Idaho National Engineering and Environmental Laboratory

INEEL/CON-01-01070
PREPRINT

Tracer Test Interpretation Methods For Reservoir Properties

G. Michael Shook

August 23, 2001

DOE Geothermal Energy Program Peer Review

U.S. DEPARTMENT OF ENERGY
GEOTHERMAL ENERGY PROGRAM
GEOSCIENCE PEER REVIEW

Project Title Tracer Test Interpretation Methods for Reservoir Properties

Principle Investigator(s) G. Michael Shook
Organization: Idaho National Engineering and Environmental Laboratory
Address: PO Box 6125
Idaho Falls, ID 83415-2107
Email: ook@inel.gov

Project Purpose
The purpose of this project is to develop tools that can be used to interpret tracer tests and obtain estimates of reservoir and operational parameters. These tools (mostly in the form of spreadsheet applications) can be used to optimize geothermal resource management.

Project Objective(s)
- From examination of energy and mass conservation equations, develop specific tracer test interpretation tools that provide estimates of:
  - geothermal reservoir pore volume and injectate sweep efficiency
  - thermal sweep efficiency, thermal velocities arising from injection of cool fluid, and arrival time of cooler injectate at extraction wells
- Develop and apply these tools for use in either heterogeneous permeable or fractured media, for either single- or two-phase flow application
- Develop a "tool kit" of interpretation tools (mostly in the form of spreadsheet applications) and make the tool kit available to the geothermal industry.

Funding

Fiscal Year	DOE Funding ($k)	Cost Share ($k)	Total
99	140	0	140
00	125	0	125
01	150	0	150

Plans and Approach
Tracer testing in geothermal fields has become somewhat a standard reservoir management tool in recent years, with over 30 tracer tests having been conducted domestically. Tracer tests provide a relatively inexpensive means of interrogating a subsurface formation (e.g., a geothermal reservoir) and determine various properties, such as fluid velocities (effective permeability field), injection sweep efficiency, reservoir pore volume and the nature of reservoir boundaries (open or closed, etc.). Injection operations, also a standard resource management practice, are designed to extract heat from reservoir rock and transport that energy to extraction wells. Intuitively one knows that injection will ultimately lead to extraction of cooler fluid, since

injectate is typically much cooler than in-situ fluids. There is a need to predict the onset of cooling that arises from injection; tracer test interpretation provides a means of making such predictions.

The goal of this project is to transfer existing and develop new methods for tracer test interpretation in geothermal applications. Reservoir and operational parameters to be estimated from tracer tests include injectate and thermal swept volumes and fluid and thermal velocities, both in porous and fractured media. By examining the form of the conservation equations, insight can be gained into the relationship between fluid and thermal velocities. Tracer return curves provide information regarding fluid velocity, and can therefore be used in determining thermal velocities.

The project started with the simplest relevant problem of interest: cool, single phase fluid injected into a hot porous geothermal reservoir containing single phase liquid. The insight gained was used to extend the study to more complex situations, including, to date, two-phase initial conditions in porous media, and single phase conditions in fractured media. The ultimate plan of the project is to complete the analyses in two-phase flow conditions in both porous and fractured media, and to develop a tool kit for test interpretation that maximizes information obtainable from tracer tests.

Results

Case 1: Single phase fluids, permeable media.

The first case studied was that of single phase flow in heterogeneous, permeable media (i.e., non-fractured). First, an example of calculating pore volume swept by injectate was given (Shook, 1999). That method is based on the mean residence time of a conservative tracer. Then, work was begun on predicting thermal breakthrough times from tracer tests. The mass and energy conservation equations can be written in combined form as:

$$\frac{\partial T}{\partial t} + v_w \left(\frac{\varphi \rho_w C_{pw}}{\varphi \rho_w C_{pw} + (1-\varphi)\rho_r C_{pr}} \right) \vec{\nabla} T = 0 \tag{1}$$

The form of this equation is important, as it shows that the velocity of the temperature wave, v_T, is proportional to fluid velocity, v_w, and a ratio of volumetric heat capacities:

$$v_T = v_w \left(\frac{\varphi \rho_w C_{pw}}{\varphi \rho_w C_{pw} + (1-\varphi)\rho_r C_{pr}} \right) = v_w \left(\frac{1}{1 + D_T} \right) \tag{2}$$

This result has long been recognized (e.g., Bodvarsson, 1972). What has not been stated in the literature is that this result is independent of heterogeneity; if one can monitor fluid velocity and estimate heat capacities, one can readily predict temperature velocities and therefore thermal breakthrough at extraction wells (Shook, 1999; 2001b). Fluid velocities vary in heterogeneous media, but tracers move at bulk fluid velocity. The variable fluid velocity (and therefore variable thermal velocity) can be captured by an appropriate variable transformation, whereby tracer recovery data is used as a predictor of a dimensionless temperature decline at extraction wells.

