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SENSITIVITY OF A REACTIVE-TRACER BASED ESTIMATE OF THERMAL BREAKTHROUGH IN AN EGS TO PROPERTIES OF THE RESERVOIR AND TRACER

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ABSTRACT

Reactive tracers have long been considered a possible means of measuring thermal drawdown in a geothermal system before significant cooling occurs at the extraction well. In this study, we examine the sensitivity of successive reactive tracer tests to reservoir cooling. Results indicate that while the sensitivity of the method as generally proposed is low, it may be sufficient to provide valuable information about the thermal evolution of the reservoir. We propose several modifications to the basic flow-through method that could provide increased sensitivity, including push-pull tracer tests at the injection well and utilization of a tracer reaction that is quenched before background reservoir temperature is reached. While preliminary numerical modeling tests of these methods demonstrate similar sensitivity to the basic inter-well test, additional sensitivity tests of the sensitivity of these methods are needed.

INTRODUCTION

Geothermal reservoir management often requires injection of produced fluids to prevent them from entering shallow aquifers and surface waters, to help extract heat from the subsurface, and to maintain pressures within the reservoir (e.g., Rose et al., 2001). Knowledge of the time to thermal breakthrough associated with these injected fluids is required for optimal management of the reservoir. While conservative, artificial tracers can provide valuable information about reservoir residence times and flow paths (Behrens et al., 2009), they provide little direct information about thermal breakthrough. It has been proposed that reactive tracers that degrade at rates that depend on temperature can be used to estimate reservoir temperatures between the injection well and the production well (Tester et al., 1987; Chrysikopoulos, 1993). 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. Recently, Behrens et al. (2009) indicated that reactive tracer breakthrough curves are not sensitive to changes in the thermal front and therefore the suggested method lacks the sensitivity necessary to provide a useful measure of thermal drawdown. In this paper, we explore the sensitivity of reactive-tracer breakthrough curves in EGS to reservoir and tracer properties and discuss alternative tracer approaches that could potentially enhance our ability to estimate thermal breakthrough.

THERMALLY REACTIVE TRACERS

Examination of piston-flow movement of a pulse of reactive tracer transported through a single fracture provides a convenient means of illustrating how temperature dependent reactions might be used to detect thermal drawdown. To illustrate the temperature changes that tracers could be used to detect, consider the thermal evolution of a single ideal fracture where flow is effectively one dimensional and the temperature history along the flowpath can be described by:

$$f(x) = erf\left(\frac{\lambda_r x}{\rho_f c_{p\_f} b v \sqrt{\alpha_r t_{op} - x/v}}\right) \qquad \text{Eq. 1}$$

[Carslaw and Jaeger 1959, Section 15.3, Case III] where

λ_r = rock thermal conductivity
x = flowpath distance traveled
b = fracture aperture
ρ_f = carrier fluid density
c_{p_f} = fluid specific heat
v = velocity in the fracture

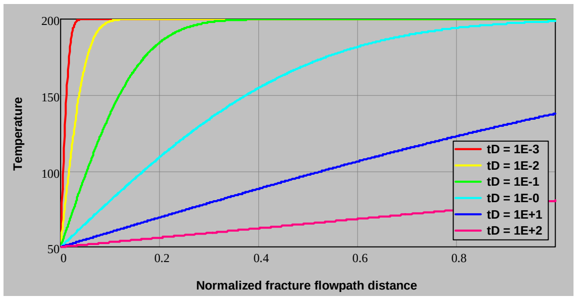


Figure 1. Evolution of temperature in a single fracture in a hypothetical geothermal system. Curves are given at t_D = 1E-3 to 1E2. The time at which thermal breakthrough occurs in the production well is defined as t_{crit} ($t_D = 1$).

α_r = rock thermal diffusivity
t_{op} = operating time

The injection temperature in this hypothetical example is 50°C and the initial reservoir temperature is 200°C. Following initiation of pumping, thermal drawdown in the fracture first occurs at the injection side of the fracture and is not felt at the, production well until a significant portion of the fracture has cooled (Figure 1). During this period, there is little or no discernible temperature change at the production well, so system operation feedback provides little or no information describing the thermal evolution of the reservoir. Methods for measuring cooling in the reservoir during this period, such as reactive tracer tests, could provide data critical to long-term system operation planning.

