alpha\tau$ where τ is the lifetime based on a porous flow calculation.

$$R_\mu = \frac{\text{Heat stored in fractures}}{\text{Heat stored in saturated rock}}$$

The fluid enters the pores and fractures of region i at temperatures T and T_{so}, respectively. These temperatures are determined from the solution for region i-1, or by the reinjection temperature if i=1.

The term H is the heat conducted from the saturated rock into the fractures. That term is approximated by an expression depending only on the time and the instantaneous values and derivatives of the average temperatures.

$$H = \frac{F(t)}{R_\mu}\left[\frac{(1-T_{fr})}{\sqrt{\pi t}} - \frac{2}{R_\mu}\sqrt{\frac{t}{\pi}}\,\frac{dT_{fr}}{dt}\right] + \frac{2\,[1-F(t)]}{R_\mu}\,(T_s - T_{fr})$$

The function F(t) varies smoothly from one at early times to zero at late times.

The approximation of H is justified by the close agreement of our calculations of the temperature in fractured, impermeable rock with those of Gringarten, et al., (1975), shown in Figure 2. Results presented at the Stanford Workshop in 1975 (Kasameyer and Schroeder, 1975) indicated better agreement between the methods, but those results were for a small range of values of τ^* and were based on the very slow finite-difference calculation with a large number of regions. Our answers differ from those of Gringarten, et al. because 1) we over-estimate the heat transfer to the fracture fluid at early times, and 2) the thermal front is smoothed out at late times because of averaging over large regions.

Correction Factors for Porous Flow Models

A set of calculated production temperature histories are shown in Figure 3. Results from many such calculations can be summarized in one figure by calculating the time, t_f, when the production temperature falls below a specified value. That value would normally be determined from power generating equipment. For the examples presented below, we have chosen a value of 0.8. The ratio of t_f/τ for different fracture systems and production rates is a correction factor for the useful lifetime.

The values of that correction factor for small R_μ are contoured in Figure 4. The contours depend on R_μ and τ^*. For no flow in fractures (Rq < 1) or for slow removal of fluid ($\tau >> {}^1/\alpha$), the porous medium calculations are correct. If those conditions are not met, the correction factor can be determined from this diagram.

Examples

I. The Salton Sea Field

The τ^* values have been related to fracture spacings (D) by assuming parameters appropriate for the Salton Sea Geothermal Field (Figure 4). Two scales of fracture systems are seen in that field. Fractures are seen in cores with spacings less than a meter. From Figure 4, we see that flow in these fractures will not shorten the useful lifetime of the field. Faults hundreds of meters apart influence the flow in several wells. If these faults carry more than half the fluid, produced and reinjected wells, the useful lifetime may be drastically shorter than predicted from porous flow calculations.

II. A Fracture-Dominated System Like Raft River

If most of the flow is from fractures, then the correction factor depends only on the fracture spacing and the rate at which heat is removed from the system. In Figure 5, we see that the dependence of the correction factor on pumping rate can be strong, and knowledge of the fracture spacing in such a system is crucial for planning exploitation rates.

III. Reinjection of Super-saturated Brines

It may be practical to inhibit silica deposition in a geothermal power plant by brine modification. Acidification of Salton Sea brine inhibits deposition of siliceous scale and decreases rates of precipitation of silica and sulfides long enough to produce power from the brine and reinject it into the ground (Owen, 1975; Owen and Tardiff, 1977). However, the formation around a reinjection well may become badly plugged by silica if the reinjected brine is not reheated rapidly.

The length of time reinjected brine stays cool can be estimated. If the fluid is injected into a porous medium, a steep boundary between warm and cool rock moves at a velocity less than the particle velocity. If R is the fraction of the heat of the reservoir stored in the pore fluid ($R \sim .3$ for 15% porosity), then the temperature moves at velocity RV_p, where V_p is the particle velocity.

