SGP-TR-94

The Generation of Response Curves from Laboratory Tracer Flow Experiments

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December 1985

Financial support was provided through the Stanford Geothermal Program under Department of Energy Contract No. DE-AT03-80SF11459 and by the Department of Petroleum Engineering, Stanford University

Stanford Geothermal Program
Interdisciplinary Research in
Engineering and Earth Sciences
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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 a potassium iodide (KI) tracer through various fractured consolidated cores and then observing the response curves by measuring the tracer ion concentration of the effluent over time. The response curves can be analyzed by the models to estimate formation parameters such as fracture width in this case.. By comparing the values of fracture width generated by the computer model to that measured on the actual core, the model's accuracy can be gauged. The original experimental apparatus did not allow for a sufficient number of measurements to define the response curves, however, the experimental limitations were defined and a practical solution was outlined.

Table of Contents

List of Figures

List of Tables

SECTION 1: INTRODUCTION

In order to predict and understand the mechanisms of fluid flow in reservoirs, characteristics of the formation and fluid must be defined. Formation charcteristics can be determined directly by analyzing actual well core samples, although indirect methods are more often used. Well tests and tracer tests are two such indirect methods, and are by far the most common. Reservoir parameters which depend on both fluid and formation characteristics, such as dispersion, diffusion, etc., are determined by developing flow models to help predict the influence these parameters have on the mechanisms of fluid flow. 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 diffficult to verify the model's accuracy. But one way to examine the applicability of the model is to run experimental tracer tests in the laboratory and then compare the estimates of the parameter values with those that can be measured directly on the laboratory core.

The model considered in this work is a two dimensional computer model developed by Walkup **(1984)** to represent the flow of tracer in a fractured reservoir. The objective of Walkup's 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 is the objective of this research.

This objective can be divided into 3 facets: (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.

SECTION 2: LITERATURE REVIEW

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 laboratory controlled tracer flow experiments. **A** series of computer models to represent tracer flow in fractures have been developed at Stanford University during the past five years and only limited attempts have been made to test their accuracy.

Because the flow mechanisms in geothermal reservoirs are affected by the highly fractured nature of the reservoir rock, an understanding of fluid flow in fractures was essential. Neretnieks, Eriksen, and Tahtinen (1982) examined this behavior with experimental runs of tracer in fractured granite. Home 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, and he also examined the dispersion of fluids in fractures. This fracture flow description by Horne and Rodriguez was incorporated into a model by Fossum and Home (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 fields in Wairakei, New Zealand. The question of tracer retention processes in geothermal reservoirs was then investigated experimentally by Breitenbach (1982) by running tracers through laboratory cores, and after a residence time, measuring the effluent concentration. By mass balance, the amount of tracer retained was determined. **A** second mathematical model by Jensen (1983), and Jensen and Horne (1983), was developed and applied to the same field data used by Fossum with a closer fit. Walkup (1984) developed a third model and applied the results to the same data with results comparable to that of Jensen.

When the three mentioned models were fit to the actual field data, the reservoir and flow parameters for each model were found. However because most of the parameters were grouped together as variables in these models, it was difficult to isolate one parameter in particular. In Walkup's model, though, one of these variables, the dimensionless distance X_D, was isolated and was made up of two physically measureable 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.

SECTION 3: EXPERIMENTAL APPARATUS

The basic experimental apparatus consisted of a core holder suspended in an 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) and is described in his Masters report. This apparatus was modified to include the tracer vessel and was described by Breitenbach (1982). The core was set in a viton tube which was enclosed in the core holder and held tight when the confining pressure was applied. **An** additional core sleeve was made by Walkup (1984) from stainless steel which could endure higher temperatures and pressures. 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.

