

## Inert and Reacting Tracers for Reservoir Sizing in Fractured, Hot Dry Rock Systems

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### Abstract

Flow characterization and volumetric sizing techniques using tracers in fractured hot dry rock reservoirs are discussed. Statistical methods for analyzing the residence time distribution (RTD) are presented. Tracer modal volumes and RTD shape are correlated with reservoir performance parameters such as active heat transfer area and dispersion levels. Chemically reactive tracers are proposed for mapping advance rates of cooled regions in HDR reservoirs, providing early warning of thermal drawdown. Important reaction rate parameters are identified for screening potential tracers. Current laboratory research and field work is reviewed.

### Nomenclature

A = effective heat transfer area  
A<sub>r</sub> = pre-exponential factor  
C, C(t) = tracer concentration  
C<sub>f</sub> = fluid heat capacity  
D<sup>p</sup> = dispersion coefficient  
E<sub>a</sub> = activation energy  
E(V) or E(t) = exit RTD for a pulse  
k = reaction rate constant  
L = characteristic reservoir length  
m<sub>p</sub> = mass of tracer pulse  
Pe = dispersive Peclet number = uL/D  
Q = volumetric flowrate  
R = Universal gas constant  
t = time  
T = fluid temperature  
u = fluid velocity  
V, <V> = modal, mean reservoir volume  
x,y,z = reservoir position coordinates  
w<sub>1/2</sub> = width of the RTD at 1/2 height  
ρ = fluid density  
a = thermal diffusivity of rock  
λ = thermal conductivity of rock  
σ<sup>2</sup> = statistical variance of the RTD

### Introduction and Motivation

This paper reviews the research and development work on tracers that has occurred in the last 11 years at Los Alamos and MIT. Details are contained in the following publications by the author and his co-workers (Tester, Bivins and

Potter (1982), Robinson and Tester (1984), Robinson (1985), Robinson, Tester, and Brown (1984), Robinson and Tester (1986 a,b,c), and Grigsby and Tester (1986)).

The primary motivation for our work with tracers has been to provide an independent estimate of reservoir lifetime in multibore, hot dry rock (HDR) geothermal systems. Because these reservoirs have been activated by the hydraulic fracturing of inherently low permeability crystalline rock, their geometry and flow characteristics deviate markedly from the more traditional assumptions applied to dispersion in homogeneous porous media. In every case we have examined in the field, the observed flow patterns are complex resulting primarily from superimposed effects of multi-dimensional flow in a discrete set of interconnected fractures. The major challenge facing us at this point is to develop suitable models of these reservoirs in order to permit estimation of performance before thermal drawdown is observed under a prescribed set of injection conditions of flow rate, temperature, and pressure. We recognized at the outset that some non-uniqueness would result in these models, reflecting a common difficulty encountered in deconvolution problems of this type where the geometry and flow patterns within the reservoir are incompletely specified.

Fortunately, tracers have become a reliable diagnostic tool as they provide a direct measure of reservoir flow characteristics that are important in determining how efficiently energy is being extracted from the fractured rock. Inert tracers have been used in field tests of HDR reservoirs at the Fenton Hill site in New Mexico (Murphy et al (1981)) and at the Rosemanowes quarry in Cornwall, U.K. (Batchelor (1986)). Model-independent information, such as fracture volumes and dispersive characteristics, obtained from inert tracer measurements has provided a means of quantifying the behavior of these fractured geothermal systems. Because, however, the information supplied by conventional inert tracers is insufficient to construct detailed reservoir models with extensive predictive capabilities, we are also developing new techniques that use temperature-sensitive, chemically reacting compounds as tracers. These reactive tracers will measure directly the

cooldown rate of the primary flow paths in the geothermal reservoir. Reactive tracers should also be useful in diagnosing some conventional geothermal reservoirs where reinjection may accelerate thermal drawdown.

To date theoretical modeling and bench-scale screening tests have been conducted to identify potential reactive tracers for field use and to explore the strengths and limitations of the reactive tracer concept for sizing HDR systems.

#### Statistical Definitions

**1. Residence Time Distribution,  $E(t)$ :**  $E(t)dt$  is the fraction of the injected fluid which leaves the system between  $t$  and  $t + dt$ . An effective tracer follows the same flow paths as the reservoir fluid, and the concentration-time response measured at the outlet to a pulse injected at the inlet is:

$$C(t) = \frac{m_p}{Q} E(t) \quad (1)$$

where  $m_p$  is the mass of tracer injected, and  $Q$  is the volumetric flow rate of fluid. The residence time distribution (RTD) curve can be also expressed as  $E(V)$ , where  $E(V)dV$  is the fraction of the produced fluid which entered at  $t = 0$  that emerges between  $V$  and  $V + dV$  where  $V$  is the cumulative produced fluid volume corrected for the finite volume of the wellbores. Thus,  $E(V) = E(t)/Q$ . With this convention fracture volumes measured in tracer experiments at different flow rates can be compared.

**2. Modal Volume,  $\bar{V}$ :** the volume corresponding to the peak of the RTD curve.  $\bar{V}$  most likely represents the volume of low impedance fracture connections which follow a direct route from inlet to outlet.

#### 3. Integral Mean Volume $\langle V \rangle$ :

$$\langle V \rangle = \int_0^{\infty} V E(V) dV \quad (2)$$

In fractured media,  $\langle V \rangle$  is the void volume of all fractures which accept flow, regardless of their impedance.