The variable transformations are given below; the physical significance of such transformations is given by Shook (2001b).

Predicted time, t*, is retarded by thermal inertia of reservoir mass:

$$t^* = t(1+D_T) = t\left(1+\frac{(1-\varphi)\rho_r C_{pr}}{\varphi\rho_w C_{pw}}\right) \tag{3}$$

Predicted temperature, Tp, is determined from tracer return data:

$$T_p(t) = \frac{\int_0^t q(\tau)C(\tau)\,d\tau}{\int_0^\infty q(t)C(t)dt}\ . \tag{4}$$

An example of these predictions (swept volume and thermal breakthrough) is given in the example below. A tracer test was simulated in a randomly heterogeneous permeable medium. Cool liquid at 35°C is injected into a medium at 175°C. Tracer return data for each well was then analyzed with respect to swept volume, and a *predicted cooling history* for each well was determined from the tracer test and the variable transformations given above. These predictions were then compared against the simulated cooling history to determine the method's utility.

A plan view of the test case, showing the permeability field and well locations is given in Figure 1. In addition to estimating injectate sweep efficiency from tracer data (from mean residence times), the velocity field was determined, and drainage volumes for each well were calculated. This comparison is given in Table 1, and shows that tracer test analysis is an excellent swept volume estimator. Two of the predicted temperature histories are compared against the simulated histories (the best and the worst agreement) for the example in Figures 2 and 3. These comparisons, and the others given by Shook 2001b, show the method of cooling prediction works very well in heterogeneous, but porous (i.e., not fractured) media.

Case 2: Two phase flow conditions.

Preliminary work on two phase flow conditions was begun in FY 01. In this case, up to two distinct temperature waves move through the porous medium, separating the *initial* temperature (T_I) from the *interfacial* temperature (T_i, the value of which is dictated by the extraction pressure), followed by the *injection* temperature (T_J). The existence of the interfacial temperature wave is dictated by the amount of excess heat (Shook, 2001a) originally in the reservoir. The velocity of the interfacial temperature is given by Shook (2001a) as:

$$v_{Ti} = v_w \frac{\varphi\rho_{wI} L_v}{\varphi\rho_{wI} L_v + (1-\varphi)\rho_R C_{pR}(T_I - T_i)} \tag{5}$$

The injected temperature velocity is the same as in the single phase liquid case. The method works well, but nevertheless requires additional work to find applicability. The problem is that the single phase fluid velocity is generally not known in two phase conditions; thus, the equation given above is an underconstrained solution. Additional work is planned in the coming FY to develop a robust solution to the problem.

