

## **NOTICE CONCERNING COPYRIGHT RESTRICTIONS**

This document may contain copyrighted materials. These materials have been made available for use in research, teaching, and private study, but may not be used for any commercial purpose. Users may not otherwise copy, reproduce, retransmit, distribute, publish, commercially exploit or otherwise transfer any material.

The copyright law of the United States (Title 17, United States Code) governs the making of photocopies or other reproductions of copyrighted material.

Under certain conditions specified in the law, libraries and archives are authorized to furnish a photocopy or other reproduction. One of these specific conditions is that the photocopy or reproduction is not to be "used for any purpose other than private study, scholarship, or research." If a user makes a request for, or later uses, a photocopy or reproduction for purposes in excess of "fair use," that user may be liable for copyright infringement.

This institution reserves the right to refuse to accept a copying order if, in its judgment, fulfillment of the order would involve violation of copyright law.

## Estimating Fracture Surface Areas from Tracer Tests: Mathematical Formulation

G. Michael Shook

Idaho National Engineering and Environmental Laboratory

### Keywords

Tracer tests, matrix-fracture surface area, characterization, fractures

### ABSTRACT

A mathematical method for estimating matrix-fracture surface area from tracer testing is presented. The method relies on differences in mean travel time between a conservative and an adsorbing tracer. That difference is related to the adsorption isotherm for the adsorbing tracer. If the tracer adsorbs at a known density to the surface, the surface area is readily calculated. The method is restricted to single phase liquid conditions and single porosity conditions – either purely fracture or porous media.

### Introduction

Characterization of fractured geothermal reservoirs remains a challenging engineering feat. Recent work has shown the fracture pore volume and fluid velocities can be estimated from conservative tracer tests (Shook, 2003). The method – known Flow Capacity – Storage Capacity, or F-C – provides information of the *distribution* of pore volume and fluid velocity in a fracture network. While this information is useful in designing or optimizing geothermal reservoirs, a critical parameter is yet missing: the matrix-fracture surface area,  $A$ . This surface area has been shown to be a key element in determining energy extraction in fractured domains (Carslaw and Jaeger, 1959; Gringarten et al., 1975). Robinson and Tester (1984) showed a relationship between apparent heat exchange surface area and reservoir volume for two EGS reservoirs. The correlation they show demonstrates the need to estimate both fracture volume and surface area to optimize EGS heat extraction and reservoir life.

This paper presents a method of estimating fracture surface area from tracer tests. The analysis relies on differences in residence times between a conservative and adsorbing tracer. Because the method includes a conservative tracer, surface area

calculation is complementary to calculating fracture volume and fluid velocity developed previously (Shook, 2003). As before, the analysis method is restricted to cases in which negligible tracer enters the rock matrix – an engineered system in crystalline rock. The theory upon which the method is based is presented; field implementation would require identifying an adsorbing tracer candidate with the requisite properties as discussed below.

### Theory

Conservation of mass for an adsorbing tracer can be written as (see Nomenclature for definition of terms):

$$\frac{\partial}{\partial t} [\varphi \rho_w C_w + (1 - \varphi) \rho_s C_s] + \vec{\nabla} \cdot (\rho_w \vec{u}_w C_w) - \vec{\nabla} K_w \nabla C_w = 0 \quad (1)$$

By assuming time- and temperature-invariant porosity and density (both rock and liquid phase) and neglecting dispersion as second-order, Equation 1 can be written as:

$$\left[ \varphi \rho_w + (1 - \varphi) \rho_s \frac{\partial C_s}{\partial C_w} \right] \frac{\partial C_w}{\partial t} + \rho_w \vec{u}_w \vec{\nabla} \cdot (C_w) = 0 \quad (2)$$

The assumption of incompressible fluids is not overly restrictive for this application. Shook (1999) used an average density in predicting thermal velocities, and concluded errors introduced were small. That was recently confirmed by Stopa and Wojnarowski (2004), who indicate that use of constant thermal properties introduced approximately 10% errors compared to analytic solutions. In heterogeneous media dispersion is dominated by mechanical mixing, and so neglecting other forms of dispersion is also acceptable. Equation 2 can be written in the following form:

$$\frac{\partial C_w}{\partial t} + \frac{\vec{u}_w}{\varphi} \cdot \frac{\varphi \rho_w}{\varphi \rho_w + (1 - \varphi) \rho_s \frac{\partial C_s}{\partial C_w}} \vec{\nabla} \cdot (C_w) = 0 \quad (3)$$

