Geothermal Resources Council, TRANSACTIONS, Vol. 10, September 1986

Experimental Tracer Response Curves for Fractured Cores

J. Flint Pulskamp, Robert A. Johns and Roland N. Horne

Stanford Geothermal Program

Dept. of Petroleum Engineering

Stanford University, CA 94303

ABSTRACT

In order to interpret tracer tests in fractured reservoirs, mathematical models have been used. However since model fitting is only an indirect process, it is necessary to examine the applicability of the model by comparing it to closely controlled laboratory flow experiments. In this way, the reliability and accuracy of the model can be evaluated and its functional limits can be defined. This study set out to collect data which could be used as a basis to test the validity of mathematical models for tracer flow in fractures, and in particular, models developed recently at Stanford. Laboratory experiments were performed by flowing potassium iodide (KI) tracer through fractured consolidated cores. The response curves can be analyzed to estimate formation parameters such as fracture width in this case. By comparing the values of fracture width generated by the flow model to that measured on the actual core, the accuracy of the model can be gauged.

1: INTRODUCTION

In order to forecast and understand the mechanisms of fluid flow in fractured geothermal reservoirs, characteristics of the formation and fluid must be defined. Formation characteristics can be determined directly by analyzing actual well core samples, although this is usually unreliable so indirect methods are more often used. Well tests and tracer tests are two such indirect methods. In order to interpret such tests, it is necessary to rely on models of the reservoir flow, in order to relate the observed response to reservoir parameters that are to be determined. Examples of reservoir parameters that govern the response to a tracer test are the tracer dispersivity and the fracture aperture. The more clearly defined the influences of these parameters, the more accurately the behavior of the reservoir can be estimated using the model. Since these parameters depend on fluid and formation characteristics, they become difficult to measure. For this reason, when these parameters are incorporated into models, it becomes very difficult to verify the accuracyof the model. One way to examine the applicability of the model is to run experimental tracer tests in the laboratory under closely controlled conditions, and then compare the estimates of the parameter values with those that can be measured directly on the laboratory core.

This work was originated as an experimental investigation into the applicability of several tracer interpretation models developed over the past few years. The most recent model is the two dimensional model developed by Walkup and Horne (1985) to represent the flow of tracer in a fractured reservoir. The objective of this model was to be able to estimate fracture aperture by comparing the model results to tracer test measurements in a fractured reservoir. This model involved six dimensionless variables, of which five are made up of combinations of eight physical flow parameters. The sixth variable, dimensionless distance, is of greatest interest because it contains only the two parameters fracture half width and core length, both of which can be measured directly on a core. The measurement of this parameter (fracture width) is the basis by which this model can be verified and was the objective of this research.

This objective can be divided into three sub-tasks: (1) to devise an experimental method by which a tracer flow test can be accurately simulated in a laboratory, (2) to devise a method to create and measure "fractures" of different widths in the core, and (3) to measure the tracer concentrations of the effluent.

2: EARLIER WORK

Laboratory work on tracer flow in fractures has been performed as a means to understand the flow mechanisms in tracer tests. These principles have been incorporated into mathematical models to simulate flow in a fracture. The models have been applied to actual field test data, but their accuracy has not been verified by controlled tracer flow experiments in the laboratory.

The flow mechanisms in geothermal reservoirs are affected by the highly fractured nature of the reservoir rock, so an understanding of fluid flow in fractures was essential. Neretnieks, Eriksen, and Tahtinen (1982) examined this behavior with experimental studies of tracer flow in fractured granite. Horne and Rodriguez (1983) derived equations characterizing dispersion and diffusion of fluid through a fracture. Gilardi (1984) verified this dispersion equation with a set of experiments using a Hele-Shaw model. The fracture flow description of Horne and Rodriguez was incorporated into a tracer flow model by Fossum and Horne (1982), and Fossum (1982), to analyze tracer flow tests in geothermal wells. This model was then applied to field tracer test results from the geothermal field in Wairakei, New Zealand. The results showed that the model was only partially successful in matching the observed field tracer response. In particular, the field response showed extended "tails" in the tracer return profiles that appeared to indicate a retention of the tracer during transport.