Particle paths and temperature boundary locations for radial flow areound a well are shown in Figure 6. A particle injected at time t after the well started flowing remains cool for a period of time, t_c, where

$$t_c = \frac{R}{1-R} t_p \sim .4 t_p \text{ for } R = .3$$

As shown in Figure 6, brine injected one year after injection begins will remain cool for nearly half a year. Short-term injection tests may not indicate the full potential for injection well damage, because the first brine which is injected will be rapidly reheated. The kinetics of precipitation from super-saturated brines and the temperature dependence of the rates of possible rock-brine interactions must be studied in order to predict the long-term success of reinjection.

References

Bodvarsson, G., On the temperature of water flowing through fractures, J. Geophys. Res., 74, 1967, 1969.

Gringarten, A. C., P. A. Witherspoon, and Y. Onishi, Theory of heat extraction from fractured hot dry rock, J. Geophys. Res., 80, 1120, 1975.

Kasameyer, P. W., R. C. Schroeder, Thermal depletion of liquid-dominated geothermal reservoirs with fracture and pore permeability, in Report of Workshop on Geothermal Reservoir Engineering, Paul Kruger and Henry J. Ramey, Jr. Eds., Stanford Geothermal Program, SGP-TR-12, 1975.

Kasameyer, P. W., and R. C. Schroeder, Thermal depletion of a geothermal reservoir with both fracture and pore permeability. Submitted to J. Geophys. Res., 1976.

Owen, L. B., Precipitation of amorphous silica from high-temperature hypersaline geothermal brines, Lawrence Livermore Laboratory Report, UCRL-51866, 1975.

Owen, L. B. and G. E. Tardiff, Eds., Lawrence Livermore Laboratory Energy Program: brine chemistry and materials status report, UCRL Report (in preparation), 1977.

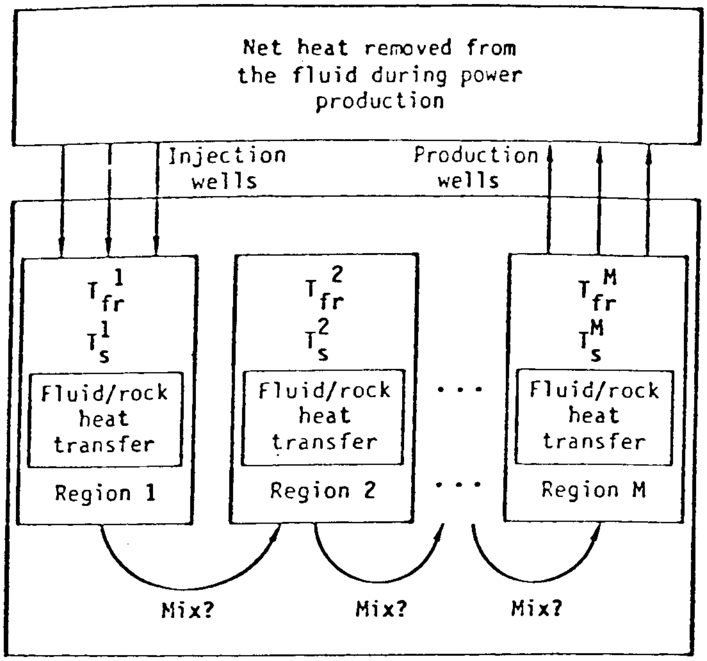

FIGURE 1. Division of reservoir into a small number of regions.

