PROCEEDINGS, Twenty-Fourth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 25-27, 1999
SGP-TR-162

PREDICTION OF THERMAL BREAKTHROUGH FROM TRACER TESTS

G. Michael Shook

Idaho National Engineering and Environmental Laboratory
Idaho Falls, ID 83415-2107
ook@inel.gov

ABSTRACT

A method of predicting thermal breakthrough from tracer test analysis is presented. Because the ratio of fluid velocity to thermal velocity is a constant, any variations in fluid flow are identically reflected in the thermal front, even in heterogeneous media. A variable transformation is presented which facilitates comparison between tracer effluent concentrations and temperature histories. An example demonstrates the success of the method in predicting the onset of thermal decline in a heterogeneous porous media.

INTRODUCTION

Reinjection of spent geothermal fluids has become a standard reservoir management strategy over the past decade. Reinjection serves not only to maintain reservoir pressure, but also increases energy extraction efficiency over the life of the resource. Of course, since the spent fluid is frequently much cooler than the fluid in situ, these benefits depend strongly on locating injection in such a fashion that "short-circuiting" within the reservoir does not occur. While optimizing an injection strategy to avoid premature thermal breakthrough is sometimes iterative, a properly designed tracer test can be used to trace flow paths within the reservoir, and to predict the timing of thermal breakthrough.

Various researchers have examined the propagation of a thermal front in single-phase, porous medium (e.g., Bodvarsson, 1972; Woods and Fitzgerald, 1993). These studies have shown that, due to the thermal inertia of the rock volume, the thermal front lags behind the fluid front by a constant factor related to the volumetric heat capacity. In homogeneous media, then, one would expect a sharp transition from far-field temperature to injection temperature behind the injection front.

In heterogeneous media, however, mixing of the injected fluids with in situ fluid results in both an earlier and more gradual decrease in production temperature. Such premature thermal breakthrough have been observed in various geothermal reservoirs, including Beowawe (Benoit and Stark, 1993) and The Geysers (Beall et al., 1994). Thermal breakthrough leads to a host of operational problems, including plant output running below design, the added cost of makeup wells, and/or modifications to field operations.

Tracer testing has become a standard tool for tracing flow within a geothermal reservoir (e.g., Beall et al., 1994; Kocabas et al., 1996; Rose et al., 1997). By injecting a finite slug of tracer with injectate, fluid flow paths and mean residence times of injectate can be estimated. Knowledge of the flow field provides a means of identifying problems with and optimizing injection. Through numerical simulation, one may further predict the onset of cooling in produced fluids.

This paper demonstrates that a finite injection (slug) tracer test can be readily analyzed and used to predict thermal breakthrough of a temperature front in single-phase, heterogeneous porous media. Equations describing conservation of mass and energy are shown and discussed. It is the form of the combined equations that indicate how tracer test analysis can be used to predict temperature declines. Transformations that allow convenient comparison between predicted and simulated temperature changes are shown, and an example of the method is given.

CONSERVATION EQUATIONS

For a single-phase fluid in porous media, the conservation of mass and energy can be expressed (Woods and Fitzgerald, 1993) as:

$$j \frac{\partial r_w}{\partial t} + \vec{\nabla}(r_w \vec{u}_w) = 0 \qquad (1)$$

$$j \frac{\partial(\overline{rC_p}T)}{\partial t} + \vec{\nabla}(r_w \vec{u}_w C_p T) = \vec{\nabla}(K\vec{\nabla}T) \qquad (2)$$

where

$$\overline{rC_p} = j\, r_w C_{pw} + (1-j)\, r_r C_{pr}$$

If we assume incompressible rock and constant heat capacities (both rock and fluid), and also neglect conduction of heat as a second order effect (Woods and Fitzgerald, 1993), we can combine Eqns. 1 and 2 to obtain an expression that describes the velocity of the thermal front in the porous medium:

$$\frac{\partial T}{\partial t} + \frac{u_w}{j}\left(\frac{j\, r_w C_{pw}}{j\, r_w C_{pw} + (1-j)\, r_r C_{pr}}\right)\vec{\nabla}T = 0 \qquad (3)$$

From Eqn. 3, the velocity of the temperature front is retarded relative to the fluid velocity by a value that is related to the volumetric heat capacities:

$$\frac{v_T}{v_w} = \frac{v_T}{u_w/j} = \left(\frac{j\, r_w C_{pw}}{j\, r_w C_{pw} + (1-j)\, r_r C_{pr}}\right) \qquad (4)$$

In fact, the retardation term in Eqn. 4 is not a constant, as liquid density changes as a function of temperature. It has been found, however, that the use of liquid density at the average temperature ((injected + initial)/2) serves very well in what follows, and does make the retardation term constant.

