A Comparison of Two Heat Transfer Models for Estimating Thermal Drawdown in Hot Dry Rock Reservoirs

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Abstract

Estimates of thermal drawdown in Hot Dry Rock geothermal systems have been made with two different models of heat transfer from hydraulically fractured reservoir rock blocks to water circulated through the fracture permeability. One model is based on deconvolution of experimental tracer response curves into a network of flowpaths connected in parallel with heat transfer calculated individually in each flowpath. The second model is based on one-dimensional flow through the rock with a block size distribution described as a group of equivalent-radius spheres for which the heat transfer equations can be solved analytically. The two models were applied to the planned Phase II long-term thermal drawdown experiment at Fenton Hill, NM. The results show good agreement between the two models, with estimates of temperature cooldown from 240°C to 150°C in a few years depending on selected operation parameters, but with somewhat differing cooldown curve characteristic shapes. Data from the long-term experiment will be helpful in improving the two models.

Introduction

The long-term success of hydrothermal and hot dry rock geothermal resources depends on a high efficiency of thermal energy extraction with reinjected or circulated fluids. Adequate reservoir management of hydrothermal systems includes the need for predicting thermal effect of reinjected separator brine and turbine condensate on production with respect to reinjection well location and estimated production rates. Similarly, reservoir management of hydraulically fractured hot dry rock reservoirs includes the need to predict reservoir size, thermal capacity, and long-term sustainable rates of energy extraction.

Several models have been developed for estimating heat extraction from fractured geothermal reservoirs (e.g., Gringarten et al. (1975), Hunsbedt et al. (1978, 1983), Bodvarsson and Tsang (1982), Pruess (1983), Zyvoloski (1983), Dyadkin and Gendler (1985), and Robinson and Jones (1987)). These models differ in assumptions about fluid flow geometry in thermal contact with the reservoir rock blocks and the physics of the heat transfer processes. Two simple one-dimensional heat extraction models are described in this paper for application to the planned Phase II reservoir long-term thermal drawdown experiment at Fenton Hill, NM. One is the 1-D Heat Sweep Model developed at the Stanford Geothermal Program (SGP), the other is the tracer-based model developed at the Los Alamos National Laboratory (LANL). The upcoming Phase II long-term thermal drawdown experiment will test the usefulness of these models and provide additional field data on the behavior of HDR reservoirs.

Model Descriptions

SGP 1-D Linear Heat Sweep Model

The linear heat sweep model, suitable for evaluation of heat extraction from fractured geothermal reservoirs by artificially circulated fluids, was developed by Kuo et al. (1977), Hunsbedt et al. (1978), and Iregui et al. (1978). Kuo showed experimentally that an irregularly-shaped rock block with aspect ratio as large as 8:1 could, for heat transfer purposes, be described as a sphere with an equivalent radius based on its surface to volume ratio. Analytical methods for solving the time dependent heat transfer equations for spherical solids are given in Carslaw and Jaeger (1973). Iregui showed that a distribution of rock block sizes and shapes could, also for heat transfer purposes, be described as a single size spherical rock block with mean equivalent radius. Hunsbedt showed that the difference in temperature between the equivalent radius rock block at a lumped mean temperature T_r and the surrounding fracture volume fluid at a temperature T_f could be expressed as

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

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

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

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

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

The thermal diffusivity is given by

$$\alpha = k/\rho C \qquad (3)$$

where k = thermal conductivity W/m°C
ρ = density (kg/m^3)
C = specific heat capacity (J/kg°C).

The Biot number is given by

$$N_{Bi} = hR/k \qquad (4)$$

where h = heat transfer coefficient (W/m^2°C)

The differential equation which describes heat transfer from the equivalent spherical rock block to the circulating fluid under linear heat 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). Application of the model to a low temperature hydraulically fractured petrogeothermal system in the USSR was described by Dyadkin and Kruger (1987).

LANL Tracer-Based Heat Transfer Model

For an HDR reservoir with flow connections established between injection and production wells, tracer experiments, in which a pulse of tracer is injected at the inlet and the concentration-time curve is measured in the production fluid, are useful for characterizing the nature of fluid flow in the reservoir. The tracer response curve provides information on the existence of short circuit flow paths via the measurement of the first arriving tracer, as well as the amount of flow through long-residence-time paths.