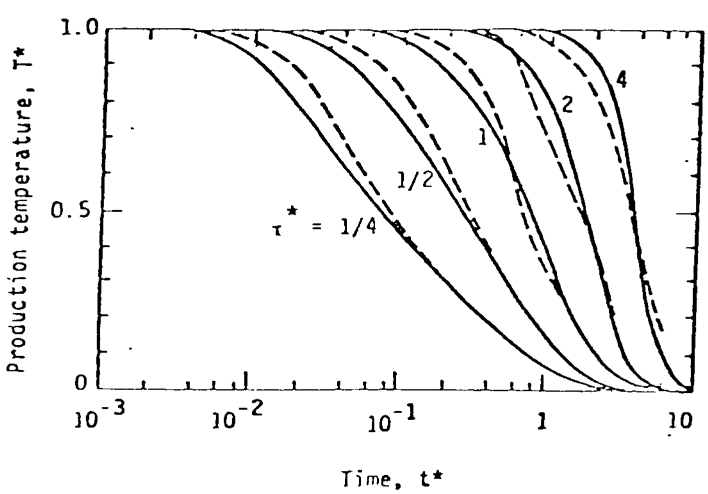

FIGURE 2. Comparison of our calculated curves for the output temperature from fractured impermeable rock (dashed) with those of Gringarten et al., 1975, (solid). Their values have been converted to our dimensionless format, where $t^* = \alpha t$.

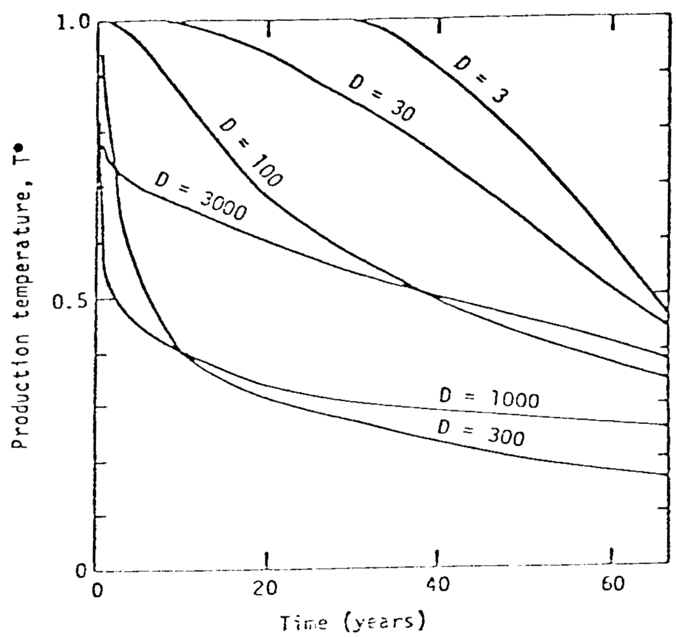

FIGURE 3.

Thermal depletion curves for different fracture spacings D (in meters). The parameters were chosen so that all the original pore fluid would be produced after 20 years, and the useful lifetime (τ) based on the exact porous flow calculation was 66 years.