One important aspect of Eqn. 3 is that no assumption of homogeneity was made in the derivation. That is, even is the presence of variations in permeability and porosity, the ratio of fluid-to-temperature velocities is a constant. Furthermore, in the absence of dispersion, a chemical wave moves at the same velocity as the bulk fluid velocity. This implies that variations in the fluid (or tracer) velocity will be identically reflected in the thermal velocity (with the appropriate shift in time from Eqn. 4). Thus, if we are able to monitor the fluid front via a tracer test, we can predict the velocity of the temperature front.

VARIABLE TRANSFORMATIONS

In a conventional tracer test, a slug of tracer is injected, followed by “clean” injectate. Due to heterogeneity and non-parallel flow lines, the tracer mixes, so that the original sharp tracer front is smeared out. Effluent tracer concentrations are originally low, increase to some maximum that is typically much smaller than the injected concentration, and again fall to zero. Temperature, on the other hand, decreases monotonically from the initial temperature (T_I) to the injected temperature (T_J). What we seek is a transformation, such that the transformed variables exhibit similar (monotonic) behavior. We have found empirically that the following variable transformations provide an appropriate means of comparing tracer concentrations and temperatures.

For the *predicted* temperature histories, plot normalized tracer recovery (T_P) vs. pseudotime (t^*):

$$T_p(t) = \frac{\int_0^t q(t)C(t)\;dt}{\int_0^\infty q(t)C(t)dt} \qquad (5)$$

$$t^* = t\left(1 + \frac{(1-j)\, r_r C_{pr}}{j\, r_w C_{pw}}\right) \qquad (6)$$

For *observed* temperature histories, plot dimensionless temperature (T_D) vs. time (t):

$$T_D = \frac{T(t) - T_I}{T_J - T_I} \qquad (7)$$

As is shown below, these transformations provide the means of predicting thermal breakthrough from a tracer test. In the following example, a tracer test is simulated and analyzed as discussed above. We then predict a thermal history at each well, and compare that with the simulated thermal history.

EXAMPLE OF THERMAL BREAKTHROUGH PREDICTION

A tracer test was simulated in a two-dimensional, heterogeneous porous medium. A random permeability field was generated, with a mean permeability of 1000 md. Permeability was assumed to be log-normally distributed and uncorrelated, with a standard deviation of 1800 md. The domain was assumed to be 200m by 200m areally and 5m thick, and was modeled with a 40 by 40 by 1 grid. Porosity was assumed to be a uniform 0.05.

Initial pressure and temperature were 1400 kPa and 175 ^{o}C, respectively, and domain boundaries were taken as closed. A single injector was placed at the approximate center of the grid, and four production wells were placed throughout the domain. No attempt was made to place these wells; rather, they were located in a somewhat haphazard fashion. Well locations and the permeability field are given in Figure 1. Other properties for this example are summarized in Table 1.

From the static initial condition, tracer was injected at a rate of 1 t/hr for 5.88 days, after which injection was switched to fresh water. Injection temperature was taken as 35 ^oC. The four production wells were produced against a bottomhole pressure of 900 kPa. Tracer effluent histories are given in Figure 2, and temperature histories are given in Figure 3.

A spreadsheet program was used to numerically integrate the tracer return curves over time for each well. The values at each time were then normalized by cumulative tracer recovery (on a per-well basis); these are the predicted temperatures. Other variables to be plotted follow simply from Eqns. 5-7 above. The predicted and simulated temperature histories are given in Figures 4-7 for each of the production wells. The excellent agreement observed in each of the wells clearly indicates the validity of this approach in predicting thermal breakthrough from tracer testing.

SUMMARY AND CONCLUSIONS

Tracer tests can be analyzed and used to predict thermal breakthrough in single-phase, porous media. Even in heterogeneous media, if thermal conductivity and dispersion can be neglected as second order effects, the thermal front moves at a constant velocity relative to the fluid flow front. By analyzing a tracer response curve (which also moves with the bulk fluid front velocity), velocity and travel time of the thermal front can be estimated. An empirical transformation of the tracer data provides a relatively simple means of predicting thermal breakthrough, as shown in an example.

Further work is required to make this method more robust. First, the variable transformations noted above were obtained empirically; it is likely there is a mathematical reason why they work so well. Also, this analysis has been restricted to single phase flow in porous media. Future work on this project will extend these results to multi-phase flow and fractured media.