The question of tracer retention processes in geothermal reservoirs was then investigated experimentally by Breitenbach (1982) who ran tracers through laboratory cores, and after a residence time, measured the effluent concentration. By mass balance, the amount of tracer retained was determined. Using a retention mechanism, a second mathematical was formulated by Jensen (1983), and Jensen and Horne (1983), and was applied to the same Wairakei field data. It was found that the match between the model and the field data was much closer than with Fossum's earlier model that had ignored the retention effect.

However, Jensen's model proved to be unacceptable for the purpose originally intended, since it did not permit the estimation of the fracture aperture from the match (this was because the aperture width was determined in combination with another parameter whose exact value was unknown). Walkup (1984) (and Walkup and Horne, 1985) developed a third model based on the same physical formulation of Jensen (1983), but was able to separate the fracture aperture from the other parameters by using a mathematical representation that considered both longitudinal and transverse directions.

In Walkup's model, the dimensionless distance x_D, was isolated and was made up of two measurable parameters--fracture half width and well spacing. Both of these physical parameters can be measured directly on a laboratory core as fracture half width and core length. Thus it is possible to confirm or deny the applicability of the model using an experiment on a well described fractured core. By doing so, it becomes possible to gain confidence in the use of the model to accurately interpret field data.

3: EXPERIMENTAL APPARATUS

The experimental apparatus consisted of a core holder suspended in a high temperature air bath and connected to three primary controlling systems: (1) a pressurized sheath around the core that provided the necessary confining pressure, (2) a water pump system that regulated the flow of distilled water through the core, and (3) a pressurized tracer vessel which regulated the injection of the tracer. This basic setup was originally assembled by Sageev (1980). This original apparatus was modified by Breitenbach (1982) to include the tracer flow circuit. Based on a suspicion that the viton sleeve in Breitenbach's apparatus was itself responsible for some of the tracer retention, an additional core sleeve was made by Walkup (1984) from stainless steel. However because the stainless steel sleeve is rigid, a sufficient seal around a consolidated core can not be achieved. Although this sleeve is useful for unconsolidated cores, this investigation dealt only with consolidated cores and therefore the viton sleeve was used. The multiple inlet end plugs, as designed originally by Sageev (1980) were used.

The rock used in this series of experiments was a Bandera sandstone from Redfield, Kansas. This was a finely striated uniform-grained sandstone with a porosity of about 20% and an absolute permeability of 40 md in the direction of laminations, as determined from a gas permeameter. The cores were cut, cleaned, and in most cases, fired at 500 C to deactivate any clays.

One of the principle goals of the experiments was to confirm the application of the flow models to fractured rocks. Thus the cores were sawed through their central axis and then reassembled. This resulted in a planar fracture along the center of the core, aligned with the direction of flow. The aperture of the fractures created in this way was of the order of 0.02 mm.

Figure 1 illustrates the configuration of the fractured core.

4: EXPERIMENTAL PROCEDURE

The experimental procedure used in this study was comprised of two parts: (1) flowing distilled water, followed by tracer through the core, and (2) measuring the tracer concentrations of the effluent.

(a) Flowing the Tracer

Once the flow of distilled water had been initiated through the core and stabilized, the inlet port of the coreholder was switched to the pressurized tracer inlet vessel. Distilled water was used so that no tracer ion would be present in the system before the tracer flow was initiated. The tracer used was potassium iodide (KI) with the the iodide ion (I^-) being the traceable halide. Iodide was selected because it is commonly used in geothermal reservoir tests. Runs were made with varying water and tracer flow rates and with different tracer concentrations. The temperatures of the runs were also varied from room temperature to 150 degrees Celsius. The input of tracer was in the form of a step input.

