PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 31 - February 2, 2011
SGP-TR-191

A REACTIVE TRACER ANALYSIS METHOD FOR MONITORING THERMAL DRAWDOWN IN GEOTHERMAL RESERVOIRS

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ABSTRACT

Tracers provide an important means of interrogating the subsurface to provide critical information about hydraulic characteristics of the reservoir. In a geothermal reservoir, reactive tracers may add information about the thermal state of the reservoir. Tracer test analysis methods vary, but generally involve curve fitting to a simple model of the system or a moment analysis approach. The Idaho National Laboratory is currently developing an analysis tool that provides a variety of commonly used approaches in a single program, and which extends to analysis of reactive tracers. To provide a reactive tracer test analysis method that can be easily implemented without extensive knowledge of the reservoir geometry, we include an approach that relies on a simplified model of the subsurface. The approach involves (1) fitting a simplified reservoir model geometry to a combination of conservative and reactive tracer data (2) using the assumed geometry to interpret changes in reactive tracer concentrations (from tests conducted at different times) and (3) examining the sensitivity of inferences about thermal evolution to the assumptions about geometry. Sensitivity of such an analysis depends on the sensitivity of a reactive tracer to changes in its temperature-time history. We illustrate sensitivity differences between several possible reaction combinations.

INTRODUCTION

Efficient operation of an engineered geothermal system (EGS) involving cold fluid reinjection requires accurate and timely information about thermal depletion of the reservoir in response to operation. In particular, accurate predictions of the time to thermal breakthrough and subsequent rate of thermal drawdown are necessary for reservoir management, design of fracture stimulation and well drilling programs, and forecasting of economic return. Periodic testing with reactive tracers has been proposed as one means of estimating thermal breakthrough before the temperature of the working fluid at the production well is affected (e.g., Tester 1987), but testing of the approach has been limited. With repeated tests, the rate of migration of the thermal front can be determined, and the time to thermal breakthrough calculated. While the basic theory behind the concept of thermal tracers has been understood for some time, effective application of the method has yet to be demonstrated.

As with conservative tracer tests, reactive tracers can provide information about the reservoir with only limited *a priori* knowledge of the reservoir. To provide an analysis method that can be easily implemented without extensive knowledge of the reservoir geometry, we are developing an approach that relies on a simplified model of the subsurface. The method is intended to incorporate and extend information from conservative tracer tests that provide information about the swept volume of the reservoir and residence time distribution. The approach generally involves (1) fitting a simplified reservoir model geometry to a combination of conservative and reactive tracer data (2) using the assumed geometry to interpret changes in reactive tracer concentrations (from tests conducted at different times) and (3) examining the sensitivity of inferences about thermal evolution to the assumptions about geometry.

Although tracer interpretation does not generally require a physical description of fracture geometry, our approach attempts to fit a simple reservoir description to observed tracer test data for several reasons. First, thermal evolution of the reservoir depends on fracture aperture, fracture length, fracture spacing and other geometric characteristics, so those features must be incorporated at some level in order to fit thermally reactive tracer data to assumptions about fundamental reservoir properties. Second, by identifying fracture geometries that are consistent with operating conditions (well pressures, well screen lengths, etc), and with conservative and reactive tracer behavior, the method provides a means of predicting response of systems that may be considered representative of the behavior of the system of interest.

As a simple geometric description of an EGS reservoir, we assume several sets of planar fractures, each with constant aperture, interfracture spacing and well-to-well distance. The streamtube distribution for dipole flow in a unform fracture yields a breakthrough curve that is asymmetric, as is commonly observed in tracer tests, and though somewhat unrealistic, provides a reasonable starting point for examining the effect of reservoir geometry on reactive tracers. Selection of a simplified reservoir geometry for analysis of reactive tracer behavior also provides an opportunity to use algorithms that are amenable to rapid solution via analytical, semi-analytical or numerical methods that can be readily implemented in a stand-alone software package for distribution to the geothermal industry. We have begun to incorporate these concepts in a development environment built on Mathsoft's Matlab.