ACKNOWLEDGMENTS

Funding for this work was provided by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Geotheraml Technology Division, under contract # DE-AC07-94ID13223. The author also wishes to thank J.L. Renner and K.K. Bloomfield for their review of the manuscript, and J.L. Brower for her help with the graphics.

NOMENCLATURE

C	Tracer concentration in effluent (fr.)
C_{pr}	Rock specific heat (J/g ^oC)
C_{pw}	Liquid specific heat (J/g ^oC)
K	Thermal conductivity (W/m ^oC)
q	Mass flow rate of well (kg/s)
t	Time (s)
t^*	Pseudotime, as defined in Eqn. 6
T	Temperature (^oC)
T_D	Dimensionless temperature as defined in Eqn. 7
T_I	Initial temperature (^oC)
T_J	Injected temperature (^oC)
T_p	Predicted dimensionless temperature (from tracer analysis)
u_w	Darcy velocity of liquid phase (L/t)
v_w	Interstitial velocity of liquid phase (L/t)
v_T	Velocity of thermal front (L/t)
φ	Porosity
ρ_w	Liquid density (kg/m^3)
ρ_r	Rock density (kg/m^3)

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Table 1. Summary of reservoir and numerical properties for example problem.	
Dimensions	200m x 200m x 5m
Porosity	0.05 (V_p = 10,000 m^3)
Permeability	mean =1000 md, log-normally distributed
Rock heat capacity	1 kJ/kg ^{o}C
Thermal conductivity	20. W/m ^{o}C
Initial conditions:	
Pressure	1400 kPa
Temperature	175^{o}C
Boundary Conditions	no-flow, insulated
Grid	40 x 40 x 1, uniform grid
Time step size	4 day maximum