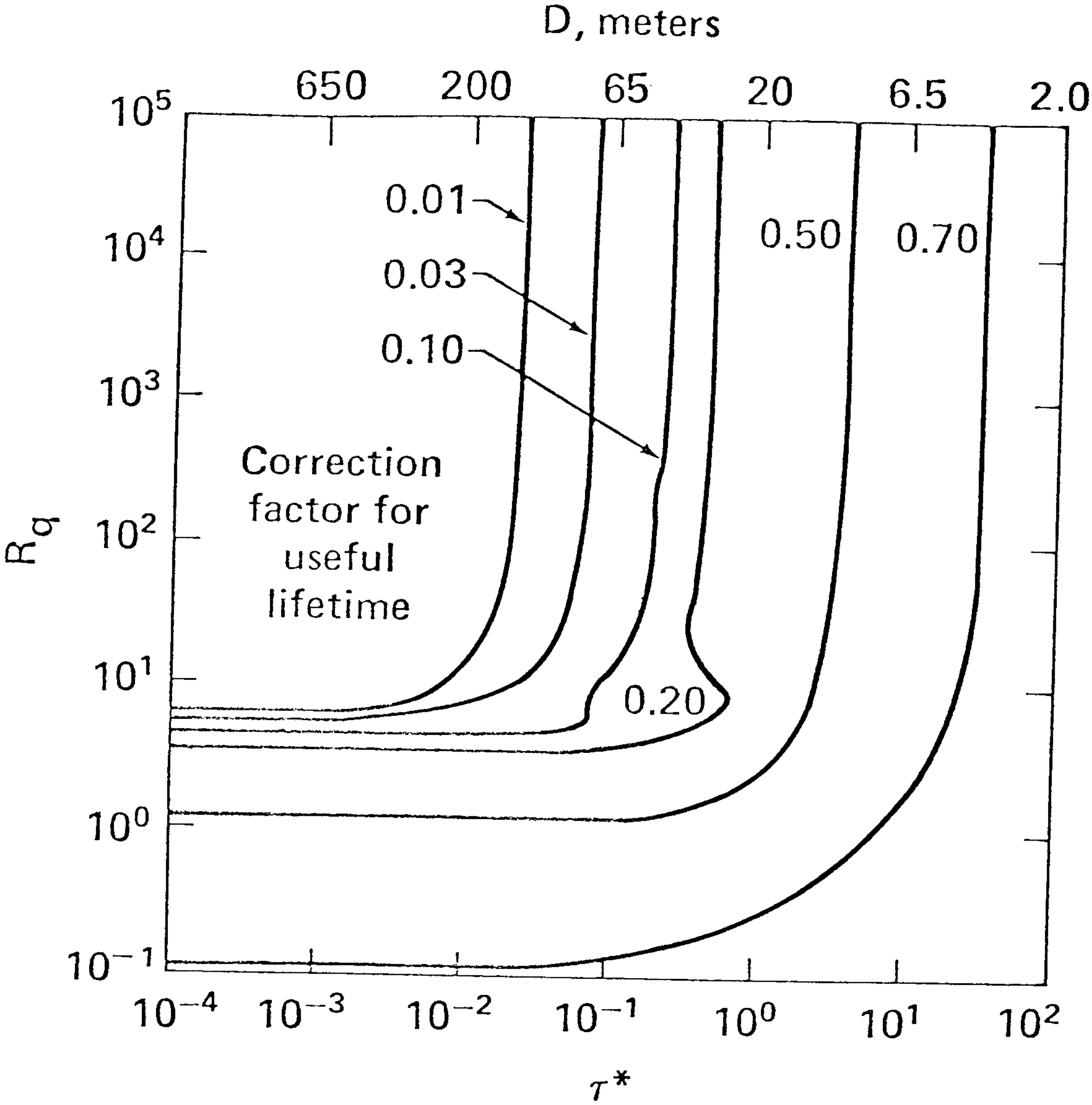

FIGURE 4.

Correction factor for lifetime estimates. The production temperature falls to 0.8 at t'_f. The ratio of t_f/τ is contoured for different flow distribution (Rq) and production rates (τ^*). The contour where the factor equals 0.20 is distorted because of our approximation of term H. The fracture spacings (D) are appropriate for the Salton Sea Field example.