Taking 1% of the difference between the injection and initial reservoir temperature as an arbitrary indication of measurable cooling at the production well, this implies, using Eq. 1, that the operating time of interest for system interrogation via reactive tracers is that less than t_{crit}, where

$$t_{crit} = \frac{x}{v} + \frac{1}{\alpha_r}\left(\frac{\lambda_r x}{b\rho_f c_{p\_f} v \cdot 1.821}\right)^2 \qquad \text{Eq. 2}$$

Using t_{crit} as the reference time for the system, we define dimensionless time, t_D, $t = t / t_{crit}$.

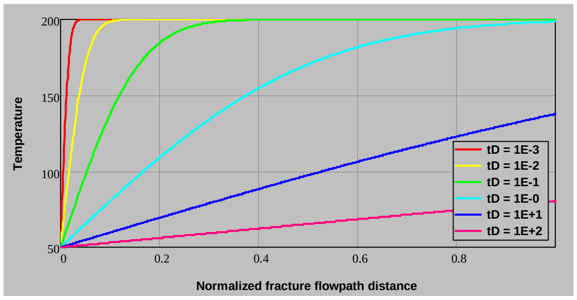


Figure 1The temperature profiles shown in Figure 1 represent dimensionless operating times ranging from 1E-3 to 1E2.

Reactive tracers can provide information about the thermal evolution of a fracture flow system because chemical reaction rates are temperature dependent. Reaction rates generally increase with temperature (Figure 2A), and the amount of conversion observed during transport between two wells should decrease as the reservoir cools. A second tracer test conducted at some Δt_D after an intial test at time t_{D_init} should have higher breakthrough curve concentrations than for the first test. Comparison of tracer tests conducted at different times can provide information about the corresponding change in temperature profiles (Figure 1), and aid in predicting the working life of the reservoir.

The relative reaction rate along a flowpath through a geothermal system is often described by a first-order or pseudo first-order equation of the form

$$\frac{dC(t)}{dt} = -k(T)C(t) \qquad \text{Eq. 3}$$

where $k(T)$ is the temperature-dependent rate coefficient given by the Arrhenius equation,

$$k(T) = A\exp\left(\frac{-E_a}{RT}\right) \qquad \text{Eq. 4}$$

where T is the temperature in kelvins, R is the gas constant, and E_a is the activation energy.

For piston-flow transport of a reactive tracer undergoing first-order decay, the relative tracer concentration, $C_{rel} = C/C_0$ with time, or equivalently, distance, can be obtained by substituting Eq. 3 into Eq. 2 and integrating to yield