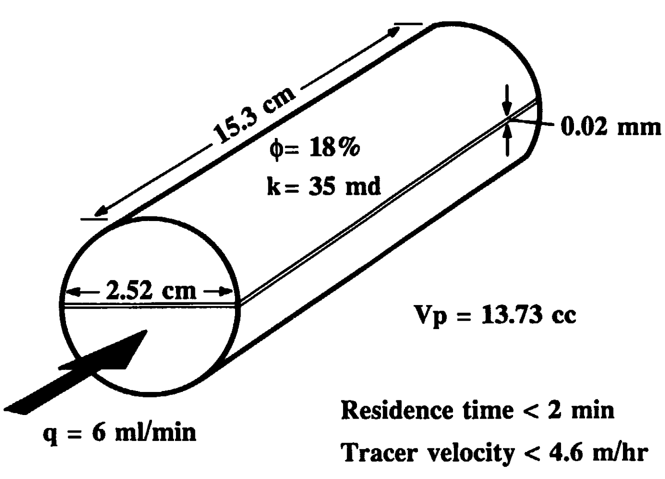

Figure 1: Schematic of Fractured Core

In order to determine the reversibility of these runs, step inputs of tracer followed by distilled water were made. A step input of tracer would be run to produce a response curve, and after the effluent concentration stabilized at its maximum value, a step input of distilled water would then be run to produce another response curve. By comparing these opposite curves, the reproducibility of the runs and the reversibility of any retention process could be determined.

The flow conditions were chosen to represent actual geothermal reservoir conditions. The flow of the background distilled water varied between 2 and 4 ml/min. The tracer pressure was varied around 270 psi and the backpressure was kept constant at 50 psi to prevent flash vaporization during the heated runs.

(b) Measuring the Tracer Concentration

The concentration of the tracer as it left the core was measured at the exit port. In the earlier experiments reported by Pulskamp (1985), the concentration was determined by collecting samples of the effluent and analyzing them individually. Samples were taken every minute at the extreme ends of the response curves, where there was little change, and every 30 seconds in the critical portion of the curve resulting in 40 to 60 samples per run. The samples were collected in glass vials and were subsequently analyzed using an ion-specific electrode.

In later experiments, the concentration of the tracer was measured directly using a conductivity probe mounted in the flow circuit at the downstream side of the coreholder. The resistance of the probe was monitored by an analog/digital converter controlled by a microcomputer.

5: RESULTS

Several experiments were performed under different conditions of temperature and flow rate. Figure 1 shows the characteristics of the core material used, the conditions of flow and the method of ion measurement for a typical run. Figure 2 shows the results of one of these runs as plots of I^- concentration versus time.

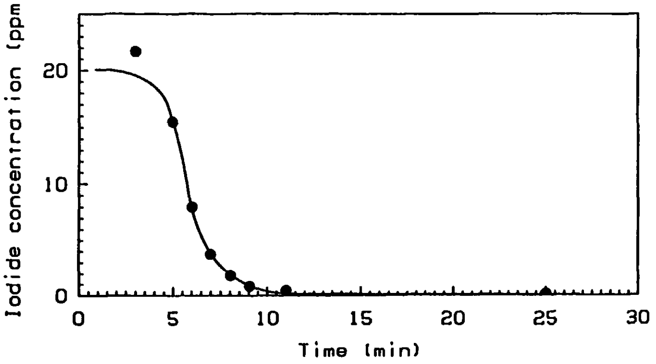

Figure 2: Tracer Response Measured by Sampling

In several of the early runs, the tracer measurement procedure prevented the gathering of useful data. Only partial response curves were obtained because the the sample collections were made too late in the tracer test. Since it is the shape of the response curves that determines the five separate variables in Walkup's model, the shape of the curve needs to be defined very accurately. After an examination of the response curves, it was decided that there were insufficient data to precisely define the response. A new method was required that would establish more points along the curve and also improve the accuracy of the measurements. The gathering of more data points along the critical portion of the step curves (that portion which showed the largest changes in concentration) was not possible with the system employed in this experiment. Samples were taken every minute and each sample was only 2 to 4 ml. In order to accurately measure the concentration of a sample with the Fisher ion meter, a sample of 50 ml is desired. In order to mass enough volume for a test, each sample was diluted 5 to 10 times with distilled water. This inherently introduced error into the final concentration reading.

Larger time intervals could not be taken as a remedy to acquire larger sample sizes because the total time span from zero to maximum concentration was only a matter of about 5 to 8 minutes. Larger time intervals for samples would result in an even sparser distribution of points in the critical region.