The tracer-based heat transfer model uses the tracer response curve to approximate the extent of flow channeling, thus accounting for the effect of nonuniform flow on the heat extraction performance. The model, first proposed in Robinson and Jones (1987), assumes multiple flow paths of different size and flow rate adjusted to match the observed tracer response. The thermal response of each path is calculated individually, then the composite outlet behavior is calculated as the weighted mean of the individual responses. The model, using only inlet-outlet tracer data, assumes that there is no thermal or hydraulic interaction between the flow paths.

The thermal model used to estimate the Phase II experiment cooldown has been modified from the model developed in Robinson and Jones (1987), which assumed highly fractured rock, so that the fluid in the reservoir was everywhere in thermal equilibium with the rock. In that model, heat extraction results in a sharp temperature front which travels from inlet well to outlet well. An ad-hoc parameter was included to simulate dispersion of the front based on an analogy to the convective-dispersion equation, but this parameter had little physical significance. In the revised model (Jones, 1987), each path is assumed to consist of a set of equally-spaced fractures, each accepting equal flow, as shown in Figure 1a. The energy balance equation in the rock in dimensionless form is

$$\frac{\partial T}{\partial \theta} = \frac{\partial^2 T}{\partial \eta^2} \qquad (5)$$

while in the fluid, the energy balance equates convection in the fluid to conduction in the rock at the interface:

$$\left.\frac{\partial T}{\partial \eta}\right|_{\text{interface}} = Bi_m \frac{\partial T}{\partial \xi} \qquad (6)$$

where the following dimensionless variables are defined:

$$\eta = \frac{2x}{S}, \quad \xi = \frac{y}{L}, \quad \theta = \frac{4\alpha t}{S^2},$$

$$Bi_m = \frac{(\dot{m}C)_f}{2k\, A_{ht}/S} = \frac{S^2(\dot{m}C)_f}{4k\, V_r} \qquad (7)$$

where S = the rock spacing (m)
L = the flow path length (m)
α = the rock thermal diffusivity (m^2/s)
t = time (s)
$\dot{m}$ = the fluid mass flow rate (kg/s)
C = the fluid heat capacity (J/kg°C)
k = the rock thermal conductivity (W/m°C)
V_r = the total rock volume of the flow path (m^3)
A_{ht} = heat transfer area (m^2)

The quantity Bi_m, a modified Biot number, governs the nature of heat extraction from the rock mass. For low Biot numbers, associated with closely-spaced fractures, low flow rates, and large rock volumes, heat extraction produces a sharp thermal front as described by Robinson and Jones (1987). At Biot numbers of order 1 or higher, the behavior deviates from a sharp thermal front, and significant temperature gradients remain in the rock in the x direction.

Equations (5) and (6) were solved by finite difference techniques. Equation (5) was approximated with centered differences for the spatial derivative and a Crank-Nicholson scheme for the time derivative. At the interface, the equation for the rock temperature is written as a finite difference form of Eqn. (6). At each time step the code starts at the entrance of the flow path and marches forward in the y direction, sequentially calculating the fluid and rock temperatures.

In the tracer response model, Robinson and Tester (1984, 1986) showed, for a nonadsorbing tracer, that a parallel plug flow path model could be used to match the measured tracer response curve or residence time distribution (RTD). The RTD f(t) is defined as follows: f(t)dt = the fraction of fluid leaving the system with residence times between t and t+dt. The RTD is calculated from experimental data using the following equation:

$$f(t) = \frac{QC(t)}{m_p} \qquad (8)$$

where Q is the volumetric flow rate, and m_p is the mass of tracer injected. For a large number of flow paths, the flow path of residence time t has a fluid flow rate of Qf(t)dt and a fluid volume of Qtf(t)dt. For modeling purposes, a finite number of paths is needed. To set the fluid volumes and flow rates of these paths, the tracer response curve is divided into time intervals 0 to t_1, t_1 to t_2, t_2 to t_3, etc., and the flow rate and fluid volume of each path are given by the following expressions:

$$Q_i = Q \int_{t_{i-1}}^{t_i} f(t)dt \qquad (9)$$

$$V_i = Q \int_{t_{i-1}}^{t_i} tf(t)dt \qquad (10)$$

Two adjustable parameters are required, the fracture half-spacing R and the rock volume V_r. Since the tracer response provides values for the fluid volumes of each path, the rock volumes are calculated as V_f/ϕ, where ϕ is the fracture porosity. Robinson and Jones (1987) outline methods for estimating fracture porosity, but the range of values obtained spans over an order of magnitude, implying that fracture porosity is essentially an adjustable parameter. The fracture spacing is also considered adjustable, since data are usually difficult to obtain in fractured geothermal reservoirs.

The Fenton Hill Phase II Reservoir

The Fenton Hill HDR program is designed to demonstrate the feasibility of creating and operating a prototype hot dry rock geothermal reservoir. In Phase I of the program, conducted in the 1970s, the feasibility of the concept was demonstrated in a series of hydraulic fracturing and flow tests (Dash et al., 1981). In the longest flow experiment, lasting 286 days, energy was extracted at an average rate of 3 MW thermal at a temperature of about 140°C.

Phase II of the program is designed to demonstrate the technology for long-term energy extraction on a larger scale at higher temperatures. In May and June of 1986, a 30-day flow test of the deeper Phase II reservoir was performed to test the hydraulic and thermal performance and to provide design input for a longer flow test. One purpose of this longer test is to operate the reservoir long enough to achieve a decrease in the temperature of the production fluid, which is needed to estimate reservoir size. This paper summarizes the predictions of thermal drawdown by the two models. A third model, which uses finite element techniques to solve the heat and mass transport equations in three dimensions, is developed in Birdsell and Robinson (1988).

Model Results

SGP 1-D Heat Sweep Model Simulation

Figure 1 shows the equivalent flow geometry for the Phase II cooldown simulation. The input data for the simulations, listed in Table 1, were matched as close as possible for the models. Runs were made for an injection temperature of 50°C, with estimated reservoir thickness of 150 and 250 m. A sensitivity analysis was made for rock block sizes with mean fracture spacings from 20 to 60 m and for varying flow rates from half to twice the anticipated flow rate.

The results of the SGP simulations for the injection temperature of 50°C are given in Figure 2. Part (a) shows the cooldown curves as a function of mean fracture spacing for a reservoir thickness of 150 (m) and part (b) for a reservoir thickness of 250 m. Part (c) shows the overlapping cooldown curves for the three values of porosity chosen for the study, and part (d) shows the cooldown curves for various values of flow rate.

The family of cooldown curves indicates that rock blocks of about 40 m mean fracture spacing (MFS) is the optimum mean size for a steady rate of temperature decline. For large block sizes, the rate of heat conduction from the interior of the block to its surface is too small for the given residence time, whereas for smaller sizes, the residence times are sufficient for effective heat extraction. The total heat extracted is given by the area under the

TABLE 1

Input Parameters

Fixed Parameters	SGP	LANL
T (initial) (°C)	240	240
T (injection) (°C)	50	50
α (m^2/s)	1.048×10^6	1.048×10^6
C (J/kg°C)	4756	4756
k (W/m°C)	2.7	2.7
Variable Parameters		
ϕ_1	0.0084	0.0084
ϕ_2	0.003	0.003
ϕ_3	0.00048	0.00048
ϕ_4	0.000197	0.000197
MFS (m)	20-60	1-20

Flowrates		Tracer Curve Deconvolution		
	Path	No	V_f	
		$\dot{m}$(kg/s)	(m^3)	
1/2 x Q (base)	10.6	1	1.395	23.0
2/3 x Q (base)	15.9	2	1.446	37.0
Q (base)	21.2	3	1.397	51.3
3/2 x Q (base)	31.8	4	1.357	73.9
2 x Q (base)	42.4	5	1.410	121.7
		6	14.196	10040.7
		total	21.2	10347