$$C_{rel}(t) = \exp(-A\theta) \qquad \text{Eq. 5}$$

where θ, the thermal reaction time, is defined by

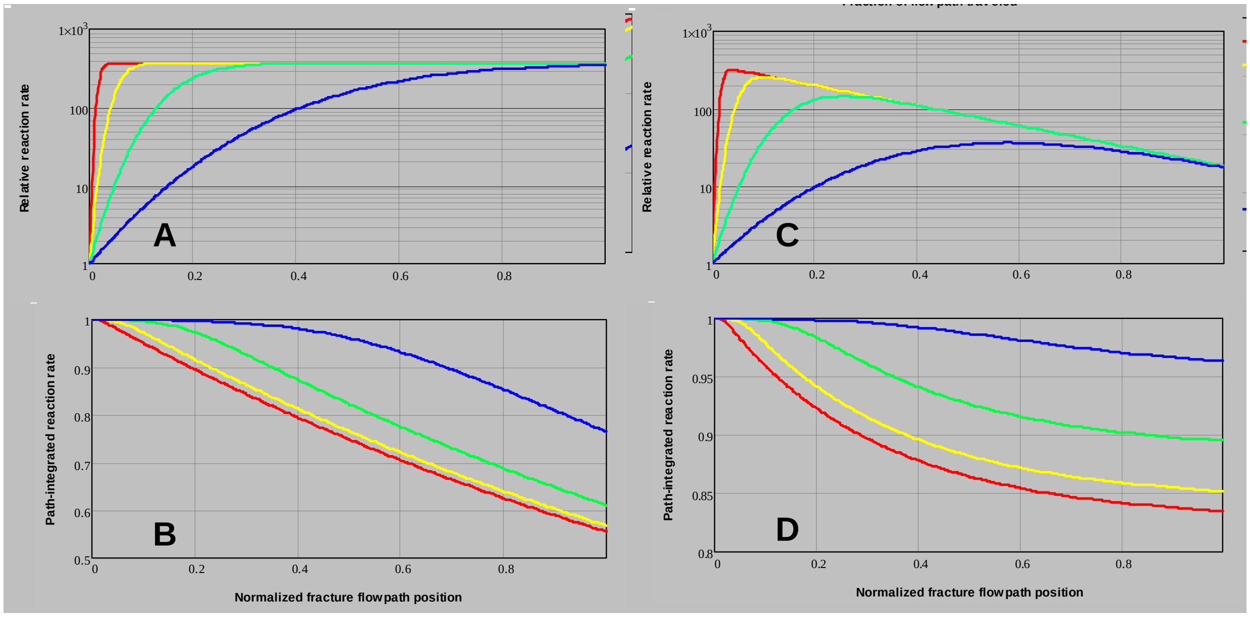
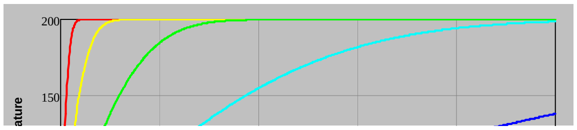


Figure 2. Reaction rate (A&C) and thermal reaction time (B&D) plots for a fracture flowpath for operating



$$\theta(f)=\int_0^f \exp\left(-\frac{E_a}{RT}\right)\frac{L}{v}\,df \qquad \text{Eq. 6}$$

and f is the fraction of the flow path traveled and L is the flowpath length (Tester et al., 1987). Examination of the relative concentration curves along the flowpath (Figure 2B) illustrates a problem with the proposed method. Only for very large differences in the operating time are the final thermal times significantly different, suggesting that the method is a relatively insensitive measure of thermal drawdown. As Behrens et al. (2009) point out, this appears to be the case for both large and small values of the activation energy, E_a. 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.

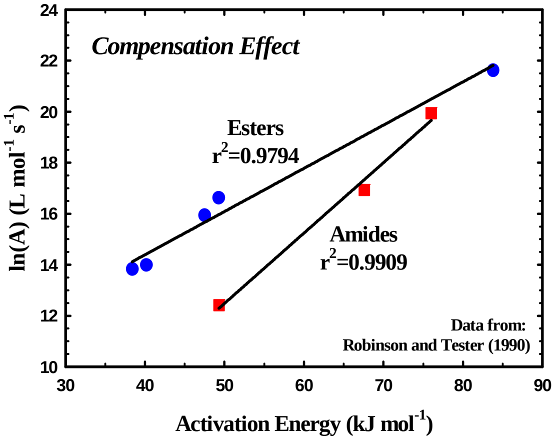


Figure 3. Entropy-enthalpy compensation effect for the second-order hydrolysis reactions of some ester and amide tracers.

While available tracers may provide some choice in E_a, the choices are limited, and each choice is explicitly tied to a corresponding pre-exponential factor, A, that is the primary control on the absolute amount of conversion that will occur between the injection and production wells. In addition, for a class of tracers with different substituents, E_a and A are correlated. This enthalpy-entropy compensation effect is well known (e.g., Lasaga, 1998; Liu and Guo, 2001) and is illustrated here with the ester and amide hydrolysis data of Robinson and Tester (1990) (Figure 3).

