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ESTIMATES OF THERMAL COOLDOWN IN FRACTURED PETROGEOTHERMAL RESOURCES*

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ABSTRACT

The potential for thermal cooldown from a petrogeothermal reservoir consisting of eight parallel hydrofractures spaced 50 meters apart has been estimated with two different models of heat transfer between the fractured massive and water circulated for heat extraction. One model is based on heat transfer processes for water circulating through the eight connected planar hydrofractures; the other is based on heat transfer processes for one-dimensional flow through a well-fractured rock block considered as a collection of spherical rocks of equivalent thermal radius. The results show good agreement between the two models and provide confidence on the range of parameters selected for the reservoir and the estimates of the lifetime of the petrogeothermal resource to a given abandonment temperature.

INTRODUCTION

Methods to predict the rate and lifetime of heat extraction from fractured geothermal reservoirs are very important for the long-term development of geothermal resources in the USSR, the USA, and many other countries seeking alternate sources of indigenous energy. The extent and distribution of hydrothermal resources in the USSR (Mavritsky and Shpak, 1983) are not considered very large. However, significant resources of thermal energy exist in petrogeothermal deposits throughout the Soviet Union (and the USA) suitable for widespread use in space heating and possibly for electric energy conversion. Many of these resources will require the use of artificial circulation systems for effective extraction of thermal energy (Dyadkin, 1987a).

Economic viability of developing abundant, but low temperature petrogeothermal resources rests with the need to extract thermal energy at a sufficient rate over a satisfactory amortization period. Heat transfer in fractured geothermal reservoirs is a very complicated process, dependent on a combination of geometric parameters of reservoir structure and hydrologic properties, production and reinjection practices, and thermal properties of the reservoir rock formation. Estimates of economic feasibility of energy extraction with artificial circulation systems are available (e.g., Murphy et al, 1985; Dyadkin, 1985). These estimates are based on many assumptions concerning the processes of unsteady, non-isothermal flow of circulating fluids through a reservoir of fracture and intrinsic permeability distributions and of heat transfer rates from irregularly shaped rock blocks.

Several models have been developed for estimating heat extraction from fractured geothermal reservoirs (e.g., Gringarten and Witherspoon, 1973; Pruess, 1983; Dyadkin and Gendler, 1985; and Hunsbedt et al., 1979). This paper describes a comparison of lifetime estimates made by two different simulation models, one developed by the Leningrad Mining Institute (LMI) and the other by the Stanford Geothermal Program (SGP). The case study was developed as part of the curriculum of the Geothermal Technology Course given by Prof. Yuri Dyadkin during his visit to Stanford as a Fulbright Scholar in the Spring Quarter of 1987. The text example involves artificial circulation of water through a multiple hydrofractured reservoir for space heating application in the USSR. The example, adopted from Dyadkin (1987b) involves production of hot water from a hydrofractured reservoir at 100 °C for delivery to a nearby community at 90 °C with cold-water reinjection at 30 °C at a steady flowrate of 100 kg/s over the lifetime of the resource.

LENINGRAD MINING INSTITUTE SIMULATION

The Mining Thermophysics Research Laboratory (MTPhRL) of the Leningrad Mining Institute (LMI) is developing numerical simulation methods for simple two-dimensional models of heat extraction with artificial circulation systems which reflect all physical interactions and mutual dependencies to estimate heat extraction rate and lifetime of petrogeothermal reservoirs including the hot dry rock type.

An approximate solution (Dyadkin and Gendler, 1985) for the cooldown time, t_a, of a geothermal circulation system (GCS) with dimensionless hot water temperature, θ_e, defined as

$$\theta_e = \frac{T_e - T_o}{T_r - T_o} \qquad (1)$$

where T_e = extracted fluid temperature (°C)
T_r = initial reservoir rock temperature (°C)
T_o = injected cold-water temperature (°C)
from a reservoir of initial temperature $\theta_e^* = 1.0$, is given by

$$t_a = C\ A\ \exp(B) \tag{2}$$

with the functions C, A, and B defined as

$$C = 3.17 \times 10^{-8} \frac{\varepsilon\ h\ L_r^2}{Q} \tag{3}$$

$$\text{where}\quad \varepsilon = (\phi\rho_w C_w + (1-\phi)\ \rho_r C_r)/\rho_w C_w \tag{4}$$

ϕ = porosity

ρ = density (w:water; r:rock) (kg/m^3)

C = specific heat (J/kg C)

h = reservoir thickness (m)

L_r = distance between injection-production wells (m)

Q = volumetric flowrate (m^3/sec)

$$A = 1/(C_1 + C_2(L_r/L_w) - C_3F) \tag{5}$$

where L_w = distance between hydrofractures (m)

$$F = (1.13/\rho_w C_w)*(\rho Ck/\varepsilon Qh)^{1/2} \tag{6}$$

k = thermal conductivity (W/mC)

$$B = \frac{(1-\theta_e)\ F\ C_4}{C_5 + C_6(L_r/L_w)} \tag{7}$$

In the text example, the cooldown temperature was selected to be $\theta_e = 0.9$, although equation (2) is suitable over the range $0.6<\theta_e<1.0$. The coefficients, C_i, for various types of injection-production well patterns were compiled from Artemieva and Piskacheva (1983) and Dyadkin and Gendler (1985), and are given in Table 1.