**4. Variance,  $\sigma^2$ :** the variance is a measure of the overall spread of the distribution. It can be defined on a volume basis as:

$$\sigma^2 = \int_0^{\infty} (V - \langle V \rangle)^2 E(V) dV \quad (3)$$

The  $V$  and  $(V - \langle V \rangle)^2$  terms in the integrals of Eqns. (2) and (3) cause the tail of the distribution at large volumes to have a significant effect on the magnitude of both  $\langle V \rangle$  and  $\sigma^2$ . Because tracer concentrations are very low in the tail region, inherent inaccuracies arise, frequently causing substantial uncertainty in estimating  $\langle V \rangle$  and  $\sigma^2$ .

**5. Width at Half Height,  $w_{1/2}$ :** the width between the two points on either side of the peak for which the tracer response is one-half its peak value. This parameter, defined analogously in chromatographic separation theory, is a measure of the outlet dispersion of the main fracture flow paths. Unlike the variance of the distribution  $\sigma^2$ , the magnitude of  $w_{1/2}$  does not depend on the tail of the RTD.

#### Dispersion Mechanisms

The spreading of the outlet tracer concentration in a fractured geothermal reservoir potentially results from three major mechanisms: (1) large-scale flow heterogeneities caused by the superposition of flows from fractures of different size and flow impedance, (2) crossflow between different fractures, and (3) dispersion within a single fracture.

The extent of dispersion in single-fracture flow can be affected by roughness along the fracture surface, tracer holdup caused by fluid permeation and molecular diffusion of tracer into the rock matrix surrounding the fracture, molecular diffusion within the fracture across a velocity gradient perpendicular to the mean direction of flow (Taylor dispersion), and two-dimensional invicid potential and/or buoyantly-driven convective flow between the inlet and outlet zones of the fracture. Horne and Rodriguez (1983) and Robinson and Tester (1984) have evaluated the magnitude of various single-fracture dispersion mechanisms for conditions likely in fractured geothermal reservoirs. Table 1 summarizes the results of these studies, using the axial dispersion Peclet number ( $Pe = uL/D$ ) as the parameter characterizing the level of dispersion. A large Peclet number indicates that the mechanism produces very little of the observed outlet dispersion. The table shows that the amount of dispersion produced within a single fracture is smaller than the overall level of tracer dispersion measured in the field.

This strongly suggests that superimposed flow from and crossflow between multiple fractures of different size and flow capacity are major contributors to the level of dispersion observed in HDR reservoirs.

#### Dispersion Models for Reservoirs

Given the complex nature of flow in a set of multiple fractures of largely unspecified geometry, many models have been used to describe tracer dispersion. These can be divided into two major categories: Deterministic and stochastic models. On the deterministic side, a steady state flow field is usually specified with appropriate geometric parameters, such as inlet to outlet well spacing, aperture size, fracture lateral or radial extent, and fracture volumes.

Table 1. Magnitudes of Different Single-Fracture Dispersion Mechanisms in Fractured HDR Reservoirs.

Sources: Horne and Rodriguez (1983), Robinson and Tester (1984).

<u>Mechanism</u>	<u>Dispersional Peclet Number Pe</u>	<u>Comments</u>
Fracture Roughness	$>10^3$	scale of dispersion (fracture aperture) is very small compared to overall length scale (well-bore separation distance)
Matrix Diffusion	$>10^3$	large apertures and rapid flow velocities minimize matrix diffusion effect
Taylor Dispersion	$(0.15 - 30) \times 10^3$	molecular diffusion coefficient varies strongly with temperature, causing wide range in Pe
Point Source-Point Sink Potential and Buoyantly-Driven Flow	55-70	calculated assuming dispersion is caused solely by flow streamlines of different length and velocity
Actual Measured Dispersion in Fractured Geothermal Reservoirs	0.5-5	observed dispersion is much greater than can be explained by flow in a single fracture

The most simplistic of these deterministic approaches couples the two extremes of infinite dispersion in a so-called continuous stirred tank reactor (CSTR) to a zero-dispersion in a plug flow reactor (PFR) to provide a best fit to the data. Although reasonable fits to data may result by treating the number of PFR's and CSTR's and their relative arrangement as adjustable parameters, the final model may bear little resemblance to the real reservoir, thus making prediction of performance impractical.

The remaining deterministic models would either deal with the flow pattern and resulting dispersion as a result of (1) a distribution of apertures and therefore flow velocities in a network of fractures that obeys Darcy's law or (2) multidimensional flow with or without molecular diffusion effects in a single fracture or in a discrete fracture set that follows the convective-dispersion equation.

Tester et al (1982) and Batchelor et al (1985) have used aperture distribution models to account for observed RTD's in HDR systems. Under Darcy flow conditions the flow rate varies with the cube of the aperture and can cause a wide RTD even with a modest distribution of apertures in a parallel set of fractures of equal length. Batchelor et al (1985) have used an orthogonal block model of the fracture system (FRIP) to provide a consistent RTD. A distribution of fluid residence times results from the 3-D nature of flow through the

jointed rock network between the injection and production zones of the reservoir. The variations in the stress field surrounding the pressurized injection region are used to determine individual joint apertures which specifies the flow impedances and fluid velocities within each joint. In many cases, it is difficult for these aperture models to simultaneously match both the RTD shape ( $w_{1/2}$  and  $\sigma^2$ ) and the fracture volumes ( $\langle V \rangle$ ) observed.