The simple analysis described thus far overlooks a factor that could significantly increase the sensitivity of the method. The reaction term in the solute transport equation of interest is kC, not just k, and C is affected by dispersion and sorption processes as well as chemical reaction. Concentration of a pulse of conservative tracer will typically decrease several orders of magnitude during flow through the system and highest concentrations should generally in the regions of lowest termperature near the injection well. Along the flow path *k(T)* will increase and *C* will decrease. To illustrate the potential effect, we use a simple exponential term to describe the decrease with distance that a conservative tracer might undergo during transport, and recalculate the reaction rate (Figure 2C) and thermal time (Figure 2D) curves of Figure 2A & B. Separation between the thermal time curves is significantly increased, and net conversion is slightly reduced relative to the base case of Figure 2B. We conclude that a more accurate solution to the heat flow and solute transport problem is needed to accurately assess the potential sensitivity of the reactive tracer approach to measuring thermal drawdown.

To illustrate how the reactive tracer approach might work when reactive solute transport effects are considered in greater detail, we simulated heat flow and solute transport using finite element methods. Solute transport in the model is coupled to the output of the heat flow solution, but solute transport efffects on heat transport are not considered. The model represents water flow through a hypothetical fracture with a length of 1 km and flow velocity of 5E-3 m/s. The fracture aperture is 2 mm and the half-width between fractures is 10 m. Based on the analyses previously discussed, which assume infinite spacing between fractures, t_{crit} for this system would be approximately 27 years.

Two tracer tests were simulated, one after a dimensionless operating time of 0.019 and a second at t_D = 0.387. Temperature profiles corresponding to these times are very different (Figure 4). Thermal drawdown extends to approximately 0.1 of the total flow distance (L) for the first profile and to approximately 0.6 for the second profile. The conservative and reactive tracers were introduced into the well over an 8-hour period. Because solute transport is coupled to heat transport, the reaction rates are based on the simulated temperature history. Reactive tracer parameters are summarized in Table 1.

Conservative and reactive tracer breakthrough curves are plotted in Figure 5. The later tracer test shows significantly higher concentrations because the net conversion is lower for the slightly cooler system. For a system with a critical time of 27 years, the tracer test times in this case correspond to 0.3 years and 6 years of system operation, indicating the timescale over which the method may prove useful.

Table 1. Reactive tracer parameters.

Simulated tracer injection parameters	
Activation energy, E_a	143300 [J/mole]
Pre-exponential factor, *A*	5E9 [1/s]
Injection period	8 hours

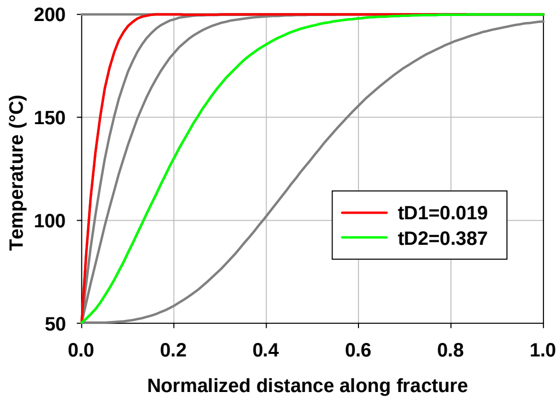


Figure 4. Temperature profiles at t_{D_init} and $t_{D\_init}+\Delta t_D$. For comparison, the profiles for t_D = 0.052, 0.142, 1.05 are also shown (gray curves).

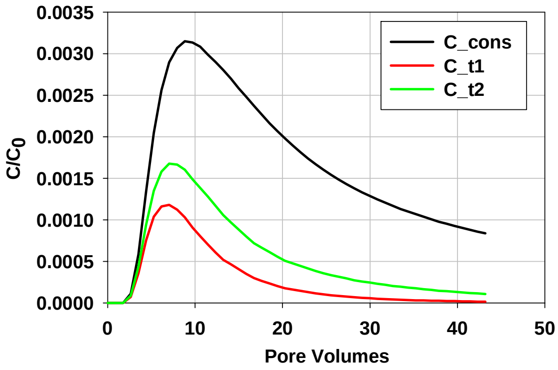


Figure 5. Conservative tracer test and base case reactive tracer test.