Another alternative would have been to construct the system such that the response curve would be more spread out--a more gradual step response. Walkup's computer model is based on five dimensionless variables which are affected by the shape of the step response. The variable x_D (dimensionless distance between wells) is the most sensitive of the five to the shape of the curve, and also the only variable that could reasonably be varied in the physical apparatus being used. From the Walkup (1984) model:

$$x_D=\frac{x}{w}$$

where: x = distance between wells
w = fracture half width

As the value of x_D increases, the step function spreads out. This is achieved by increasing the distance between wells (core length in experiment) or by decreasing the fracture half width. The core length, X, is about 6 in. and cannot be changed in this system because of the design of the experimental apparatus. The fracture half widths of the cores were between 0.010 and 0.006 mm. This was achieved by cutting the experimental cores in half with a diamond rock saw. The two faces of the fracture were then relatively smooth and were fit together with very little but constant aperture. In order to spread out the step response, these fracture widths would have had to be decreased. These values are already very small and it would have been difficult to achieve a closer spacing without polishing the surfaces of the fracture, which would have reduced the physical similarity of the experiment.

The solution was to obtain a continuous measurement of concentration with much more accuracy than the previous system. An electrode was placed in the outflow stream of the core and measurements of conductivity at the rate of one per second were taken. The electrode was similar to the ones used by Gilardi (1984) in the large Hele-Shaw fracture model. A junction to the outlet flowline of the experimental apparatus was constructed so the electrode would be in direct contact with the effluent. The use of this measurement method resulted in more accurate and well defined response curves, such as the one shown in Figure 3.

The step function response shown in Figure 3 can be converted into a spike input response by differentiating with respect to time, as in Figure 4. The resulting response is then directly comparable to the response of a geothermal reservoir during a standard slug-input, well to well tracer test. Confirmation of the applicability of the model to the experimentally generated responses adds confidence in the application of these same models to actual field tests.

Figure 5 shows a match of one of the flow models to the experimental data of Figure 3.