From the form of Equation 3, it is straightforward to show the velocity of the adsorbing tracer can be written as (e.g., Stopa and Wojnarowski, 2004):

$$v_{Tr} = \frac{\bar{u}_w}{\varphi} \cdot \frac{\varphi \rho_w}{\varphi \rho_w + (1-\varphi)\rho_s} \frac{\partial C_s}{\partial C_w}$$

$$= \frac{\bar{u}_w}{\varphi} \cdot \frac{1}{(1-\varphi)\rho_s} \frac{\partial C_s}{\partial C_w} = \frac{\bar{u}_w}{\varphi} \cdot \frac{1}{1+D}$$

$$1 + \frac{1}{\varphi \rho_w} \frac{\partial C_s}{\partial C_w} \quad (4)$$

Equation 4 above indicates that the velocity of the adsorbing tracer is retarded, relative to the fluid velocity, by a factor related to its adsorption isotherm,  $\partial C_s/\partial C_w$ . Conservative tracers move with bulk fluid velocity. By calculating mean residence times for the tracers, we are able to determine the value of the retardation factor, and, from it, infer in-situ adsorption properties. Assuming the conservative and adsorbing tracers follow the same streamlines, the ratio of residence times directly gives D:

$$\frac{\bar{t}_{Ads}}{\bar{t}_{Cons}} = 1 + D \quad (5)$$

The ideal tracer for calculating surface areas would exhibit linear, reversible adsorption; that is, mass fraction adsorbed is linearly related to mass fraction of tracer in the aqueous phase. Figure 1 shows an example. For linear sorption, we are able to solve Equations 4 and 5 for the adsorbed mass,  $\rho_s C_s$ , which has units of (mass tracer / volume of rock). This can be expressed as a function of surface area:

$$\frac{\text{MassTracer}}{\text{VolumeRock}} = \frac{\text{MassTracer}}{\text{SurfaceArea}} \cdot \frac{\text{SurfaceArea}}{\text{PoreVolume}} \cdot \frac{\text{PoreVolume}}{\text{RockVolume}}$$

or

$$\rho_s C_s = C_p \cdot \bar{A} \cdot \left( \frac{\varphi}{1-\varphi} \right) \quad (6)$$

If a tracer can be identified that adsorbs at a known (measured) density to a mineral assemblage on a fracture surface ( $C_p$ , the first term on the right in Equation 6), Equation 6 can be solved for specific surface area,  $\bar{A}$ . The pore volume, as estimated from the conservative tracer (Shook, 1998), can then be used to convert specific surface area to total surface area:

$$V_p = q \bar{t}_{Cons}$$

$$A = \bar{A} V_p$$

## Limitations of the Method

Mathematically, the method described above is straightforward. The essential requirement is that the tracers not interact with rock matrix. If the tracers do enter the rock matrix, their

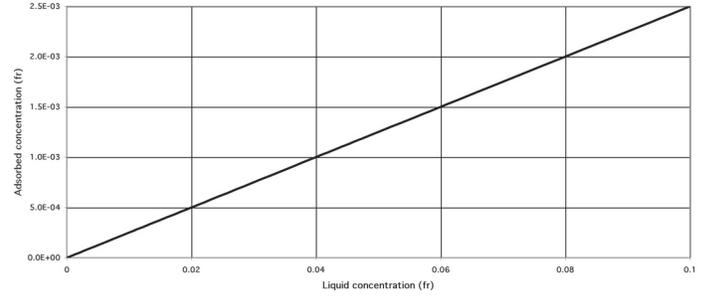


Figure 1. Example of a Linear Adsorption Isotherm.  $C_s = 0.025 C_w$

residence times and surface area calculations will be artificially large. Because the adsorbing tracer would adsorb within the rock matrix, it is not likely that recovery fractions of the two tracers would be similar, so such behavior would be readily noticeable.

The biggest potential drawback of the method is reliance on a tracer that adsorbs at the appropriate density to a surface area. Such a tracer is not currently known, and would of course be site-specific. Clearly, additional research is required before this method is deployable.

It should also be noted that tracer tests give *volume-averaged* estimates of what properties they estimate. Therefore, adsorption isotherms would have to be estimated on sufficient rock sample so as to be representative of bulk conditions.