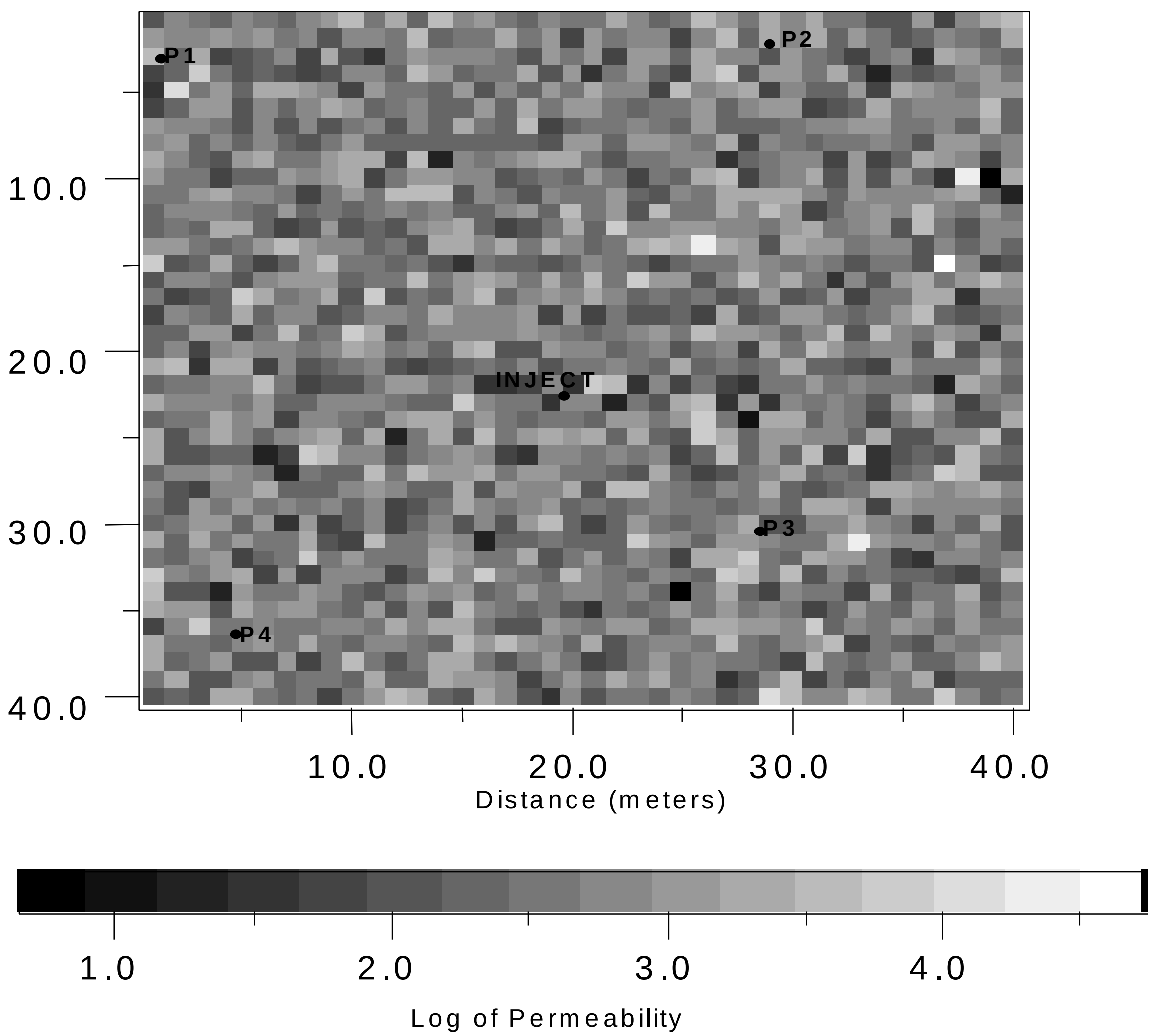

Figure 1. Permeability field for example simulation of a tracer test.

Figure 2. Tracer concentration histories for example problem.

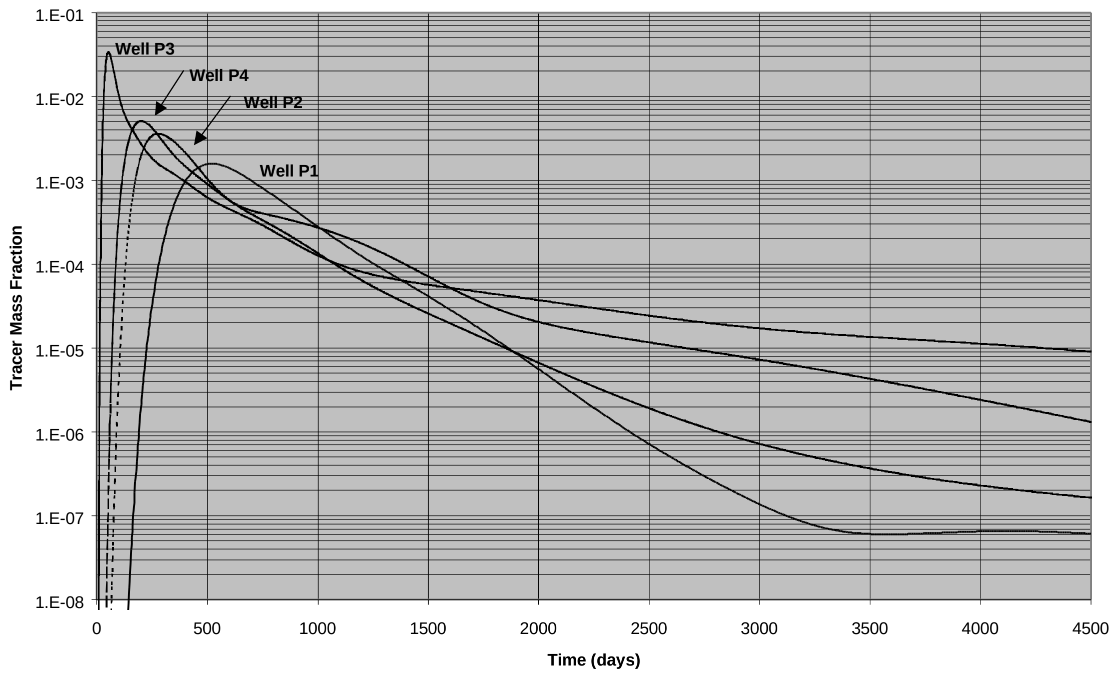

Figure 3. Temperature histories for example problem.