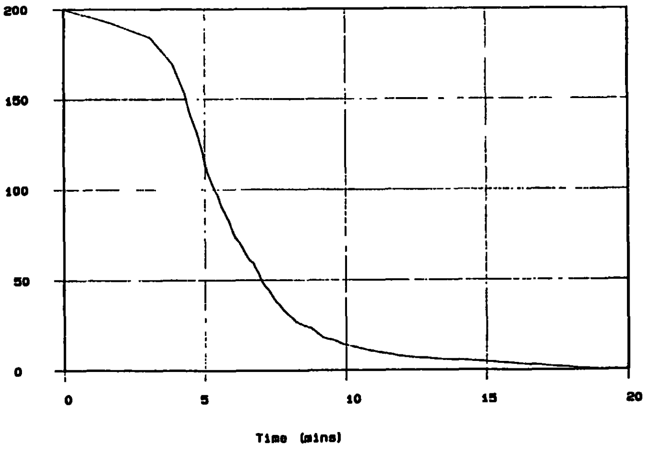

Figure 3: Tracer Response Measured with Inline Electrode

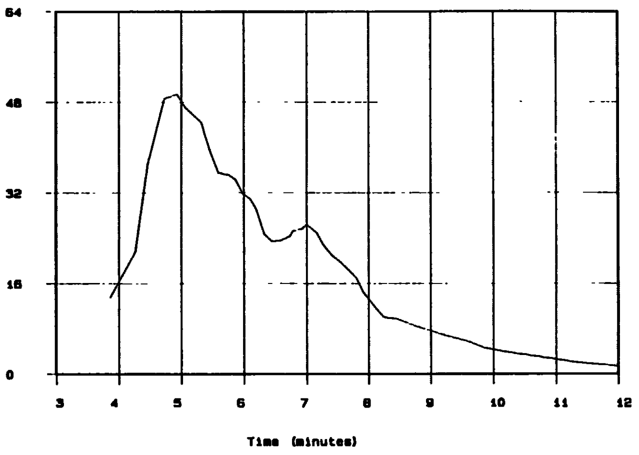

Figure 4: Equivalent Spike Input Response Derived from Step Input Measurement

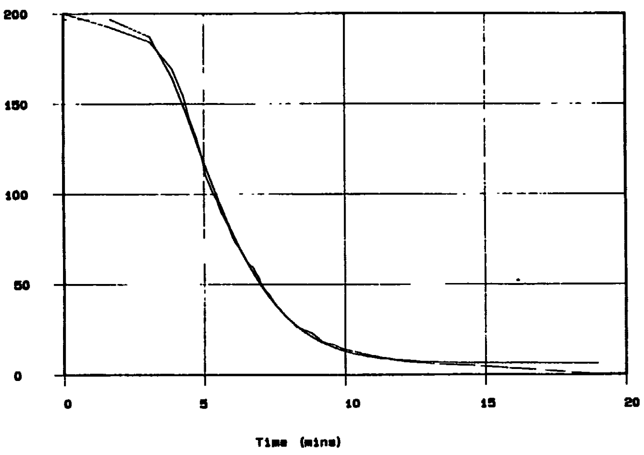

Figure 5: Match of Experimental Data to Fracture Flow Model

6: CONCLUSIONS

Experimentation that simulated tracer flow tests in fractured geothermal reservoirs was performed and response curves were generated. By physically measuring parameters of the cores used in experimentation, in this case fracture width, the validity of mathematical flow models such as Walkup's can be examined. Several conclusions were reached based on these results:

--The Fisher ion analyzer is an accurate means of measuring sample concentrations for discrete, large samples, but its application in measuring frequent and small effluent volumes is difficult.

--By utilizing an electrode to measure conductivity and taking readings in the flow path itself, much quicker and better defined response curves were generated.

--A method to accurately measure and maintain the fracture width in the rock core during the flow experiments is essential.

7: ACKNOWLEDGEMENT

This research was funded by the U.S. Department of Energy, under contract number DE-AS07-84ID12529.

8: REFERENCES

1. Breitenbach, K.A., Chemical Tracer Retention in Porous Media, Stanford Geothermal Program SGP-TR-53, Stanford University, May 1982.
2. Fossum, M.P., Tracer Analysis in a Fractured Geothermal Reservoir: Field Results from Wairakei, New Zealand, Stanford Geothermal Program SGP-TR-56, Stanford University, June 1982.
3. Fossum, M.P., Horne, R.N., "Interpretation of Tracer Return Profiles at Wairakei Geothermal Field Using Fracture Analysis", Geothermal Resources Council Transactions, Vol. 6, pp. 261-264, 1982.
4. Gilardi, J.R., "Experimental Determination of the Effective Dispersivity in a Fracture", Stanford Geothermal Program SGP-TR-78, Stanford University, June 1984.
5. Horne, R.N., Rodriguez, F., "Dispersion in Tracer Flow in Fractured Geothermal Systems", Geophysical Research Letters, Vol. 10, No. 4, pp. 289-292, April 1983.
6. Jensen, C.L., "Matrix, Diffusion and its Effects on the Modeling of Tracer Returns from the Fractured Geothermal Reservoir at Wairakei, New Zealand", Stanford Geothermal Program, SGP-TR-71, Stanford University, December 1983.
7. Jensen, C.L., Horne, R.N., "Matrix Diffusion and its Effect on the Modeling of Tracer Returns from the Fractured Geothermal Reservoir at Wairakei, New Zealand", Ninth Workshop on Geothermal Reservoir Engineering, SGP-TR-74, Stanford University, December 1983.
8. Neretnieks, I., Eriksen, T., Tahtinen, P., "Tracer Movement in a Single Fissure in Granite Rock: Some Experimental Results and their Interpretation", Water Resources Research, Vol. 18, No. 4, pp. 849-858, 1982.
9. Pulskamp, J.F., "The Generation of Response Curves from Laboratory Tracer Flow Experiments", Stanford Geothermal Program, SGP-TR-94, Stanford University, December 1985.
10. Sageev, A., "Design and Construction of an Absolute Permeameter to Measure the Effect of Elevated Temperature on the Absolute Permeability to Distilled Water of Unconsolidated Sand Cores", Stanford Geothermal program SGP-TR-43, Stanford University, December 1980.
11. Walkup, G.W., Jr., Characterization of Retention Processes and their Effects on the Analysis of Tracer Tests in Fractured Reservoirs, Stanford Geothermal Program SGP-TR-77, Stanford University, June 1984.
12. Walkup, G.W., Jr., Horne, R.N., "Characterization of Retention Processes and their Effects on the Analysis of Tracer Tests in Fractured Reservoirs", Paper SPE13610,presented at the 1985 California Regional Meeting, Bakersfield, CA, March 1985.