APPROACH

The tracer analysis approach, requires that conservative tracer tests are first used to constrain the volume and residence time distribution of the reservoir, using the method described by Shook and Forsmann (2005), including calculation of the flow capacity – storage capacity (F-Φ) curve for the aggregate system. Flow – storage (F-Φ) curves for dipole flow between two wells in a single permeable layer, such as a fracture, depend on the extent that streamtubes extend outward from a line connecting the two wells. To illustrate F-Φ curves for such a system, we use the equations of Grove and Beetem (1971) to define travel time through streamtubes connecting two wells in a single permeable layer. Figure 1 illustrates differences in F-Φ curves for a range of dipole scenarios for which well location or fracture aperture limits the angular extent of streamtubes away from a center connecting line. These curves are very similar to those expected for a reservoir consisting of a large number of fractures with a wide distribution of apertures or lengths (Figure 2). That many tracer tests in fractured rock systems yield much more irregular F-Φ curves suggests that interpretation of a reservoir as being characterized by a small set of dominant fractures, rather than a well distributed set of lengths or apertures, may be a reasonable assumption.

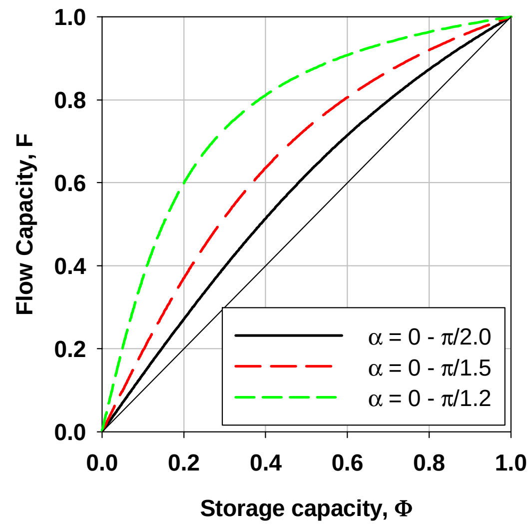

Figure 1. Flow capacity vs storage capacity curves for dipole flow between two wells but with the range of streamtubes between the wells assumed to be limited by well location or fracture shape. α defines the angle between a well and the direction of the streamtube away from a line connecting the wells. Wells on the edge of a disk-shaped fracture would extend to α= π/2

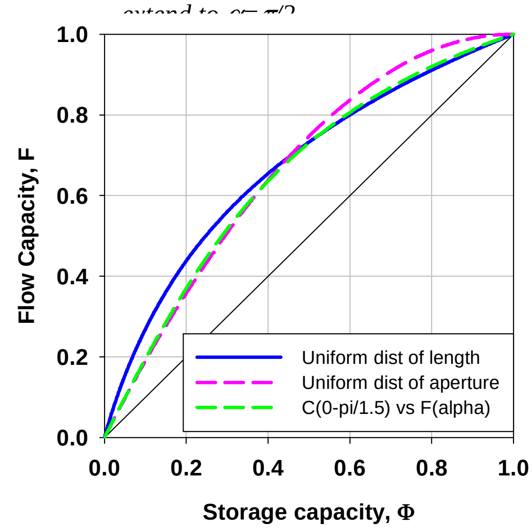

Figure 2. Flow capacity vs storage capacity curves for (1) a set of fractures with uniform distribution of lengths but constant width and aperture, (2) a set of fractures with uniform distribution of apertures but constant width and length, and (3) dipole flow between two wells.

Flow-storage information is combined with reservoir operations data to constrain the total fracture volume and ratio of fracture radius to aperture, which defines hydraulic conductivity, via the cubic law. That information defines flowpath velocities and other parameters necessary for calculation of temperatures along each flow path, which are calculated via numerical inversion of the solution of the Laplace transformed equation of Gringarten et al. (1975) (Figure 3).