## Summary and Future Work

A method for determining fracture-matrix surface area from tracer tests is presented. The method relies on differences in residence times for conservative and adsorbing tracers and a known adsorption isotherm to calculate surface area. Because a conservative tracer is also injected, this work is complementary to our previous methods of calculating pore volume, flow capacity, and storage capacity of fractured networks. The ability to estimate surface area independently of pore volume is crucial to optimum design of EGS systems.

Additional work is required before deploying this method. Identifying a tracer with the appropriate sorptive properties will be instrumental to the method's success. There are various other constraints on the formulation that bear additional investigation. For example, similar methods are used to infer residual saturations in environmental applications (Pope et al., 1994). A rigorous error analysis was used to constrain the tracers' partition coefficients for adequate estimation of saturation (Dwarkanath et al., 1999). A similar approach is needed here, in order to constrain adsorption parameters. These issues remain a focus of INEEL's research program in geothermal characterization.

## Acknowledgements

This work was supported by the U.S. Department of Energy, Assistant Secretary for Energy Efficiency and Renewable Energy, under DOE Idaho Operations Office Contract DE-AC07-99ID1377, whose support is gratefully acknowledged.

## Nomenclature

$A$	Surface area of fractures (or matrix-fracture surface area) [=] $L^2$
$\bar{A}$	Specific surface area of fractures [=] $L^2/L^3$ , or $L^{-1}$
$C_w$	Mass fraction of tracer in the aqueous phase [=] dimensionless
$C_s$	Mass fraction of tracer adsorbed to stationary phase [=] dimensionless
$D$	Retardation factor for adsorbing tracer as defined in Equation 4 [=] dimensionless
$K_w$	Dispersion tensor [=] $L^2/t$
$q$	Volumetric flow rate [=] $L^3/t$
$t$	time
$\bar{t}_{Ads}$	Mean residence time of the adsorbing tracer [=] $t$
$\bar{t}_{Cons}$	Mean residence time of the conservative tracer [=] $t$
$u_w$	Darcy velocity of liquid phase [=] $L/t$
$v_{Tr}$	Interstitial velocity of the adsorbing tracer [=] $L/t$
$V_p$	Pore volume [=] $L^3$
$\varphi$	porosity
$\rho_w$	liquid phase density [=] $m/L^3$
$\rho_s$	solid phase density [=] $m/L^3$

## References

- Carslaw, H.W., and J.C. Jaeger, 1959, *Conduction of Heat in Solids*, 2<sup>nd</sup> Ed., Oxford: Clarendon Press.
- Dwarakanath, V., N. Deeds, and G.A. Pope, 1999, "Analysis of Partitioning Interwell Tracer Tests," *Environmental Science Technology*, 33, pp. 3829–3836.
- Gringarten, A.C., P.A. Witherspoon, and Y. Ohnishi, 1975, "Theory of Heat Extraction from Fractured Hot Dry Rock," *J. Geophysical Research*, Vol. 81, No. 2, pp 1120-1124.
- Pope, G.A., M. Jin, V. Dwarakanath, B. Rouse, K. Sepehrnoori, 1994, "Partitioning Tracer Tests to Characterize Organic Contaminants," *Proceedings of the Second Tracer Workshop, Center for Petroleum and Geosystems Engineering, The U. Texas at Austin*, Nov. 14–15.
- Robinson, B.A., and J.W. Tester, 1984, "Dispersed Fluid Flow in Fractured Reservoirs: An Analysis of Tracer-Determined Residence Time Distributions," *J. Geophysical Research*, Vol. 89, No. B12, pp 10374-10384.
- Shook, G.M., 1998, "Prediction of reservoir pore volume from tracer tests," *Trans., Geothermal Resource Council*, Vol. 22, pp 477-480.
- Shook, G.M., 1999, "Prediction of thermal breakthrough from tracer tests," *Proc of the 24<sup>th</sup> Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, Ca.*, pp 24-30.
- Shook, G.M., 2003, "A Simple, Fast Method of Estimating Fractured Reservoir Geometry from Tracer Tests," *Trans., Geothermal Resource Council*, Vol. 27, pp 407-411.
- Stopa, J. and P. Wojnarowski, 2004, "Analytical Model of Cold Water Front Movement into Geothermal Reservoir," *Geothermics*, in print.