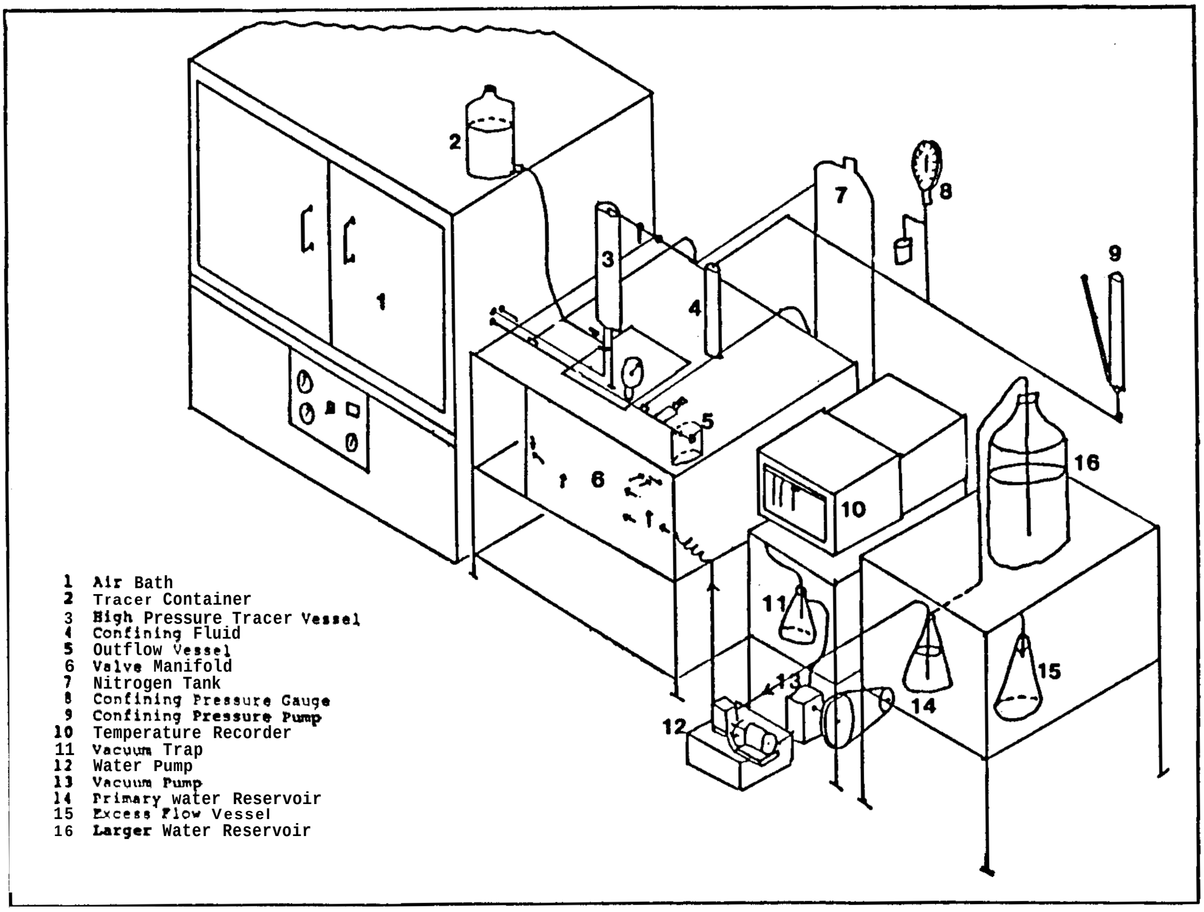
The rock used in this series of experiments was a Bandera sandstone from Redfield, Kansas. This was a finely striated uniform-grained sandstone with a porosity of about 20% and an absolute permeability of 40 md in the direction of laminations, as determined from a gas permeameter. The cores were cut,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

SECTION 4: EXPERIMENTAL PROCEDURE

The basic experimental procedure used in this study was comprised of two parts: (1) running first distilled water and then tracer through the core, and then collecting the effluent, and (2) measuring the tracer concentrations of each of the collected samples.

RUNNING THE TRACER

A detailed procedure of the preliminary phase of this experiment, that of preparing the system for flow, is given by Sageev (1980). 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. A schematic of this apparatus is given by Breitenbach (1982).