Table 1
Empirical Coefficients

Well Pattern	C_1	C_2	C_3	C_4	C_5	C_6
One Inj-Prod well pair in infinite layer	0.27	0.98	0.66	0.55	0.21	0.56
Simple Gallery: one row of Inj-Prod wells	0.27	0.98	0.66	0.55	0.21	0.56
Periodic changes of row of Inj-Prod wells	0.64	0.38	0.44	0.67	0.25	0.10
Parallelogram network of Inj-Prod wells	0.32	0.47	0.39	0.73	0.25	0.18

For application of the general equation (2) to an artificial circulation system of multiple hydrofractured vertical cracks (Murphy, et al., 1985), Dyadkin (1985) revised functions (3), (5), and (7) to

$$C = 9.8\times10^{-5} \left(\frac{\rho C}{\rho_w C_w}\right)^2 \frac{b^3}{Q_f} \tag{8}$$

$$A = \frac{k\ b}{\rho C\ Q} \tag{9}$$

$$B = -\ 5.3\ \theta_e \tag{10}$$

where b = half width of the cracks (m)
Q_f = volumetric flowrate per crack (m^3/s)

The numerical simulation was achieved by the method of Artemieva and Piskacheva (1983) for vertical fractures of elliptical shape with complex flowline distribution as shown in Figure 1a, constrained by Grashoff to Reynolds numbers ratio for the crack aperture to the range

$$0 < Gr/Re \leq 12.8 \tag{11}$$

The input values for the case study are given in Table 2.

Table 2

Input Parameters for the LMI Cooldown Estimate

Parameter	Value
Reservoir Temp	100 °C
Injection Temp	30 °C
Abandonment Temp	90 °C (θ_e = 0.9)
Flowrate	100 kg/s
Granite	
ρC	2.86 MJ/m^{3}C
k	3 W/m C
Water	
$\rho_w C_w$	4.19 MJ/m^{3}C

For this case, the Gr/Re ratio was 10.4, satisfying condition (11). The derived functions were C = 98.62×10^3, A = 26.4×10^{-3}, and B = -4.77 By equation (2), the lifetime to the abandonment temperature, (θ_e = 0.9) was t_a = 22.08 years.

The lifetime of an artificial reservoir depends strongly on two major parameters; one is the crack radius, R, determining the heat transfer surface area, and the other is the fluid flowrate, Q, determining the mean residence time for heat transfer. In the course notes, the dependence was given by Dyadkin (1987b) as

$$t_a = 0.1925\times10^{-12} \frac{R^4}{Q^2} \quad \text{(years)} \tag{12}$$

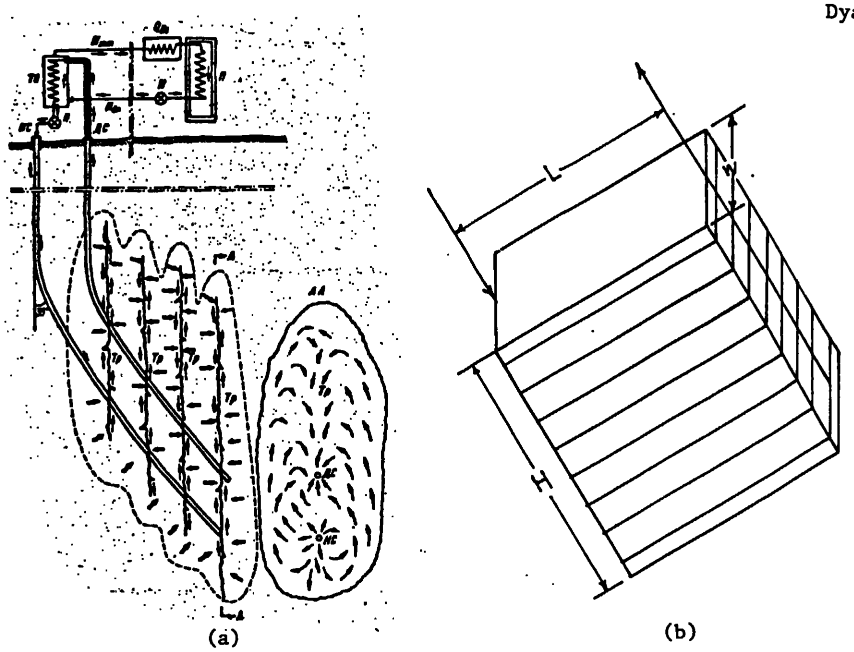

Figure 1. Flow geometries for the two heat extraction simulations: (a) LMI sweep through 8 parallel hydrofractures spaced 50 m apart (from Dyadkin, 1985); (b) SGP heat sweep equivalent with rectangular flow.