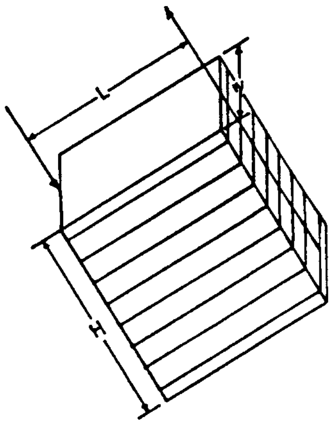
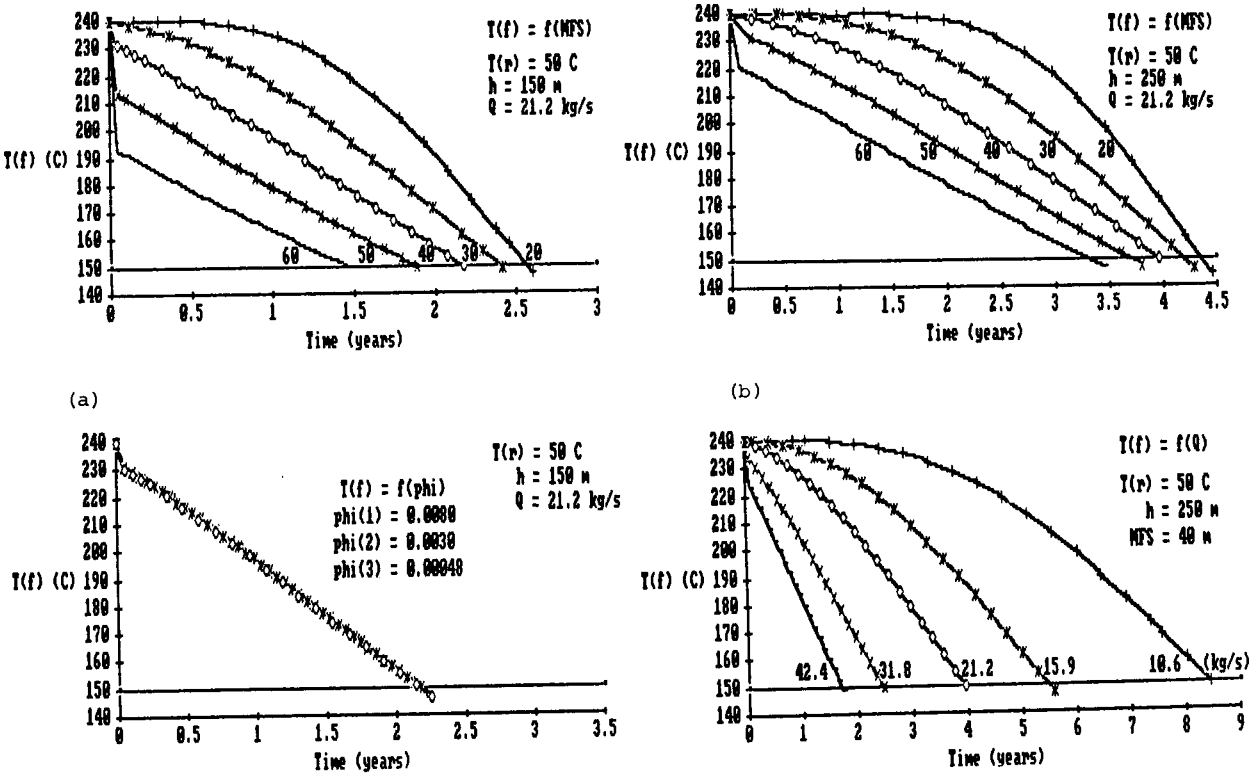


Figure 1. Equivalent Flow Geometry for the 1-D SGP Model.