IG. 1: Experimental Setup (from Breitenbach(1982))

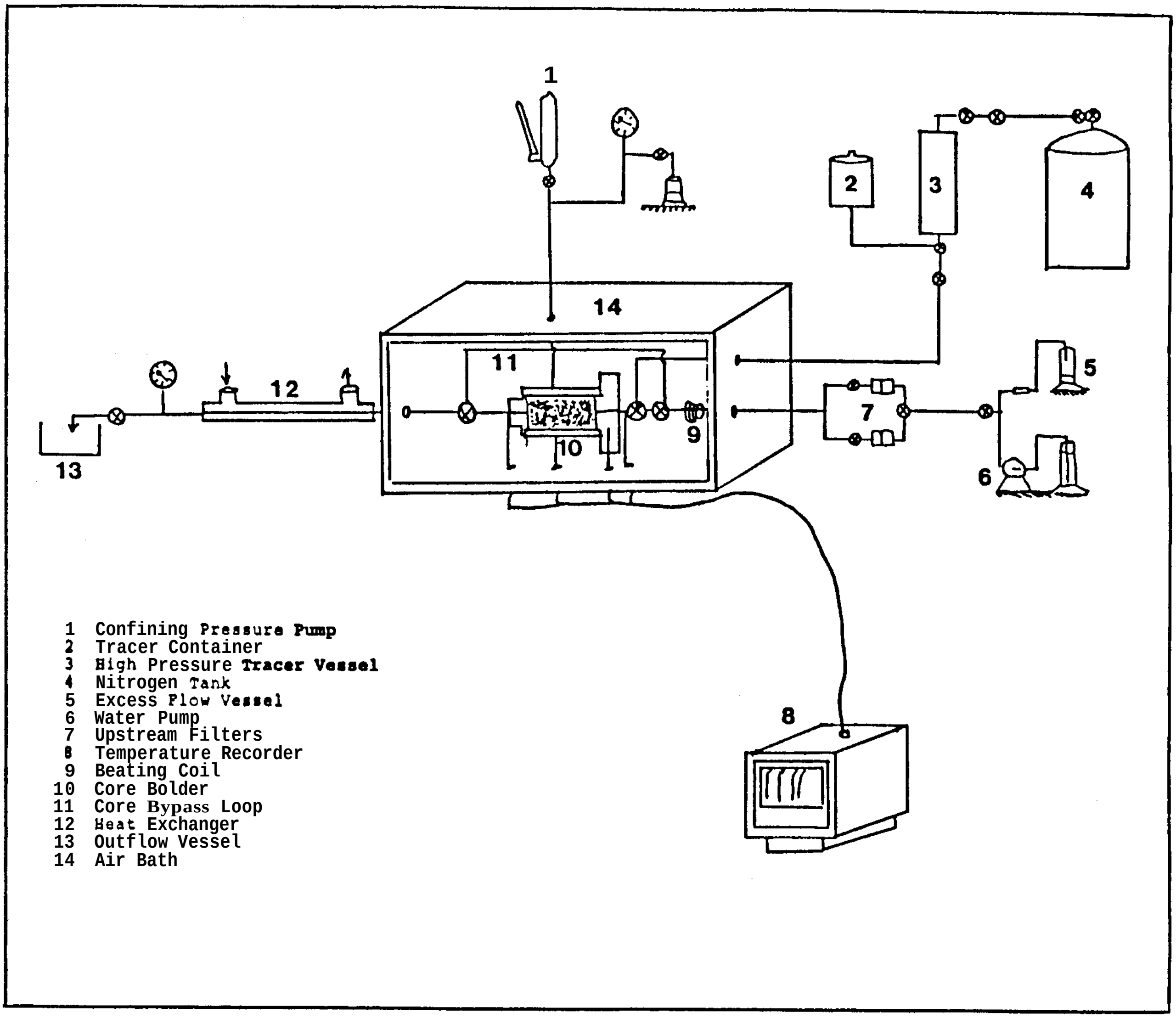


FIG. 2: Schematic of **Apparatus** (from Breitenbach(1982))

The background water used in all runs was distilled water so that no tracer ion would be present in the system before the tracer flow was initiated. The tracer 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 slightly varying water and tracer flow rates and with different tracer concentrations. The temperatures of the runs were also varied. The input of tracer was in the form of a step input as opposed to a spike input.