The relative sensitivity of the method is expected to increase with the magnitude of the E_a. To examine how an increase in E_a would affect results, we repeated the same tests after doubling E_a and increasing *A* by a factor of 6.7E15 to maintain the same maximum rate coefficient. The resultant breakthrough curves (Figure 6) suggest significantly greater sensitivity to the difference in thermal profiles, with approximately a 10-fold concentration difference. Maximum concentrations in this example are one to two orders of magnitude lower than for the base case, suggesting that the compensating multiplier for A would be better based on a lower or intermediate rate for better comparison.

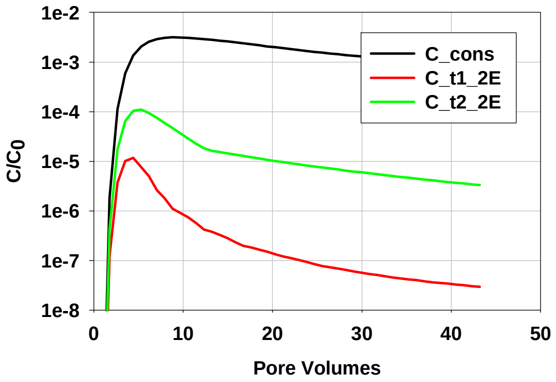


Figure 6. Breakthrough curves, on common log scale, for flow-through tracer test with activation energy doubled relative to the test results in Figure 5.

Because of the limited choice of kinetic parameters, and the relatively low sensitivity that the basic method gives, it appears that some means of enhancing the sensitivity of the method may be necessary in order to make thermal tracers a useful measure of thermal drawdown. In this study, we examine two modifications to the commonly described reactive tracer test approach:

1. Application of push-pull tests at the injection well, to limit the tracer movement to that zone over which significant temperature change has occurred.
2. Application of a quenching agent to limit the reactive tracer reaction to the interval over which reservoir temperature has changed.

Other alternatives (e.g., tracers with reactions other than simple first-order decay) may also enhance the use of reactive tracers.

SINGLE-WELL, PUSH-PULL TESTS

Push-pull tracer tests conducted at the injection well have the advantage of avoiding contact with the fracture surface that remains at background reservoir temperature. While this may be impractical in some systems, breakthrough curves from a sequence of push-pull tests could be more sensitive to the thermal drawdown occurring between those tests. In addition, multiple tracers could be injected, at different times, to interrogate different zones around the well, which is important because the zone of thermal drawdown is not known *a priori*. Alternatively, different lengths of a rest stage between injection and extraction can be applied.

As an example of application of a pair of push-pull tests with a reactive tracer, we injected water at the same velocity used for the through-flow test described in the previous example, but with flow direction reversed after approximately 2 pore volumes. The duration of the injection period was calculated to limit solute transport to the zone of strong thermal drawdown. While that distance would not be known in practice, this approach should provide an indication of the maximum sensitivity in this system.

The reversal in flow during the extraction phase of the push-pull test will cause the hot water to flow over the cooler rock, resulting in a lowering of the water temperature and an increase in the rock temperature. To correctly account for this change in thermal regime, coupled heat and solute transport equations must be solved. Results, including the temperature at the well and the reactive tracer breakthrough curves (Figure 7) illustrate that there is significant separation between the first and second tests and that it should be feasible to determine the rate of migration of the thermal front.

During the extraction phase of a push-pull test, the temperature of the extracted water will likely increase with time. This increase in temperature data could be could be interpreted to provide information about the thermal state of the reservoir and the rate of heat transfer. In future work, we will explore the advantages of combining reactive tracer and thermal information from push-pull tests for characterizing the thermal state of the reservoir.