Use of the convective-dispersion equation has been widespread in chemical and petroleum engineering as a basis of flow modeling (Robinson (1985), Horne and Rodriguez (1983), and Tester et al (1982)). The general form of the equation is

$$\nabla \cdot (\tilde{D} \nabla C) - \tilde{u} \cdot \nabla C = \frac{\partial C}{\partial t} \quad (4)$$

where  $\tilde{D}$  is the dispersion coefficient tensor, and  $\tilde{u}$  the flow velocity vector. Although Eq (4) can be regarded as a rigorous statement of mass conservation it cannot be applied in practice unless the  $\tilde{D}$  tensor terms are known. In most practical applications, a 1-D or 2-D steady flow field is assumed and  $\tilde{D}$  is reduced to one or two terms that may be constant or dependent on the local velocity in a straightforward manner. Thus with this heuristic simplification,  $\tilde{D}$  becomes an effective dispersion coefficient  $\tilde{D}$  that is empirically fit to the data. It includes the combined effects of molecular diffusion and local mixing and turbulence on a macroscopic as well as microscopic or pore size level.

Given knowledge of individual fracture zone flow fractions and volumes, the convective-dispersion approach can be formulated to deal with superimposed flows (Tester et al (1982)). However, any application of this model for predictive purposes requires that the assumed reservoir geometry and flow patterns are being represented realistically. For example, treating the effective dispersion coefficient as an adjustable parameter to match the RTD does not guarantee that it will result in reservoir sizes (apertures and lengths) that will predict the proper thermal drawdown history of the system. A certain amount of non-uniqueness is inevitable in modeling such complex reservoirs.

Purely stochastic models would seem justified because of the geometric uncertainties in these fractured reservoirs. Deterministic simulations of hydrodynamics, although appealing because of their "mathematical exactness," can in practice become no more than exercises in curve-fitting when only limited information is known about the reservoir. In a typical stochastic analysis, flow patterns are simulated for different randomly-constructed fracture networks. Monte Carlo methods may be used to generate such structures where such parameters as fracture length, orientation, and aperture will be specified within known or assumed distribution functions (Long, et al (1982)).

We are currently working on hybrid models that incorporate a deterministic approach for the main fracture zones with a stochastic approach for the secondary flow paths. We believe this will provide a realistic model for heat extraction performance prediction while requiring only a small number of adjustable parameters.

#### Field Results with Inert Tracers

The observed levels of dispersion in the Fenton Hill and Rosemanowes systems studied to date are dominated by multi-fracture flow. This conclusion was corroborated in some radioactive  $^{82}\text{Br}$  tracer experiments at Fenton Hill using gamma logging in the production wellbore. As shown in Figure 1, distinct concentration-time curves were identified for three exit regions in the production wellbore (Tester, et al (1982)). Thus at least three different fractures were contributing to the observed total dispersion. Not only were the three fracture zones identified, but the dispersion from each individual fracture zone was too great to result from any combination of single-fracture dispersion mechanisms (Robinson and Tester (1984)). Crossflow among the different fractures was occurring, perhaps in a highly-fractured region near the inlet to the reservoir as depicted in Figure 2.

Recent tracer test results for the Phase II reservoirs at Fenton Hill and Rosemanowes are shown in Figure 3 where the characteristic shape of the RTD is similar for both reservoirs (see also Robinson (1986) and Batchelor (1986) for additional data and analysis). Superimposed, multi-fracture flow is probably the dominant mechanism contributing to the overall RTD but it cannot be proven from the tracer tests alone. A direct comparison to the observed thermal performance of these prototype HDR reservoirs is necessary as discussed in the next section.

#### Tracer-Determined Flow and Thermal Performance

In analyzing past tracer experiments in the Fenton Hill and Rosemanowes systems, we have found an empirical approach to be very useful in comparing the nature of flow and heat transfer in these reservoirs.

Large scale heterogeneities such as the superposition of flows from multiple fractures undoubtedly exert great influence on heat transfer behavior, since the positioning of low impedance conduits effectively defines the accessible volume of rock. In many systems, the onset and subsequent rate of thermal drawdown is probably controlled by the surface area of the smallest low impedance connection. Because the modal volume  $V$  corresponds to the low impedance fracture connections, it should correlate with the reservoir's heat transfer capacity which can in turn be estimated from a simplified model: Assuming plug flow up a single vertical, rectangular fracture of surface area  $A$  (on one face of the fracture), the fluid temperature within the fracture during long-term operation is given by (Murphy et al (1981)):

$$\frac{T - T_i}{T_r - T_i} = \text{erf} \left[ \frac{\lambda A (z/L)}{\rho C_p Q \sqrt{at}} \right] \quad (5)$$

in which  $T$ ,  $T_i$ , and  $T_r$  are the temperatures of the fluid at point  $z$ , at the inlet, and throughout the rock initially, respectively. The parameters  $\lambda$  and  $a$  are the thermal conductivity and thermal diffusivity of the rock,  $\rho$  and  $C_p$  the average density and heat capacity of the fluid, and  $t$  is the time of operation of the reservoir. The outlet fluid temperature is obtained by setting  $z/L = 1$ . Although simplistic, this model conveniently describes the thermal behavior of a fractured reservoir with a single adjustable parameter,  $A$ . Assuming Figure 4 is correct, a single inert tracer experiment can provide a modal volume and thus a crude estimate of the heat extraction capability of a fractured reservoir.