Thus for an increase in flowrate by a factor of two (to Q = 200 kg/s), the lifetime would be reduced from 22 to 5.5 years, while for a decrease in crack radius by a factor of two (to R = 183 m), the lifetime would be only 2 months. For both changes together, the lifetime would be 4 days.

SGP 1-D HEAT SWEEP MODEL SIMULATION

The text example was also simulated with the 1-D Heat Sweep Model described by Hunsbedt, Lam, and Kruger (1983). This model evaluates the difference in temperature between a distribution of rock blocks described for heat transfer purposes as a spherical rock of equivalent radius at a lumped mean temperature, T_r, and the surrounding fracture volume fluid at a temperature, T_f, for a linearly decreasing reservoir fluid temperature as

$$T_r - T_f = \mu\tau(1 - e^{-t/\tau}) \qquad (13)$$

where μ = cooldown rate (°C/h)
τ = time constant for the rock (h)

Hunsbedt, Kruger, and London (1978) showed that the time constant for spherical rock blocks can be expressed as

$$\tau = \frac{R^2}{3\alpha}(0.2 + 1/N_{Bi}) \qquad (14)$$

where R = equivalent rock radius (m)
α = thermal diffusivity of the rock (m^2/h)
N_{Bi} = Biot number of the rock.

The thermal diffusivity is given by

$$\alpha = k/\rho C \qquad (15)$$

where k = thermal conductivity (W/mC)
ρ = density (kg/m^3)
C = specific heat (J/kgC)

The Biot number is given by

$$N_{Bi} = \frac{h\ R}{k} \qquad (16)$$

where h = heat transfer coefficient (J/hm^2C)

The differential equation which describes heat transfer from the equivalent spherical rock to the recharge fluid under linear sweep was given in Hunsbedt et al. (1983). The solution for the given linear sweep boundary and initial conditions is initiated by conversion to a Laplace transform equation and the inversion is accomplished numerically with the algorithm reported by Stehfest (1970). Applications of the 1-D Heat Sweep Model were described by Kruger (1985) and Kruger et al. (1987).

Figure 1b shows the equivalent flow geometry for the text example. The reservoir thickness is 400 m, equivalent to the length of 8 fractures spaced 50 m apart, the width is 600 m, equivalent to twice the fracture half width of 300 m, and the length of the reservoir was modeled from 300 m (the case distance between inlet and outlet wells was 400 m) and 700 m (equivalent to the fracture length of a rectangle with the same surface area as the elliptical fractures. Table 3 lists the input parameter values for the heat sweep calculations.

Table 3

Input Parameters for the SGP Cooldown Estimate

Parameter	Value
T (initial)	100 °C
T (recharge)	30 °C
Q (injection-production)	variable
Mean Fracture Spacing	variable
Porosity	variable
Reservoir Length	variable
Width	600 m
Thickness	400 m
Rock Density	2600 kg/m^3
Specific Heat Capacity	1100 J/kgC
Thermal Conductivity	3.0 W/mC
Fluid Density	1000 kg/m^3
Specific Heat Capacity	4190 J/kgC
Heat Transfer Coefficient	1703 W/m^2C

Table 4

Results of the SGP Simulations*

I MFS (L = 700m, $\phi = 10^{-4}$, Q = 100 kg/s)

MFS (m)	Time to Cooldown to T_a = 90°C (yr)
25	30.0
50	26.0
75	21.0
100	16.0

II Fracture Pathlength (MFS = 70m, Q = 100 kg/s)

L (m)	Time to Cooldown to T_a = 90°C (yr)
300	6.3
400	10.0
500	13.8
600	17.8
700	22.0

III Flowrate (MFS = 70m, L = 700m)

Q (kg/s)	Time to Cooldown to T_a = 90°C (yr)
50	52.0
100	22.0
200	8.0

*compared to LMI Simulation (T_a = 90°C) of t_a = 22.1 years

In addition to reservoir length, the sensitivity of other parameters evaluated with the heat sweep model were the mean fracture spacing, varied about the 50 m fracture spacing from 25 m, essentially porous media for heat transfer, to 200 m, for which heat transfer would be very slow, porosity, which effects the mean residence time in the fractures, and flowrate, to test the quadratic dependence shown in equation (12).