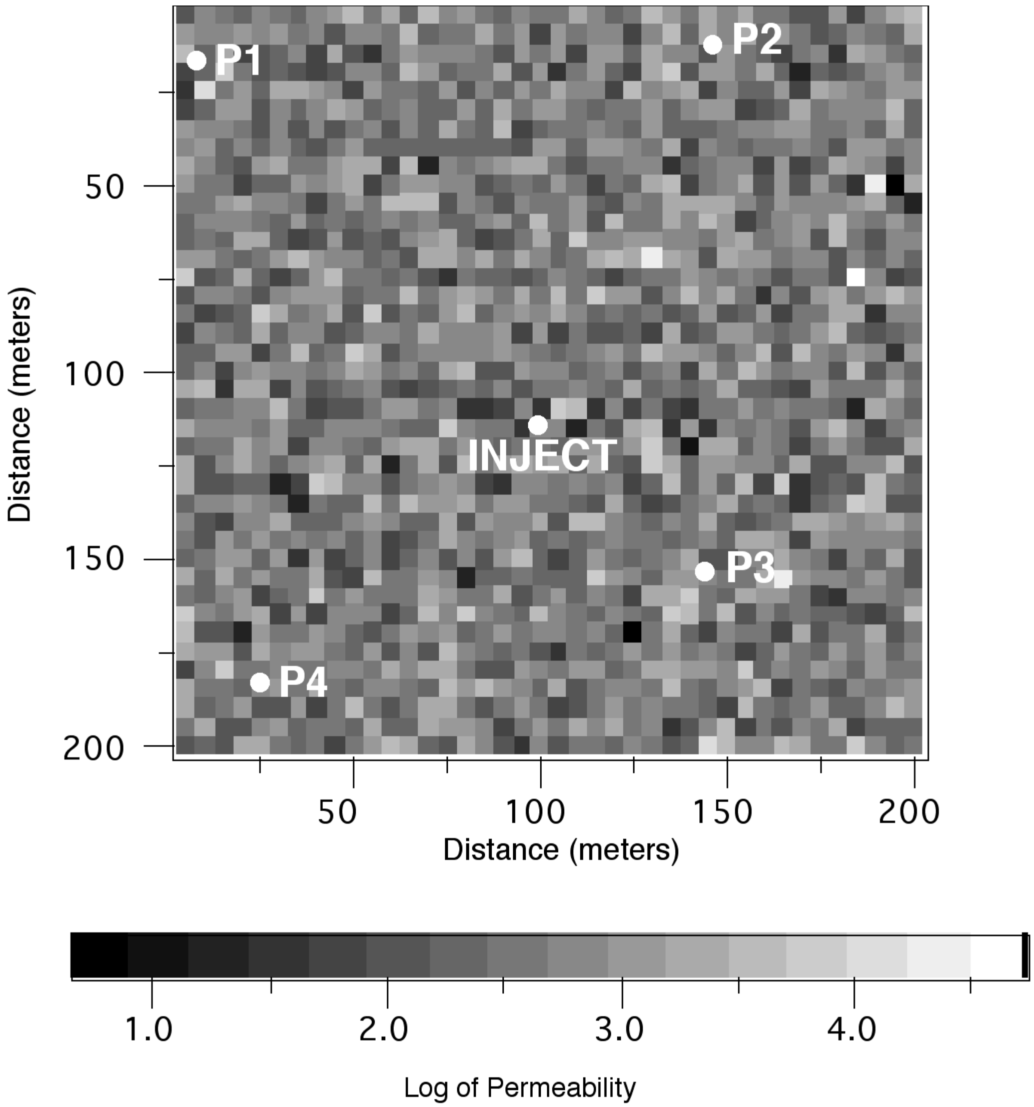

Figure 1. Permeability field and well locations for Example 1.

Table 1. Summary of Drainage Volume Estimates for Example 1.			
Well "quadrant"	V_p from moment analysis	V_p from velocity field	Error
I	2267 m^3	2260 m^3	-0.3%
II	2902 m^3	3007 m^3	-3.5%
III	2618 m^3	2550 m^3	2.7%
IV	2140 m^3	2180 m^3	-1.8%
Total Volume	9929 m^3	10,000 m^3	0.7%