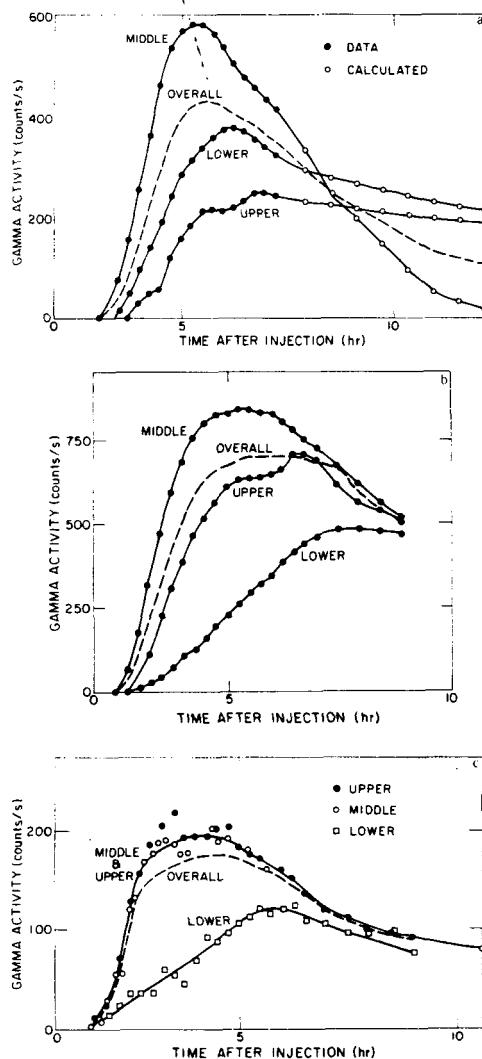


Figure 1 Individual fracture zone concentration-time curves obtained by  $^{82}\text{Br}$  pulse injection followed by gamma logging in the production well bore. (a) Exp. 217-A2, 5/9/80. (b) Exp. 217-A4, 12/2/80. (c) Exp. 217-A5, 12/12/80.

The Rosemanowes Phase II points in Figure 4 are extrapolated, as extensive energy extraction has not yet been carried out in this reservoir, so measurable drawdown has not been observed. Only the modal volume has been plotted. For this new larger reservoir and for commercially-sized systems in general, use of the modal volume to estimate  $A$  is as yet unjustified because of the large extrapolation required from smaller sized systems. A more legitimate approach for large systems with multiple entrance and exit regions perhaps would be to size individual fracture zones using preferential injection of a radioactive tracer and production well gamma logging (Tester, et al (1982)). These zones or subsystems are likely to be small enough to warrant the use of Figure 4 without extrapolation.

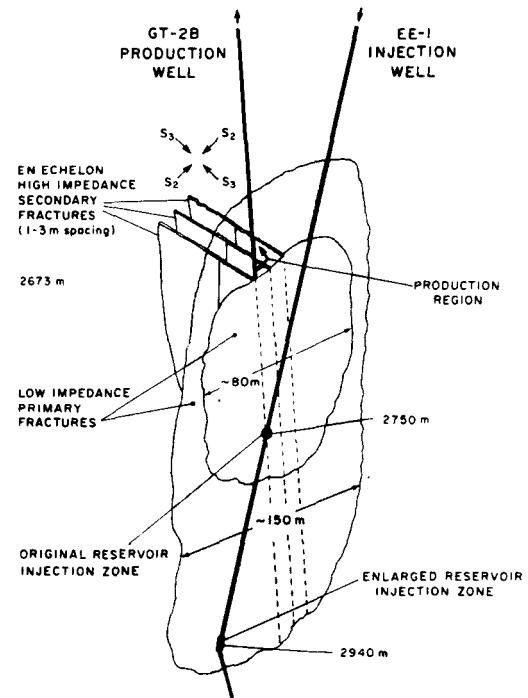


Figure 2 Conceptual schematic of the EE-1/GT-2 fracture system (adapted from Tester et al (1982)). Schematic of the fracture-well bore geometry.

Another factor regarding Figure 3 is the fact that the slope of the line through the data is about 0.7 and statistically different than unity. Thus the effective aperture of fracture comprising the modal volume must change disproportionately with changes in effective heat transfer surface area. This simple analysis ignores the fluid that does not flow through the low impedance fractures. Based on modeling of quartz dissolution kinetics in the main fracture flow path, it was recognized that at least 30% of the production fluid during Run Segment 5 must have flowed through long residence time flow paths which had experienced no thermal drawdown (Grigsby and Tester (1986)). This observation is supported by tracer experiments (5/9/80 to 12/12/80) where roughly 70% of the tracer is recovered in the main peak of the RTD and the remainder is recovered in the tail of the distribution. This result appears to be quite common in the HDR reservoirs tested to date: flow through several low impedance joints accounts for the early tracer response, while a substantial secondary flow travels through a large volume of rock, probably at the periphery of the reservoir.

A comparison of the volumes of the low impedance primary flow paths and the high impedance secondary paths can be made. The modal volume represents the low impedance volume and the integral mean volume [Eqn. (2)] is the total fracture volume (main fractures plus secondary flow paths). As seen in Table 2, the computed integral mean volumes for the  $^{82}\text{Br}$  tracer experiments of Run Segment 5 are much larger than the corresponding modal volumes. The enormous potential capacity of this reservoir appears to have gone largely unused due to the tendency of the fluid to short-circuit through low impedance joints. Total reservoir size estimates using microseismic mapping and geochemical information substantiate this conclusion.