In order to determine the reversability 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 could be determined.

The flow conditions such as pressure and flowrate were determined so as to represent actual reservoir conditions. The flow of the background distilled water was varied around **3** ml/min. The tracer pressure was varied around **270** psi and the back-pressure was kept constant at 50 psi to prevent flash vaporization during the heated runs.

The effluent rate from the core varied from 2 to **4** ml/min. Samples were taken every minute in 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,

MEASURING THE TRACER

The tracer concentrations in the samples were measured with a Fisher Accumet

Model 750 Selective Ion Analyzer using an Orion iodide ion-selective electrode. **A** description of the ion analyzer and electrodes is given by Jackson (1982).

Three different methods of determining ion concentration with the ion analyzer were used to establish the most accurate method.

The direct measurement method consisted of constructing a plot of log concentration (ppm I^-) versus electrode potential (mv). The ion analyzer records potential in millivolts directly from the electrodes. For iodide this plot is linear in the range from about 0.01 ppm to over 50,000 ppm. By measuring the potentials of 2 iodide standards which bound the region of interest, a calibration line is formed. Direct measurements of samples is then made with the ion analyzer and from the calibration curve, the ion concentration is found. This measurement method is the most direct because only one reading is needed and no solute is added to the sample, unlike the next two methods.

The other two methods are incremental methods in that the ion concentration of the sample is determined by the change in potential of the measured liquid. In this way, calibration curves are not needed, but the analyzer must be standardized with samples of known concentration. The AA/AS method (analate addition/analate subtraction) consists of measuring the potential of a known volume of a standard. **A** volume of the the sample is added and the potential is measured again. By knowing the volumes of the added sample and the initial standard and the concentration of the standard, the concentration of the sample is determined.

The third method, KA/KS (known addition/known subtraction), works on the same principle as the AA/AS method except the inital potential measurement is made with the actual sample. A volume of standard is then added and the potential is measured again. By programming the volumes of sample and standard and the concentration of the standard, the concentration of the sample is again determined.

A step by step procedure for standardizing the ion analyzer and also for operating the KA/KS and AA/AS methods are given in the Fisher Accumet Owner's Manual (1984). A procedure for preparing standards and standardizing the ion meter is also given by Jackson (1982). The incremental methods require more effort than the direct method, but the incremental methods are in theory more accurate.

SECTION 5: DISCUSSION OF RESULTS

The tracer runs are tabulated in Tables 1 to 5 with data describing important characteristics of the core material used, the conditions of flow and the method of ion measurement. Figures 3 to 9 show the results of these runs as plots of I^- concentration versus time.

Ten runs were made, three on one core (unfired) with a fracture width of 0.0203 mm and seven on another core (fired) with a fracture width of 0.0127 mm. Data from some of the runs are not presented because problems with the experimental apparatus or measuring procedure prevented the gathering of useful data. Runs #4,5,6 resulted in only partial response curves because the timing of the sample collections were made too late in the tracer test. Since the shape of the response curves is what determines the five separate variables in Walkup's computer model, the shape of the curve should be defined very accurately. Upon analysis of the response curves, it was found that a new method of analysis could result in more accurate results. A method was required that would establish more points along the curve and ensure that the actual points are very accurate. 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 be 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 effected by the shape of the step response. The variable x_D (dimensionles distance between wells) is the most sensitive of the five to the shape of the curve, and also the only variable that could be reasonably measured and 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 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 aperature. The fracture width was measured from the difference in width between the entire core and the sum of the two halves. In order to spread out the step response, these fracture widths must be decreased. These values are already very small and it is very difficult to prevent these fracture widths from being altered during the experiment. The viton sleeve alone maintains the correct fracture width on the core. So the confining pressure of 2000 psi or even the pressure difference caused by the flowing tracer through the core is enough to affect the fracture width however small the effect may be.