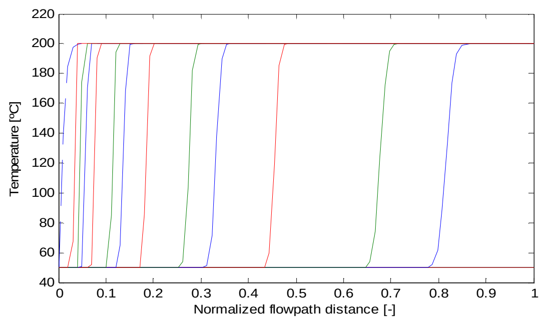

Figure 3. Temperature profiles for 5 sets of 20 fractures, for 3 paths through each fracture, where interfracture spacing ranges from 10 to 50 meters. Operating time is selected to demonstrate differences in temperature profiles between fractures. Different colors represent different paths within a single fracture. Dashed line represents temperature profile for infinite fracture spacing.

Transport of a reactive tracer slug, with a temperature-dependent rate coefficient described by the Arrhenius expression, is then calculated using one of several options for dispersive or non-dispersive 1-D transport through a set of streamtubes through the fracture. The flow-weighted average of the resulting

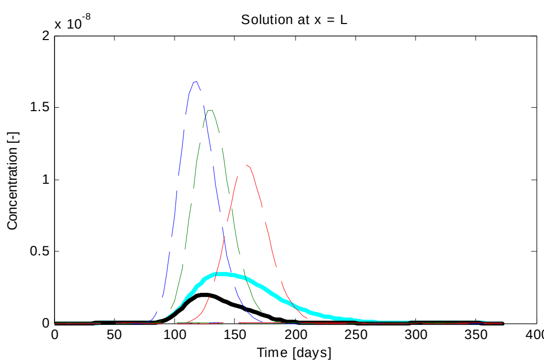

Figure 4. Breakthrough curves for a reactive tracer in a reservoir of 5 sets of 20 fractures each. Dashed lines represent different paths within a single fracture. Solid black curve is the flow-weighted average reactive transport breakthrough curve. Cyan curve is the conservative solute breakthrough curve.

breakthrough curves defines the reactive tracer breakthrough curve at the production well. The description of the fracture system is then altered, via an optimization routine, so that the modeled breakthrough curve fits all of the available observations. The goal is use both conservative and reactive tracer test data to define fracture geometries that fit the available data and then use the same modeling approach to predict the thermal evolution of the reservoir. Preliminary testing suggests that many different fracture geometries may combine to produce essentially the same tracer breakthrough curves in different ways, indicating that additional information, from other reservoir interrogation methods, will be necessary for reliable predictions of

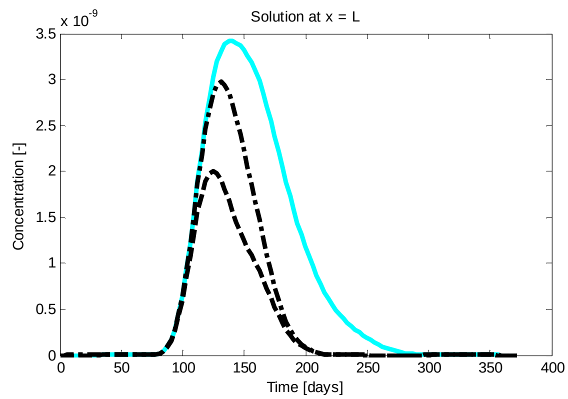

Figure 5. Comparison of breakthrough curves for conservative tracer (solid cyan curve), and reactive tracer at initial operating time and later operating time. Later time curve shows reduced loss of tracer via reaction because of lower temperatures in the system. Note that temperature at production remains at initial reservoir

thermal evolution based on reactive tracer testing.