In addition to the absolute sizes of the low-impedance fractures and the total reservoir, reservoir growth during energy extraction may be monitored using  $V$  and  $\langle V \rangle$  from a series of tracer tests. Fracture volume growth may be caused either by thermal contraction and stress cracking of rock during cooldown, or through opening new fractures by water permeation into pre-existing joints in the rock matrix (hydraulic fracturing). For example, the increases in modal and integral mean volumes during the Run Segment 5 are plotted against total energy extracted in Figure 5. The maximum amount of new fracture volume possible via thermal contraction of rock is denoted by the free thermal expansion line. The large increase in integral mean volume suggests that additional fracturing must have been occurring along with thermal contraction. However, much of this new volume is apparently not available for heat extraction as shown by the modest increase in modal volume.

#### Reservoir Analysis Using Reacting Tracers

Thermal drawdown analysis of small, prototype reservoirs was possible because a measurable temperature decline in the produced fluid occurred after only a few months of operation. However, for larger systems, reservoir simulators will have to be used in a predictive way, since years could pass before produced fluid temperature measurements yield useful modeling information. More importantly, commercialization of HDR requires that a method exists for predicting a priori the lifetime of a reservoir. The normal battery of diagnostic experiments (pressure transient, well logging, inert tracer, microseismic, and fluid geochemical) will not provide all the information necessary to construct these detailed reservoir models with predictive capability. Chemically reactive tracers, which are sensitive to internal changes to the reservoir's temperature field, may help solve this problem in future HDR systems.

The kinetics of most chemical reactions are extremely temperature-sensitive. For first-order reactions carried out in batch reactors, the following equation is often used to express the instantaneous rate of conversion of reactant at concentration  $C$  to product:

$$\frac{dC}{dt} = -kC \quad (6)$$

The rate constant  $k$  is the parameter which contains the temperature sensitivity. It normally can be described by an equation of Arrhenius form:

$$k = A_r \exp(-E_a/RT) \quad (7)$$

For typical reactions in solution,  $k$  will vary by several orders of magnitude for the range of temperatures typically encountered in an operating HDR reservoir.

Suppose a tracer is injected into an initially hot reservoir, and the reaction proceeds about half way to completion during its stay in the system. Then, after some cooldown has been achieved, a second experiment should show less conversion because of the shorter time the fluid spends in hot zone of rock. A series of reactive tracer experiments will, in theory, map the rate of progress of the cooled region as it approaches the exit well, giving an early warning of thermal drawdown.

In practice, the transient response of a reacting tracer depends on both the temperature field and the dispersive nature of the fluid flow within the reservoir. To illustrate this coupled dependence conceptually, we assumed that the tracer behavior could be modeled using the one-dimensional form of the convective-dispersion equation with a first-order chemical reaction included:

$$D \left( \frac{\partial^2 C}{\partial z^2} \right) - u \left( \frac{\partial C}{\partial z} \right) - kC = \frac{\partial C}{\partial t} \quad (8)$$

Equation (8) is directly coupled to the rate of heat extraction because  $k$  is a strong function of temperature (Eqn. (7)). Thus, in order to solve Eqn. (8) for  $C(t,z)$  we must know the axial ( $z$ -direction) temperature field. The single-fracture temperature solution [Eqn. (5)] was used in preliminary calculations. This simplified temperature field assumption is perhaps questionable given the evidence for superimposed multifracture flow. Each fracture is likely to have unique temperature characteristics, e.g. the small ones (corresponding to short residence times) cooling down more rapidly than the large ones. Nonetheless, the model as formulated should be sufficient for parameter sensitivity studies.

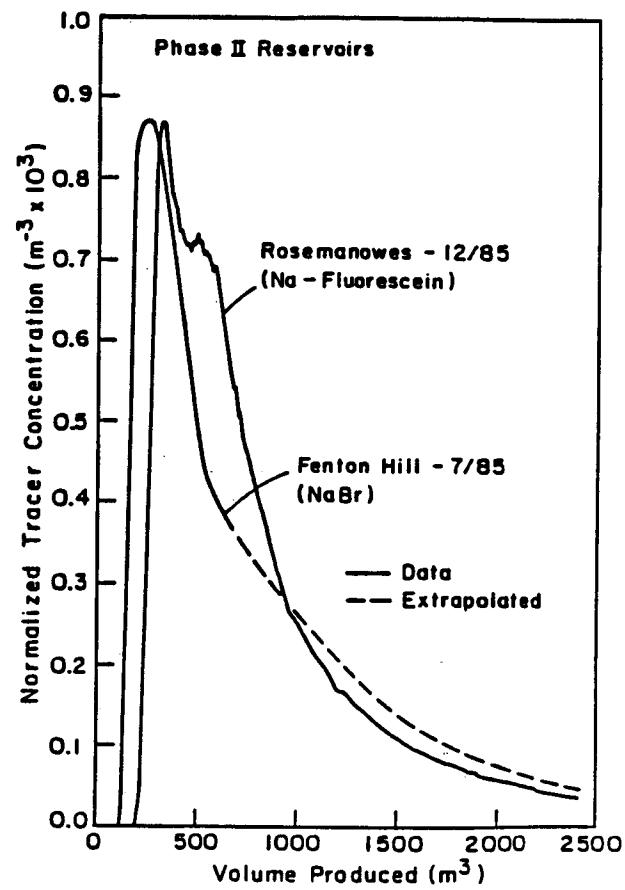


Figure 3 Comparison of RTD from pulse tracer injections in the Fenton Hill and Rosemanowes Phase II HDR reservoirs. Curves are normalized with respect to peak tracer concentrations at the modal volume.