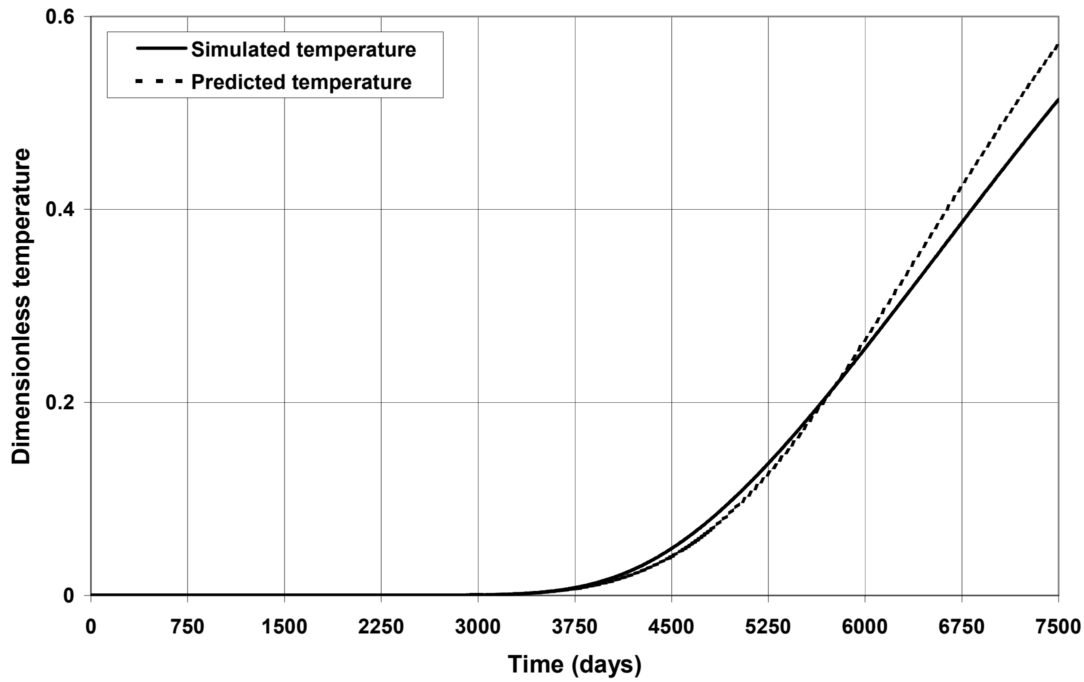

Figure 2. Comparison between predicted and simulated temperature histories for Well P1, Example 1.

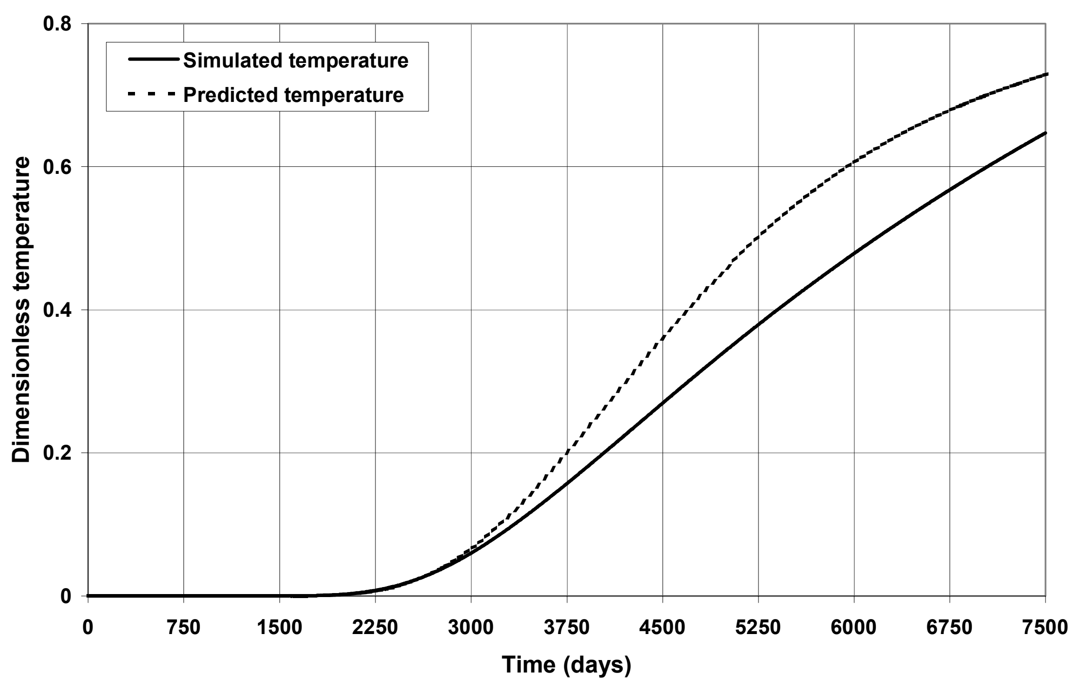

Figure 3. Comparison between predicted and simulated temperature histories for Well P2, Example 1.

Case 3: Single phase flow in fracture media
Work began this FY on extending the methods to fractured media. The relative simplicity of variable transformations given above warrants an attempt to apply it to fractured media. Shook (2001c) points out the most significant difference between the two cases is that in porous media the fluid and energy waves travel through the same bulk volume; in fractured media the energy wave also travels through a time-varying rock matrix volume. This, then, leads to a time-dependant retardation factor similar to that given in Eqn. 3 above but with an additional term:

$$v_T = v_w \left(\frac{1}{1 + D_{T1} + D_{T2}} \right) \tag{5}$$

where

$$D_{T1} = \left[\frac{(1-\varphi)\rho_r C_{pr}}{\varphi \rho_w C_{pw}} \right]_{fr} \tag{6}$$

and

$$D_{T2} = \left(\frac{V(t)_{ma}\, \overline{\rho C}_p}{(V_b \varphi)_{fr}\, \rho_w C_{pw}} \right) \tag{7}$$