A possible solution would enable a nearly continuous readout of concentration with much more accuracy than the previous system. An electrode could be placed in the outflow stream of the core and measurements of conductivity at the rate of 1 per second could be taken. Gilardi (1984) employed the use of these electrodes in his work, and Bouett (1985) developed a procedure to convert the conductivity as measured by the electrode to ion concentration in a single electrode. 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 electrode measuring method should result in more accurate and well defined response curves.

Table 1

RUN #3

CORE MATERIAL:	Bandera Sandstone (uncooked) Porosity = 18% Permeability = 35 md Length = 15.304 cm Fracture width = 0.0203 mm Diameter = 2.52 cm Pore volume = 13.73 cc
FLOW CONDITIONS:	Temperature = room Confining pressure = 2500 psi Water flow rate = 6 ml/min Tracer Pressure = 250 psi Downstream pressure = 0 psig Tracer:= 5 PPM KI
CONC. MEASUREMENTS:	Collected from 12:12 PM to 1:10 PM method= KA/KS VARIABLE

Table 2

RUN #4, 5, 6

CORE MATERIAL:	Bandera Sandstone(cooked at 500 C) Porosity = 22% Permeability = 50 md Length = 15.397 cm Fracture width = 0.0127 mm Diameter = 2.52 cm Pore volume = 16.89 cc
FLOW CONDITIONS:	Temperature = room Confining pressure = 2500 psi Water flow rate = 3.5 ml/min Tracer Pressure = 280 psi Downstream pressure = 50 psig Tracer:= 7 PPM KI
CONC, MEASUREMENTS:	Collected from 4:35 PM to 5:15 PM, 8:45 PM to 9:30 PM and 10:22 AM to 11:10 AM method:= KA/KS VAR, AA/AS VAR

Table 3

RUN #7

CORE MATERIAL:	Same as Run #4,5,6
FLOW CONDITIONS:	Same as Run #4,5,6 except Temperature = 200 F
CONC. MEASUREMENTS:	Collected from 4:45 PM to 5:20 PM method:= KA/KS VARIABLE

Table 4

RUN #8, 9

CORE MATERIAL:	Same as Run #4, 5, 6
FLOW CONDITIONS:	Temperature = room Confining pressure = 2000 psi Water flow rate = 2.8 ml/min Tracer Pressure = 290 psi Downstream pressure = 50 psig Tracer:= 20 PPM KI
CONC. MEASUREMENTS:	Collected from 4:11 PM to 4:50 PM, and 6:31 PM to 6:55 PM method:= DIRECT, KNKS VARIABLE

Table 5

RUN #10

CORE MATERIAL:	Same as Run # 4, 5, 6
FLOW CONDITIONS:	Temperature = 200 F Confining pressure = 1300 psi Water flow rate = 2.8 ml/min Tracer presure = 250 psi Downstream pressure = 50 psig Tracer:= 20 PPM KI
CONC. MEASUREMENTS:	Collected from 2:40 PM to 3:20 PM method:= KNKS VARIABLE