\*Rosemanowes data uncorrected for wellbore volumes

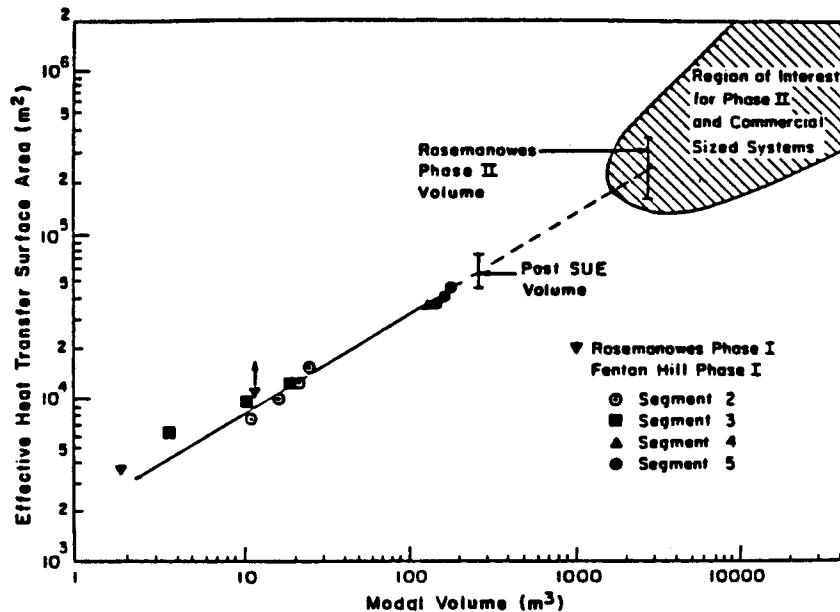


Figure 4 Effective heat transfer surface area vs. modal volume.

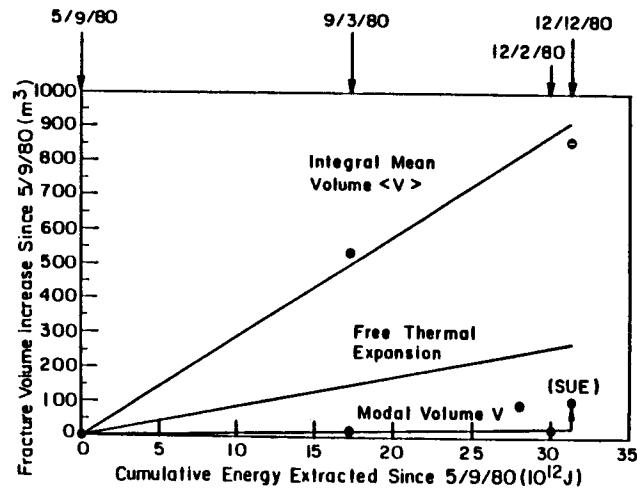


Figure 5 Fracture volume growth vs. cumulative energy extracted.

Table 2. Summary of Tracer Field Experiments

Fenton Hill Experiments

<u>Date(tracer)</u>	<u><math>\hat{V}</math> (m<sup>3</sup>)</u>	<u><math>\langle V \rangle</math> (m<sup>3</sup>)</u>	<u><math>w_{1/2}</math> (m<sup>3</sup>)</u>	<u><math>w_{1/2}/\hat{V}</math></u>
<b>Phase I (GT2B-EE-1)</b>				
2/9/78(NaF)	11.4	-	18.1	1.59
3/1/78(NaF)	17.0	-	40.3	2.37
3/23/78(NaF)	22.7	-	62.5	2.75
4/7/78(NaF)	26.5	-	70.8	2.67
5/9/80(Br)	161	1311	227	1.41
9/3/80(Br)	178	1845	323	1.81
12/2/80(Br)	187	-	303	1.62
12/12/80(Br)	266	2173	479	1.80
<b>Phase II (EE-2 - EE-3)</b>				
7/85(NaF/NaBr)	300	-	279	0.93

Rosemanowes Tracer Experiments

<b>Phase I</b>				
RH6A(1982)(NaF)	1.42	-	1.68	1.18
RH12(1983)(NaF)	12.3	-	7.0	0.57
<b>Phase II (RH11-RH12)</b>				
#3(1984)(NaF)	2390	-	4870	2.04
<b>Phase IIB (RH12-RH15)</b>				
#4(9/85)(NaF)	136	964	545	4.01
#5(10/85)(NaF)	122	1058	509	4.17
#6(11/85)(NaF)	123	982	509	4.14
#7(12/85)(NaF)	119	913	473	3.98
(EA)	119	-	298	2.43
(EtOH)	119	-	474	3.98
(ISO-PA)	119	-	710	5.97

NaF - sodium fluorescein

Br - <sup>82</sup>Br<sup>-</sup> isotope

EtOH - ethanol

NaBr - sodium bromide

EA - ethyl acetate

ISO-PA - isopentyl acetate

The internal temperature field for a particular model reservoir at various times is shown in Figure 6. To achieve 10°C of produced fluid thermal drawdown (a practical minimum for estimating reservoir size), over five years of continuous operation are required.