The only difficulty with the equation given above is in estimating the bulk volume, V(t), of rock matrix contacted by the temperature wave. This volume can be estimated from the analytical solution as the "thermal penetration distance" (e.g., Bird, Stewart, and Lightfoot, 1960) as:

$$V(t) = \int_0^L W z(x,t)\,dx = \frac{8}{3} W v_w \sqrt{\kappa} \left(t^{3/2} + \left(\frac{\rho_w C_{pw} b}{K_r} - 1 \right) \left(t - \frac{L}{v_w} \right)^{3/2} \right) \tag{8}$$

The predicted temperature variable, Tp is as given above. This trial function has been tested on a simple fractured domain. A schematic of the problem is given in Figure 4. As before, a tracer test was simulated, and the tracer return curve was used to predict the (future) temperature history at the extraction well. A comparison between the predicted and simulated temperature history is given in Figure 5. As in the porous media case, good agreement between the two indicates applicability of the predictive method. The method fails at long time (large dimensionless temperature) because of the assumed infinite rock matrix in the analytical solution.

Despite the apparent good agreement in the fractured case discussed above, there are known limitations to this method that require investigation. These include limits on fracture spacing / length ratios, and the effects of multi-dimensional fracture networks. These will be explored in the coming FY.

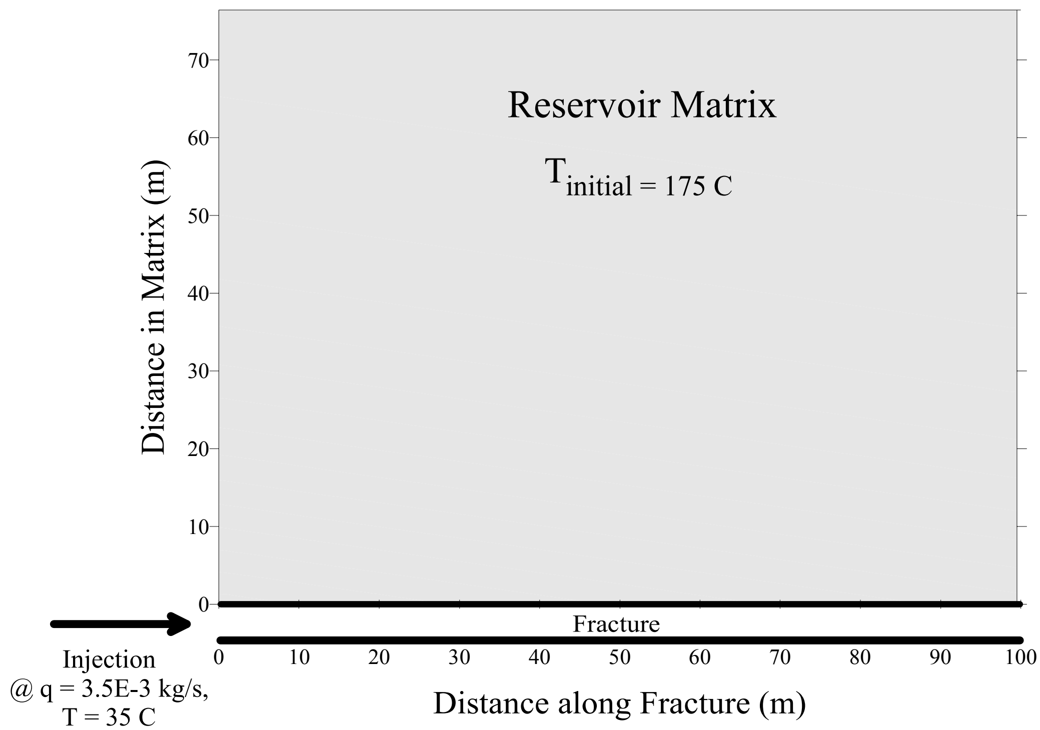

Figure 4. Schematic of example problem in fractured media

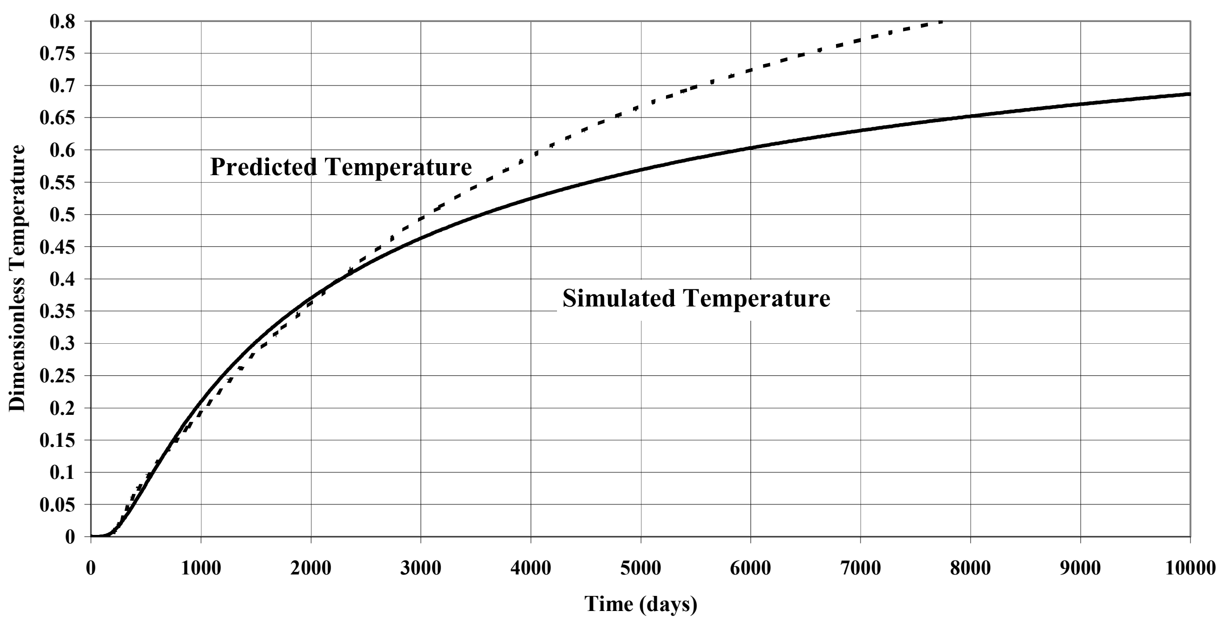

Figure 5. Comparison between predicted and simulated temperatures for Example 2.

Technology Transfer/Collaborations

Results that have been obtained from this project have been published and presented at several geothermal meetings (GRC and Stanford workshops), and in peer-reviewed journals as follows:

Shook, G.M., 1998, "Prediction of Reservoir Pore Volumes from Conservative Tracer Tests," **Trans.**, Geothermal Resources Council, Vol. 22.

Shook, G.M., 1999, "Prediction of Thermal Breakthrough from Tracer Tests," **Trans**., 24nd Stanford Workshop on Geothermal Reservoir Engineering.

Shook, G.M., 2001a, Thermal Velocities Arising from Injection in 2-Phase and Superheated Reservoirs," **Trans**., 26th Stanford Workshop on Geothermal Reservoir Engineering.

Shook, G.M., 2001b, "Prediction of Thermal Breakthrough in Heterogeneous Media from Tracer Tests," accepted for publication, *Geothermics*.

Shook, G.M., 2001c, "Prediction of Thermal Velocities from Tracer Tests in Fractured Media," accepted for presentation, Geothermal Resources Council annual meeting.

In addition to the presentations and publications listed above, various discussions have been held with field operators for field validation of the methods developed to date. In particular, discussions were held with Oxbow Geothermal Company in 1999 and 2000 for access to tracer test and cooling information at Dixie Valley field; those discussions will be continued with the current field operator, Caithness. Numerous discussions have also been held with Energy and Geoscience Institute researchers who select, design, and field tracers. Collaborative work with EGI is ongoing.

Plans for Project Completion

As noted above, two parts of this project require additional work in FY 02, including extension of the method to two-phase conditions, and evaluating possible limitations of the method in complex fractured media. The approach taken to date will be used in FY 02 to complete this project.

Also in FY 02 we anticipate field-testing the methods in a single phase, fractured medium. Those results will be made available to interested parties, and the methods will be refined as necessary. Finally, we anticipate creating a spreadsheet-based set of tools for tracer test interpretation.