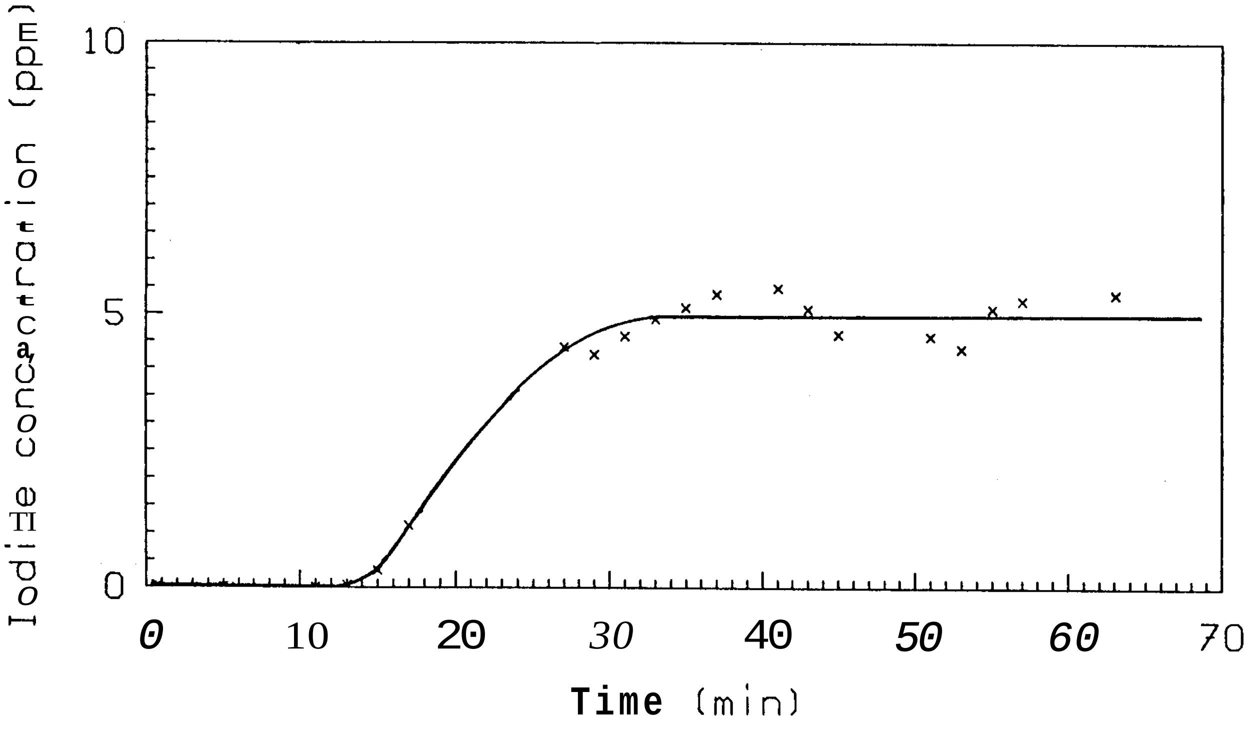


FIG. 3: Step Input of **5** PPM KI RUN #3

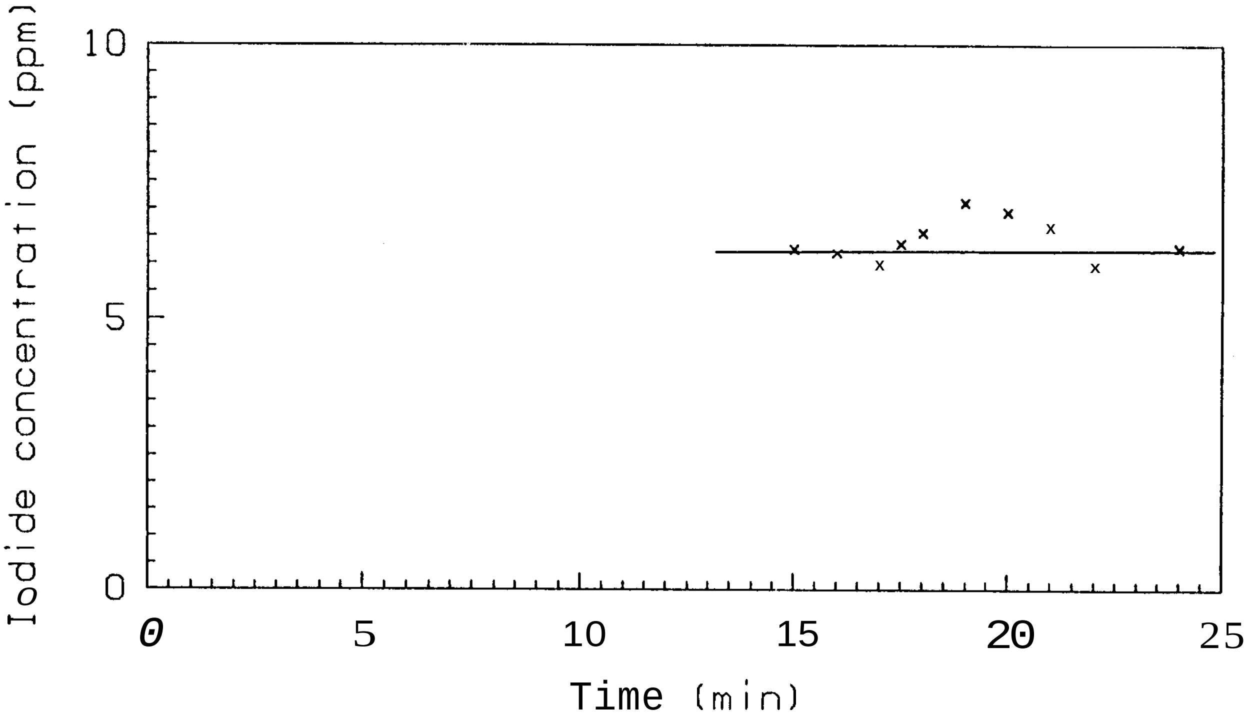