The reactive tracer response to a step change in inlet concentration for the same model system is shown in Figure 7. Just 1 to 2 years of operation are required to obtain a sensitive estimate of heat exchange capacity.

Parameter studies using the 1-D convective-dispersion model also support the following trends:

1) For thermal behavior such as that in Figure 6, reactions with higher activation energies are more sensitive to small levels of thermal drawdown.

2) Tracer dispersion affects the shape of the response curves, but not the sensitivity of the measurement. However, if dynamic shifts in reservoir size occur during production, inert tracers should also be used in conjunction with reactive tracers.

3) The reactive tracer response is sensitive to the extent of thermal drawdown, but not to the specific shape of the temperature field. Reactions which are moderately fast at the highest reservoir temperature are extremely slow at temperatures 100°C below this. Thus, the exact shape of the temperature field in the cooled region of the reservoir is unimportant. The conversion of a reacting tracer is essentially a measure of the amount of hot rock remaining between the two wellbores.

### Reactive Tracer Screening Studies

A significant portion of our research efforts have been and are currently directed toward identifying appropriate reactive tracers for use in HDR systems having a range of mean residence times and rock temperatures. The desired kinetic parameters ( $A_r$  and  $E_a$ ) should be such that the reaction time ( $1/k$  for a 1st order reaction) at the average reservoir temperature is approximately of the same order as the mean residence time. In addition, each reactive tracer must have the same characteristics required of an inert tracer in that it must be non-adsorbing and easily detectable in low concentrations.

In our early work, the kinetics of alkaline hydrolysis of a number of organic esters and amides were determined in aqueous solutions for temperatures varying from 100 to 300 °C (Robinson (1984) and Robinson, Tester, and Brown (1984)). For this system a pseudo-first order reaction was created by conducting the hydrolysis in excess  $\text{OH}^-$  or in a buffered solution. The results of these early studies are summarized in Fig. 8. Ethyl acetate, ethyl propionate and isopentyl acetate would be suitable for HDR systems at 70 to 125°C having reaction times ranging from 10 to 200 hr.

The first test of reactive tracers in the field was conducted in December of 1985 in the redrilled Phase II reservoir at Rosemanowes in the U.K. operated under continuous circulation conditions (Batchelor (1986)). Na-fluorescein as an inert tracer was injected simultaneously with concentrated solutions of ethyl acetate and isopentyl acetate. Figure 9 shows the preliminary response curves for all three tracers. The shape of all three curves is very similar indicating that ethyl acetate (EA) and isopentyl acetate are not selectively adsorbed on the formation. The RTD for ethanol (EtOH) which is a reaction product of the hydrolysis of ethyl acetate was determined as well. By proper weighting of the EA and EtOH RTD's with their molecular weights (MW), we can sum the curves to estimate the RTD of EA had it not reacted:

$$\frac{[\text{EA}]}{\text{MW}_{\text{EA}}} + \frac{[\text{EtOH}]}{\text{MW}_{\text{EtOH}}} = \frac{[\text{EA}_{\text{non-reactive}}]}{\text{MW}_{\text{EA}}} \quad (9)$$

where the [ ] brackets refer to concentrations.

Using Eqn. (9) to calculate the peak non-reactive EA concentration, a value of 20 ppm results. This is consistent with the estimated peak concentration of 20.2 ppm for non-reactive EA for a 27 kg injection scaled to the observed 1.8 ppm peak for Na-Fluorescein which resulted from a 2 kg injection of dye. At constant pH, EA hydrolysis

will follow a pseudo-first order mechanism with  $k = (A_r \exp(-E_a/RT))[\text{OH}^-]$ . If we assume that the average pH seen by the tracer was 8.5 with  $A_r = 3.05 \times 10^6$  liter/mols and  $E_a = 40.9$  kJ/mol, an average reservoir temperature of 94°C is estimated from the ratio of the measured peak for EA of 10 ppm at 13.4 hr after injection to the calculated non-reactive EA peak of 20.2 ppm. This estimated temperature is within 5°C of actual measured rock temperature and is a strong indicator that the EA tracer is working as expected. Ethyl pivalate and acetamide would work well for reservoirs between 150 to 200°C over the same residence time range. We are presently involved with identifying reactive tracers for use in hotter reservoirs at 200 to 300°C. A number of thermal decompositions involving fluorinated, low molecular weight hydrocarbons, peroxides, and organic dyes and the hydrolysis of bromobenzene and its substituted derivatives are currently under laboratory study with field tests planned for the near future.

### Conclusions

1. Levels of tracer dispersion from field experiments in HDR reservoirs indicate a dominant mechanism caused by the superposition of flow from multiple fractures of different size and impedance. At Fenton Hill, about 70% of flow is through a number of low impedance fractures with the remaining 30% contained in high impedance secondary flow paths of large volume and long residence time.
2. Reservoir heat transfer capacity measured by effective heat transfer surface area  $A$  correlates with tracer modal volume  $V$ .
3. Preliminary modeling and field test results suggest that the injection of chemically reactive tracers should be a sensitive reservoir test for measuring thermal drawdown far in advance of actual produced fluid temperature decline.
4. Laboratory kinetic studies have identified several chemically reactive tracers for use in geothermal reservoirs having temperatures ranging from 80 to 200°C.