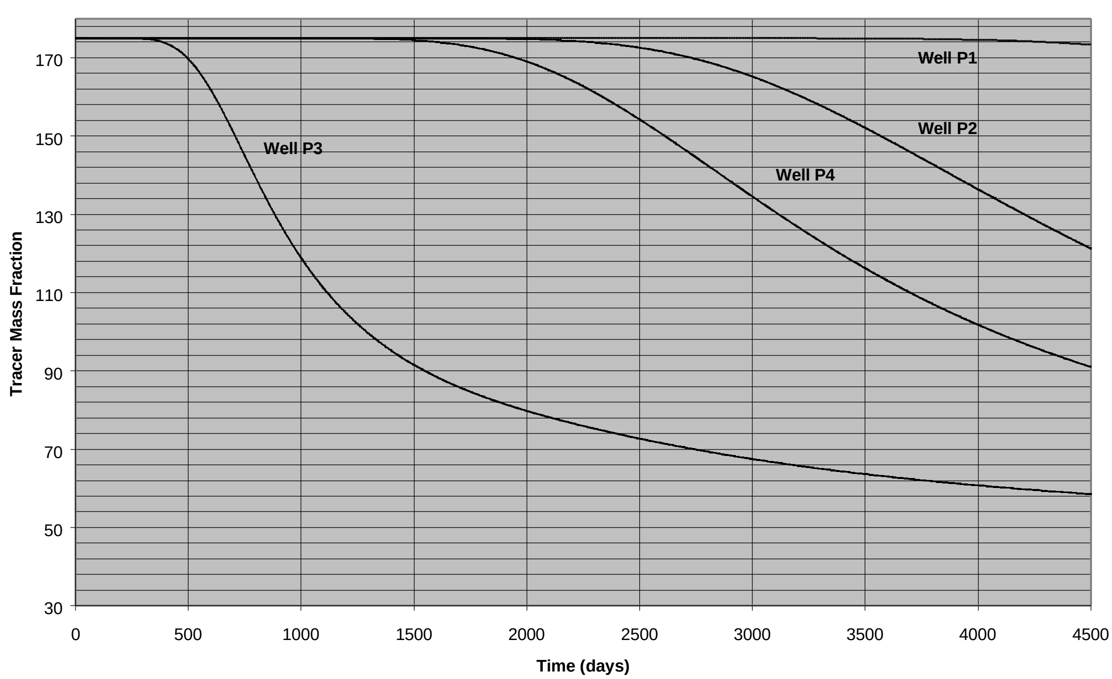

Figure 4. Predicted vs. Simulated Temperature Histories, Well P1

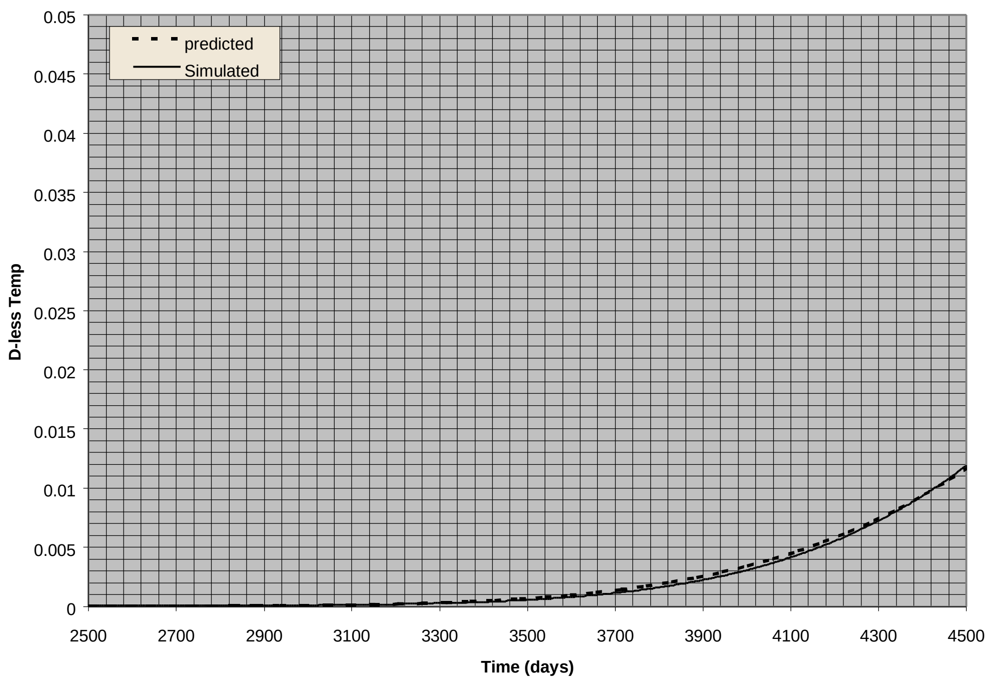

Figure 5. Predicted vs. Simulated Temperature Histories, Well P2