The results of the simulations are shown in Figure 2 and the time to T_a = 90 °C for the parameters varied with base case values of $\phi = 10^{-4}$, L = 700 m, Q = 100 kg/s, and MFS = 70 m are summarized in Table 4. The data show that porosity is not a major factor in lifetime to T_a = 90 °C. For the base case of L = 700 m (the full surface area path length), Q = 100 kg/s, and MFS = 50 m, the cooldown time was 26 years, which agrees reasonably well with the value of 22.1 years by the LMI model. Cooldown to 90 °C in 22.1 years for these conditions interpolates to a mean fracture spacing of 70 m for the 50x700x600 m elliptic slabs), which was used in the subsequent variable parameter estimates. The data for changes in flowrate show that in contrast to the LMI expectation of variation in t_a as a function of $1/Q^2$, the linear 1-D model shows a relationship closer to $1/Q^{1.3}$. For the fracture path length, the SGP data show a trend of t_a as a function of $L^{1.5}$ in contrast to the LMI expectation of L^4.

CONCLUSIONS

The simulations made by two very different simple models of heat transfer from hot fractured rock to colder circulating water give approximately similar results. Heat extraction from parallel fractured reservoirs may be estimated for anticipated flow geometries. For the text example of a hydrofractured petrogeothermal reservoir, used to produce 100 °C water for space heating, a value of 70 m for the equivalent radius of a distribution of rock slabs spaced 50 m apart gave the same cooldown time to abandonment temperature as a model based on physical description of the heat exchange in the physical system. The description of the parallel hydrofractured reservoir as a collection of equivalent radius spheres for heat transfer in the SGP model results in a more linear dependence of cooldown time on flow path length and rock radius compared to the expectation of dependence as L^4/Q^2 in the LMI model. However, the ability of both models to yield the same cooldown time for the text problem indicates its potential use in evaluating new petrogeothermal fields where little production data are available.

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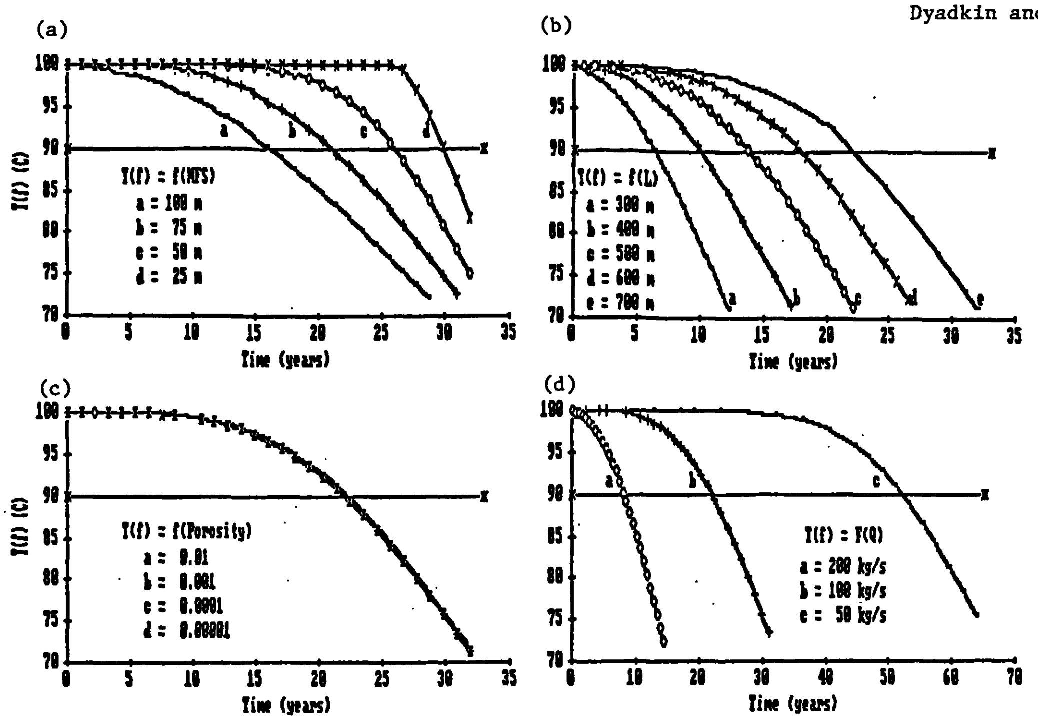

Figure 2. Cooldown times to T_a = 90 °C modeled with (a) mean fracture spacing, (b) fracture flow path length, (c) porosity, and (d) flow rate.

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