(a)

(b)

(c)

(d)

Figure 2. Results of the 1-D Heat Sweep Simulations of Cooldown to an Abandonment Temperature of 150°C for: (a)different values of mean fracture spacing for a fractured reservoir of 150 m thickness; (b) for 250 m thickness; (c) as a function of fracture porosity; and (d) as a function of flowrate.

cooldown curve relative to the total heat content above the injection temperature. At a mean fracture spacing of 20 m, the fracture of heat content extracted exceeds 90% after about 80 residence times (2.6 years). The ratio of cooldown times of 3 to 5 years to the abandonment temperature of 150°C varies linearly with the ratio of reservoir thickness of 150 to 250 m.

The apparent independence of cooldown time from fracture porosity is indicative of the small mean residence time compared to the rock time constant, so that the number of heat transfer units is small for all values of small porosity. The heat extraction is essentially limited for a constant production rate by the rate of heat conduction from the rock blocks. The dependence of heat extraction on flow rate appears to follow a relationship given by $t_a = f(1/Q^n)$, for which $n = 1.15$ compared to the value $n = 1.3$ for the low-temperature parallel fractured petrogeothermal reservoir described by Dyadkin and Kruger (1987).

Tracer-Based Heat Transfer Model

The tracer response used to perform the heat transfer calculations, shown in Figure 3, was measured near the end of the Phase II 30-day flow test. The curve, normalized by Eqn. (8), shows both an early response due to channeling flow between the two wells and the long tail caused by dispersed flow through a large volume of rock. A large fraction of the tracer (67%) had not been recovered at the end of the tracer test, and extrapolation techniques developed in Robinson and Tester (1986) were used to estimate the tracer response for long times. The tracer response curve was divided into six paths, the first five with approximately the same flow rate, and the sixth representing the extrapolated tail of the tracer response curve.

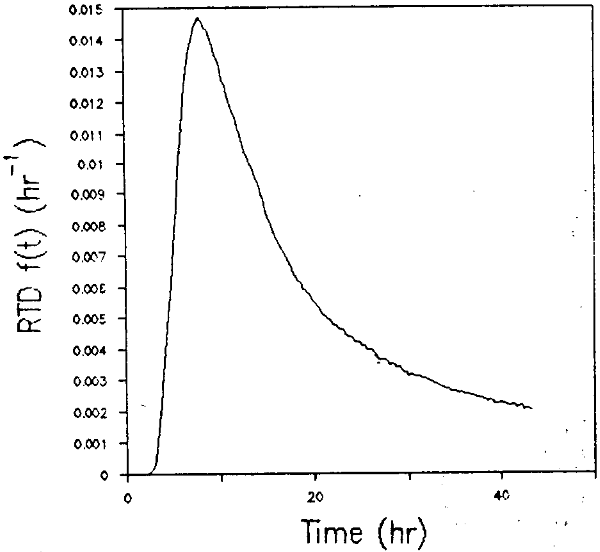


Figure 3. Tracer Response for the Fenton Hill Phase II Reservoir.

The input data for the tracer-based heat transfer model are also listed in Table 1. The range of values for ϕ (determining the rock volume heat content) were selected from various estimates by others. The values of 0.0084, 0.003, and 0.00048 were obtained from Robinson and Jones (1987) based on various assumptions. The value of 0.000197 was obtained from Birdsell and Robinson (1988) based on their finite element model. Figure 4 shows the model results for different values of fracture spacing. All of the curves exhibit an early drop in production temperature within the first 200 days due to cooldown of the short-residence-time, channeling flow paths. Fracture spacing controls the time at which the thermal drawdown occurs and the shape of the cooldown curve. Smaller fracture spacings lead to more efficient heat extraction from the rock mass. However, since in each case the same quantity of heat is potentially available, the long term behavior is similar.

Figure 5 shows the cooldown curves for different values of porosity. As seen in Figure 5 and Table 2, the largest values of ϕ, 0.0084, results in a small rock volume and rapid thermal drawdown. The low value, 0.000197, leads to the prediction of a large, long-lasting energy source. This 40-fold difference in predicted reservoir rock volume points out the need to develop better field experimental techniques for estimating fracture porosity, or more fundamentally, the reservoir rock volume exposed to fluid flow. Simple reservoir geometrical considerations can be used to place these porosity estimates in perspective. Table 2 lists the calculated reservoir rock volumes and dimensions assuming a cubic rock block in each case. The smaller sized reservoirs correspond to flow confined to a region of rock defined by the separation distance between the wellbores, roughly 100-150 m. The larger reservoirs require a flow model of potential-like flow which sweeps through a much larger rock volume. The upcoming long term flow test will determine which estimates of porosity and rock volume are closest to reality.