REACTIVE TRACER SENSITIVITY

For the reactive tracer method to be viable, the concentrations in the production well must be sensitive to changes in the temperature distribution in the reservoir. Several researchers have questioned whether single reactive tracers are sufficiently sensitive to detect changes in temperature for other than very large differences in operating times between tracer tests (e.g., Plummer, et al., 2010; Behrens et al., 2009). The primary difficulty is that the highest reaction rates occur in the downstream portion of the flowpath, where temperatures converge on the initial reservoir temperature, and this is true for $k(T)$ with either strong or weak temperature dependence. While sensitivity increases slightly with E_a, the net conversion with large E_a also decreases toward immeasurably small values.

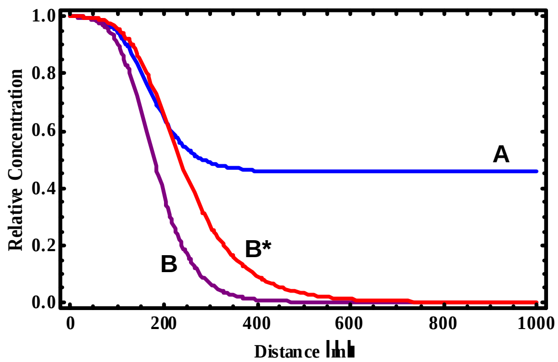

Figure 6. Relative concentration of A and B in a parcel of water as it flows between the injection and production wells for two parallel reaction paths. B denotes the concentration of B in the absence of A.*

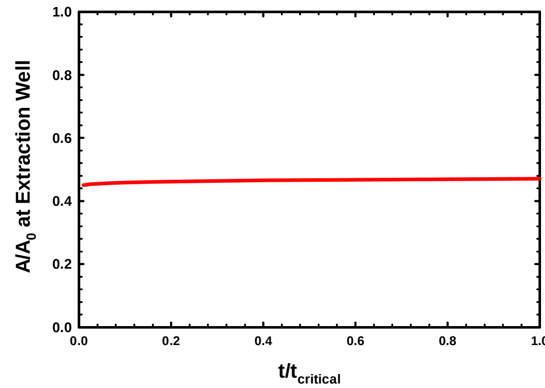

Figure 7. Relative concentration of A as a function of the fraction of the cooling time of the reservoir for a parallel reaction pathway for B.

To help circumvent these difficulties, Plummer et al. (2010) suggested that a reactive tracer may be more sensitive to changes in temperature distribution in the reservoir if the reaction could be quenched at some appropriate temperature. To further investigate this possibility, we considered two parallel reactions involving tracers A and B:

$$A + B \xrightarrow{k_1} C \quad \text{Eq. 1}$$

$$B \xrightarrow{k_2} D \quad \text{Eq. 2}$$

We assume that the rates for these reactions are respectively given by

$$\frac{dA}{dt} = -k_1 AB \quad \text{Eq. 3}$$

$$\frac{dB}{dt} = -k_1 AB - k_2 B \quad \text{Eq. 4}$$

where the rate coefficients k_1 and k_2 are given by the Arrhenius equation :

$$k_i = \alpha_i \exp\left(\frac{-E_i}{RT}\right) \quad \text{Eq. 5}$$

where E_i is the activation energy for the ith rate coefficient, R is the gas constant, T is temperature in kelvins, and α_i is the pre-exponential factor. Conceptually, we expect that A and B will react to form C while B is also consumed via a second pathway to D. A and B will continue to react to form C until all of the B is consumed. At this point, the concentrations of A, C, and D become fixed. In this sense, the A+B reaction is quenched when all of the B has been consumed. An example of the potential distribution of tracer concentrations in a parcel of water as it travels along a flow path between the injection well and the extraction well shows the concentration of A deceasing to a constant value (Figure 6).

We have tested several sets of parameters and for a particular set, we presented the values of A as a function of the fraction of the reservoir that has been cooled (Figure 7). The results indicate that the concentration of A is not sensitive to the amount of cooling in the reservoir (generally < 1%) and therefore this approach is unlikely to be useful.