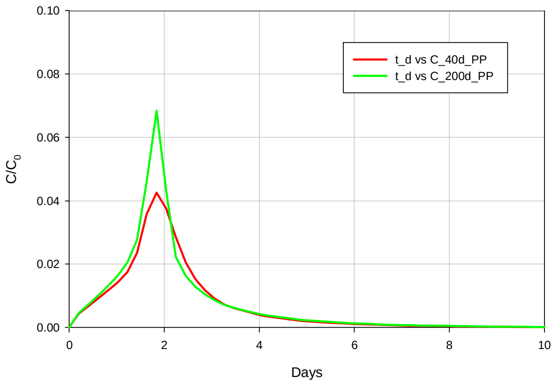


Figure 7. Breakthrough curves for the extraction phase of a push pull test,

REACTION QUENCHING

Another method of increasing the sensitivity of the reactive tracer method is suggested by the dominance of the late-time reaction rates. Quenching the reaction near the initial reservoir temperature should effectively reduce that influence, so that the resultant breakthrough curves are a more sensitive measure of the zone of thermal drawdown. Such quenching reactions may be feasible using the encapsulation techniques described by Redden et al. (2010). To illustrate the potential of such a tracer, we altered the base case simulation by including a term that halts the reaction when the temperature reaches 10°C below the background temperature. For easier comparison with other results, we increased the value of A in these simulations to compensate for the dramatically reduced reaction time. In these scenarios, breakthrough curve concentrations (Figure 8) for the later tracer test are lower than for the initial test, reflecting the longer reaction time induced by later quenching. The magnitude of the difference in concentrations appears similar to that observed for the base case (Figure 5).

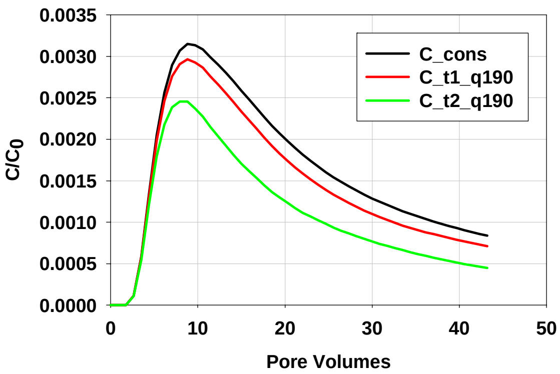


Figure 8. Breakthrough curves for base case conditions, with reaction quenched at T_{res}-10°C,

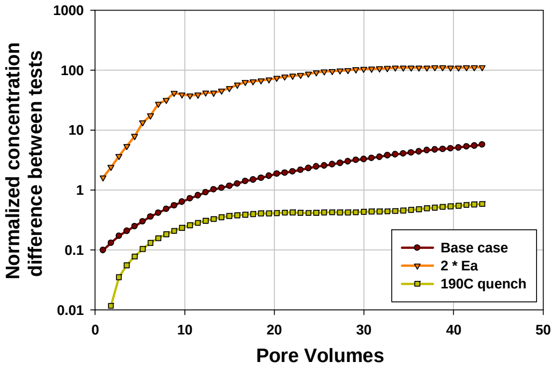


Figure 9. Absolute concentration difference between tests, normalized to breakthrough curve with lowest concentration.

Comparison of the absolute concentration differences between each pair of flow-through tests, normalized to the lower concentration for each pair, suggests that the standard method provides greatest sensitivity to thermal drawdown, with sensitivity increasing slightly with E_a. In these examples the quenched reaction pair of tests showed the lowest relative concentration difference. The values used in this and other examples given here may not, however, be optimal for this system. Future work will examine how to optimize reactive tracer methods for detecting and measuring thermal drawdown.

CONCLUSIONS

The application of reactive tracers as a means of measuring thermal drawdown has long been proposed, but the sensitivity of the method has been questioned. Our preliminary analyses suggest that the basic flow-through tracer method may be more sensitive than a simple piston-flow analysis would indicate, because of dispersive processes. The sensitivity of the flow-through method may be significantly enhanced if the reaction kinetics can be controlled. Simulations of tracers incorporating quenching behavior at near-background reservoir temperature, however, demonstrate reduced sensitivity relative to the commonly proposed method. When practical, push-pull tests at the injection well may provide better estimates of the rate of thermal drawdown. Further examination of reactive tracer methods and their application to different thermal and solute transport conditions is warranted.

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