Comparison of Model Results

The two models used in this study represent different approaches for estimating thermal cooldown of fractured geothermal reservoirs. The 1-D SGP model assumes uniform flow, in a single path, through a volume of rock of given dimensions with assumed rock block size distribution. The LANL tracer-based model uses an observed tracer response curve to obtain the degree of flow nonuniformity and

TABLE 2

Predicted Phase II Cooldown Times to T_a=150°C

SGP 1-D Heat Sweep Model

Mean Fracture Spacing (MFS) (m)	Time (yr) to T_a=150°C for Reservoir Thickness (m)	
	150	250
20	2.57	4.35
30	2.4	4.17
40	2.15	3.94
50	1.86	3.71
60	1.47	3.30

Flowrate (kg/s)	Time (yr) to T_a = 150°C for MFS = 40 (m), H = 250 m
10.6	8.44
15.9	5.45
21.2	3.94
31.8	2.46
42.4	1.71

LANL Tracer-Based Model

Fracture Spacing (m)	Time (yr) to T_a = 150°C for ϕ = 0.003
1	3.41
5	3.20
10	2.73
20	1.73

Porosity	Time (Yr) to T_a=150°C for 5 m spacing	Total Rock Volume (m^3)	Calculated Cubic Volume Dimension (m)
0.0084	1.04	1.23×10^6	107
0.003	3.20	3.45×10^6	151
0.00048	21.8	2.16×10^7	278
0.000197	>27	5.25×10^7	374

the total fluid volume. The rock volume is determined by the choice of fracture porosity. Thus, the apparent dependence on ϕ for the LANL model is due to the way the rock volume is defined, and not due to any major differences in the fundamental physics of the model. In the SGP model the rock volume was chosen to be consistent in size with the LANL estimates for the base case of ϕ = 0.003.

The shapes of the output cooldown curves at short times are somewhat different for the two models due to different assumptions about the flow field. The LANL model assumes nonuniform flow as determined by the tracer response. Thus, an initial rapid cooldown is predicted for the short-residence-time, channeling flow paths. These paths are mixed with larger flow paths which cool more slowly, and the overall thermal cooldown is more gradual than that of the channeling paths. The SGP model on the other hand assumes a uniform rate of heat transfer based solely are the mean rock temperature and surrounding fluid temperature.

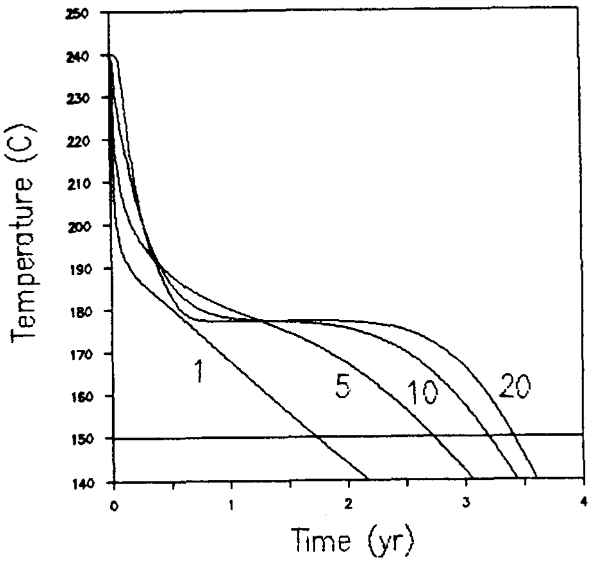


Figure 4. Predicted Cooldown Curves Using the LANL Tracer-Based Model for Different Values of the Fracture Spacing S.