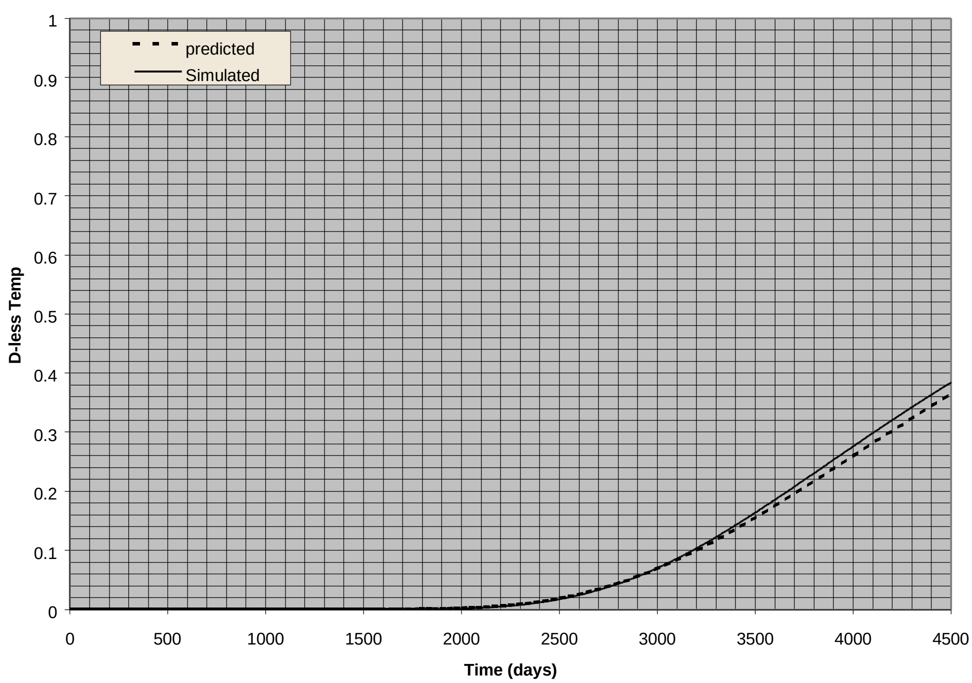

Figure 6. Predicted vs. Simulated Temperature Histories, Well P3

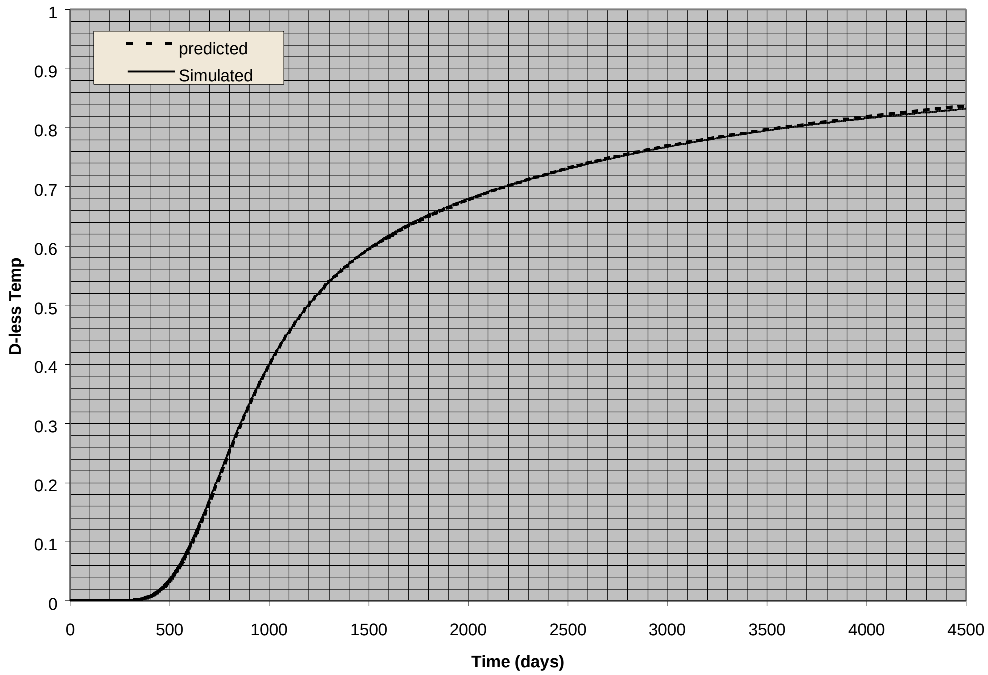

Figure 7. Predicted vs. Simulated Temperature Histories, Well P4