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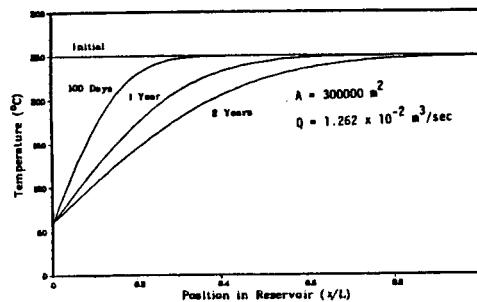


Figure 6 Internal temperature profiles during long-term energy extraction in a single fracture.

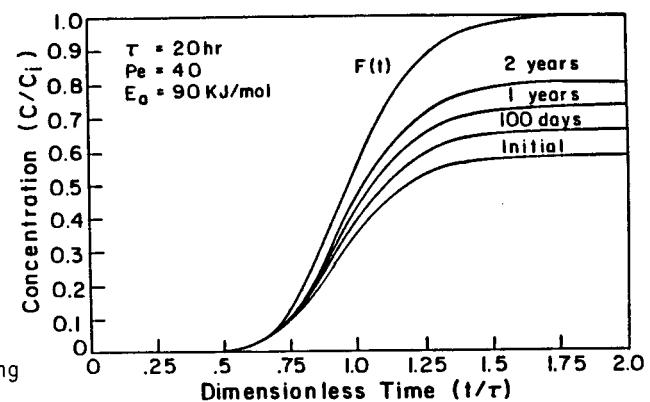


Figure 7 Reactive tracer behavior during long-term energy extraction in the single fracture as described in Fig. 6.

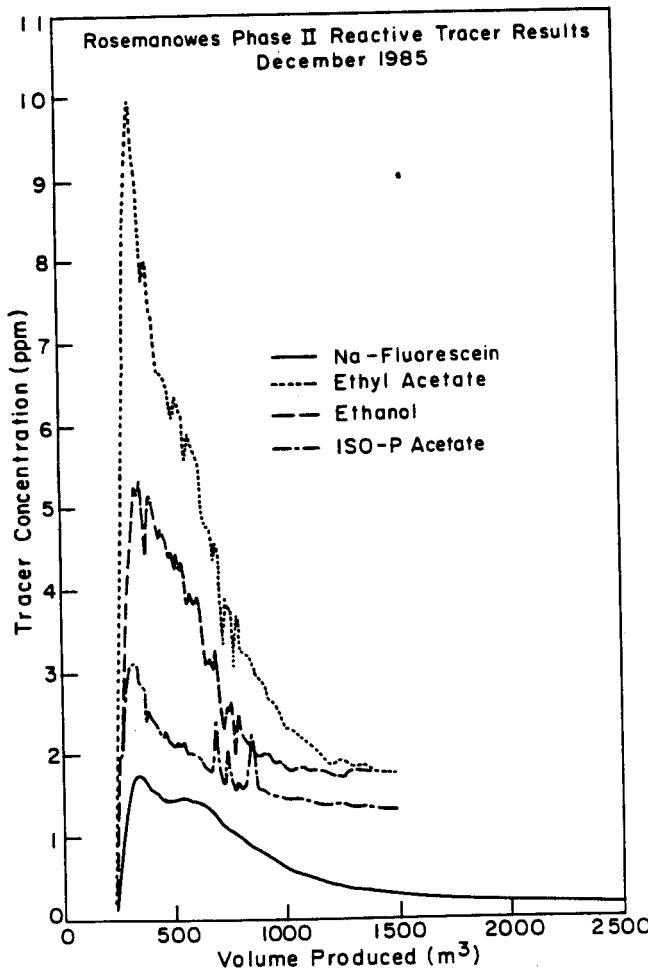


Figure 9 Results of the first reactive tracer field test in the Phase II Rosemanowes Reservoir (December 1985).

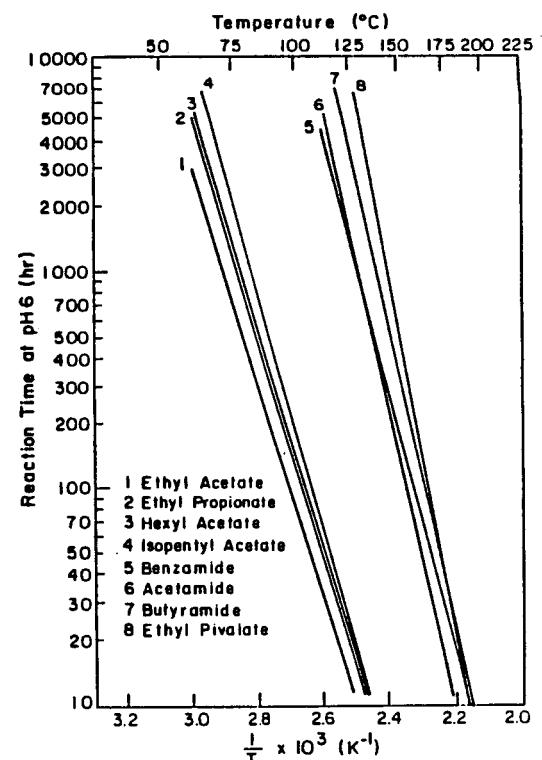


Figure 8 Summary of kinetic results for the ester and amide hydrolysis reactions: characteristic reaction time as a function of reciprocal temperature.

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