For the base case input data with similar rock volumes, the two models predict similar times for cooldown to the abandonment temperature of 150°C. For this case, the SGP simulations for reservoir thickness of 150 m based on the LANL values of ϕ = 0.003 results in the same values for the rock volume. The time to reach 150°C ranges from 1.5 to 2.6 years for the SGP model and 1.7 to 3.4 years for the LANL model. The agreement is close; the differences can be attributed to differences in fracture spacing and model assumptions about the nature of the flow field. The greatest uncertainty in using either model is in the choice of the adjustable parameters which control the reservoir rock volume available for heat transfer to the circulating fluid.

Conclusions

Two heat transfer models have been used to predict thermal cooldown in the Fenton Hill HDR reservoir. The SGP model assumes uniform flow through the fracture network, while the LANL tracer-based model adopts a nonuniform flow field for heat extraction based on observed tracer test data. The differences in predicted thermal cooldown occur at early

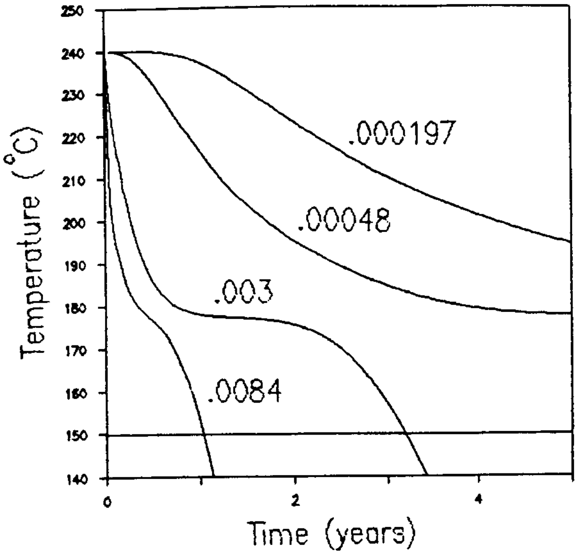


Figure 5. Predicted Cooldown Curves Using the LANL Tracer-Based Model for Different Values of the Fracture Porosity ϕ.

times, with the LANL model predicting a sharp cooldown initially, but a slower decline at later times, whereas the SGP model predicts a smooth temperature-time curve. Nonetheless, when parameters are chosen which result in similar values of the rock volume, the two models predict similar times to reach the abandonment temperature, assumed to be 150°C. Conservative estimates for this time are 1.5 - 3.2 years at the expected flow rate of the upcoming long term flow test. The comparison of the two models emphasizes the uncertainly over the appropriate value for the rock volume. New field techniques are needed to estimate this parameter. Future tests will allow the model predictions made in this study to be evaluated as well as providing additional information on the nature of fluid flow and energy transport in HDR geothermal reservoirs.

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Nomenclature

A_{ht}	heat transfer area (m^2)
Bi_m	modified Biot number (Eqn. 7)
C	fluid heat capacity (J/kg°C)
C(t)	tracer concentration-time response curve (kg/m^3)
f(t)	tracer residence time distribution (s^{-1})
h	heat transfer coefficient (W/m^2°C)
H	reservoir thickness (m)
k	rock thermal conductivity (W/m°C)
$\dot{m}$	fluid mass flow rate (kg/s)
m_p	tracer pulse mass (kg)
N_{Bi}	Biot number (Eqn. 4)
Q	fluid volumetric flow rate (m^3/s)
Q_i	fluid volumetric flow rate for path i (m^3/s)
R	equivalent rock radius (m)
S	fracture spacing (m)
t	time (s)
T	temperature (°C)
t_a	reservoir abandonment time (y)
T_a	reservoir abondonment temperature (°C)
T_f	fluid volume (m^3)
T_r	rock temperature (°C)
V_f	fluid volume (m^3)
V_i	fluid volume of path i (m^3)
x	direction perpendicular to flow (m)
y	direction of flow (m)
α	rock thermal diffusivity (m^2/s)
η	dimensionless variable (Eqn. 7)
ρ	rock density (kg/m^3)
ϕ	fracture porosity
μ	cooldown rate (°C/s)
θ	dimensionless variable (Eqn. 7)
τ	time constant for the rock (s)
ξ	dimensionless variable (Eqn. 7)

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