An alternative approach is to use a tracer that degrades in several consecutive steps as chain decay. Consider the decay of A through the intermediate B and then to C:

$$A \xrightarrow{k_1} B \quad \text{Eq. 6}$$

$$B \xrightarrow{k_2} C \quad \text{Eq. 7}$$

If these are first order reactions, the rate equations can be written as

$$\frac{dA}{dt} = -k_1 A \quad \text{Eq. 8}$$

$$\frac{dB}{dt} = k_1 A - k_2 B \quad \text{Eq. 9}$$

$$\frac{dC}{dt} = k_2 B \quad \text{Eq. 10}$$

where the rate coefficients are given by the Arrhenius equation (Eq. 5). We numerically solved this system of differential equations with the initial conditions A(0) = 1, B(0) = 0 and C(0) =0. A typical set of response curves (Figure 8) show A decreasing with residence time with B simultaneously increasing to a maxima. B does not attain unit relative concentration because of the mass loss due to transformation of B to C which increases as B decreases. The concentrations of B and C as a function of the fraction of the reservoir that has been cooled (Figure 9) indicate that these concentrations are much more sensitive to the amount of cooling in the reservoir than for the parallel reaction pathway case and therefore the use of consecutive reaction pathway may prove useful in delineating the migration of thermal fronts in reservoirs.

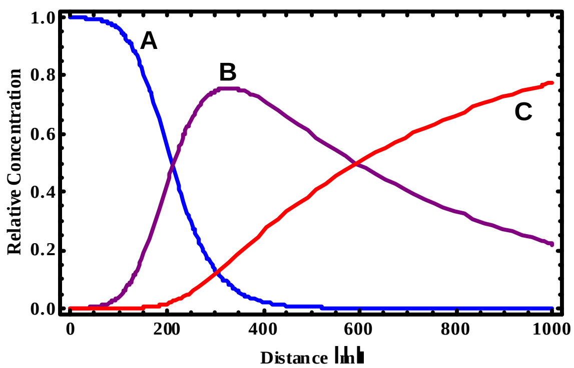

Figure 8. Relative concentrations of A, B and C for the case of consecutive reactions (chain decay).

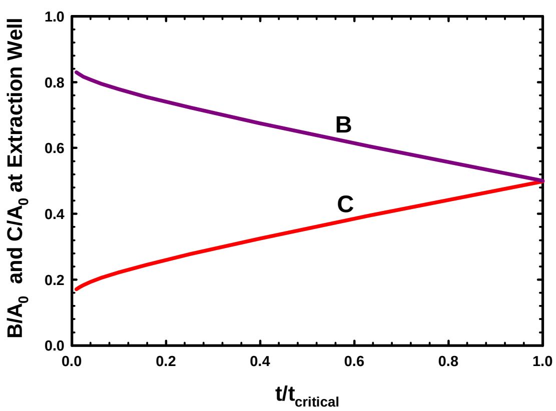

Figure 9. Relative concentration of A and C as a function of the fraction of the cooling time of the reservoir for a chain decay.

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SUMMARY

We have been developing a reactive tracer analysis method for monitoring thermal drawdown in geothermal reservoirs. The method involves using both conservative and reactive tracers and employs several approaches including flow capacity – storage curves. It is based upon geometric models of multiple fracture sets with multiple stream tubes in each fracture set. The analysis is performed in a standalone software tool built in MATLAB (Mathworks, Inc.). Preliminary results of investigating alternative approaches to improving reactive tracer sensitivity to changes in temperature distribution in the reservoir suggest that a reactive tracer undergoing consecutive reactions (e.g., chain decay) may be sufficiently sensitive to track changes in thermal conditions in the reservoir.

ACKNOWLEDGEMENTS

Work supported by the U.S. Department of Energy, Office of Geothermal Technologies under DOE Idaho Operations Office Contract DE-AC07-05ID14517.