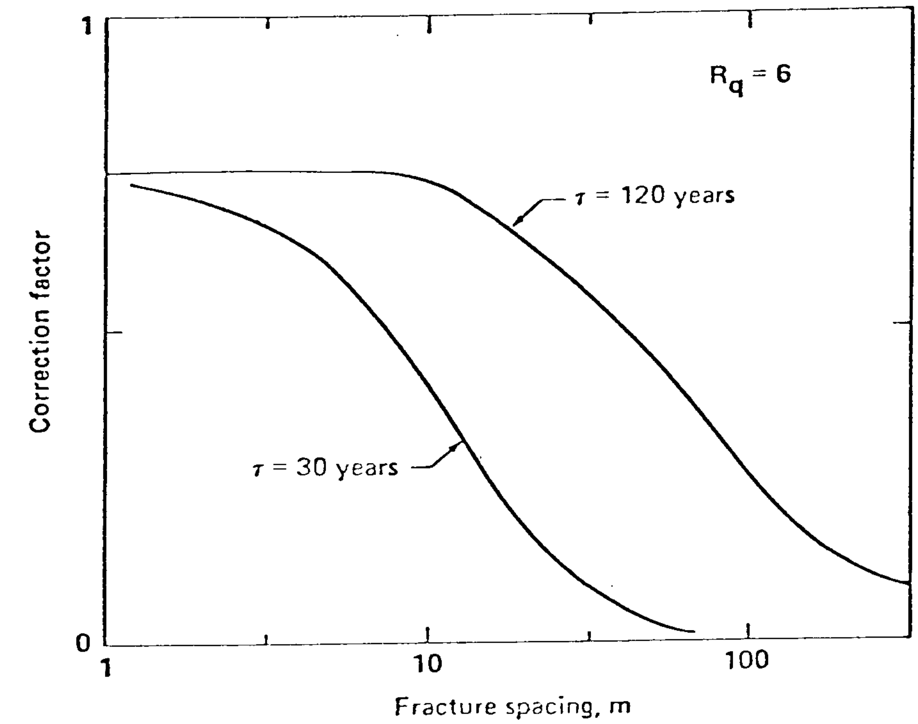

FIGURE 5. The effect of production rate on the correction factor. If the fracture spacing is around 10 meters, more than twice the energy can be removed from the system at the slow production rate (τ = 120 years) as at the fast rate (τ = 30 years).

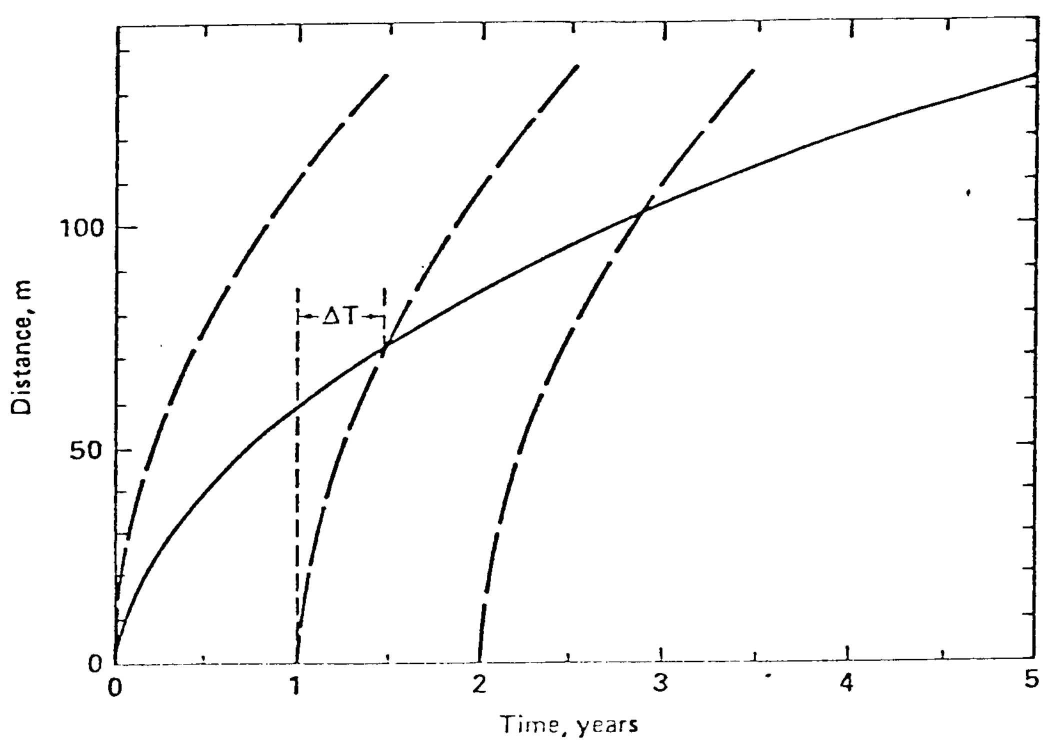

FIGURE 6. Location of temperature front and fluid particles as function of time since reinjection started. The curves in the figure are for (R = 0.3, and radial flow of 0.05 m^3/sec. into a 200m thick aquifer with 20% porosity. The solid line shows the distance to the temperature front. The dashed curves are the trajectories of particles injected at different times. A particle injected one year after injection started remains cool for ΔT years.