FIG. 4: Step Input of **7** PPM KI RUN #4

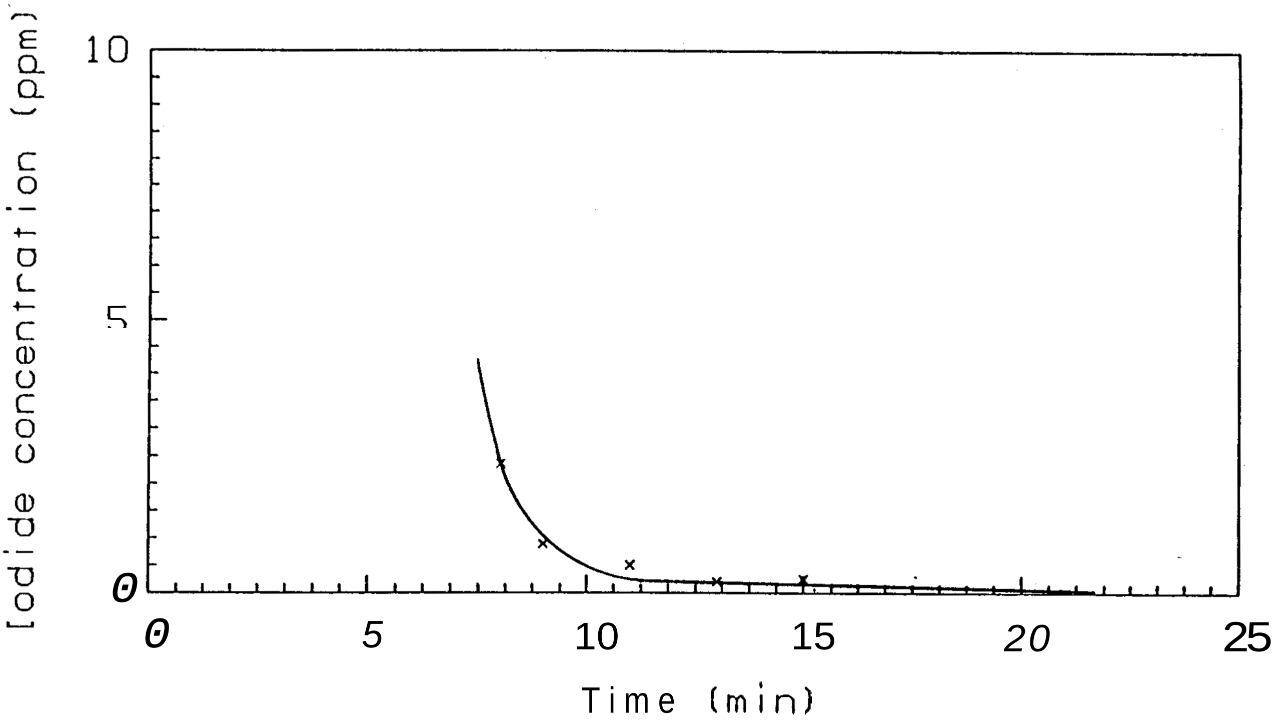


FIG. *5:* Step Input of 7 PPM KI RUN #5

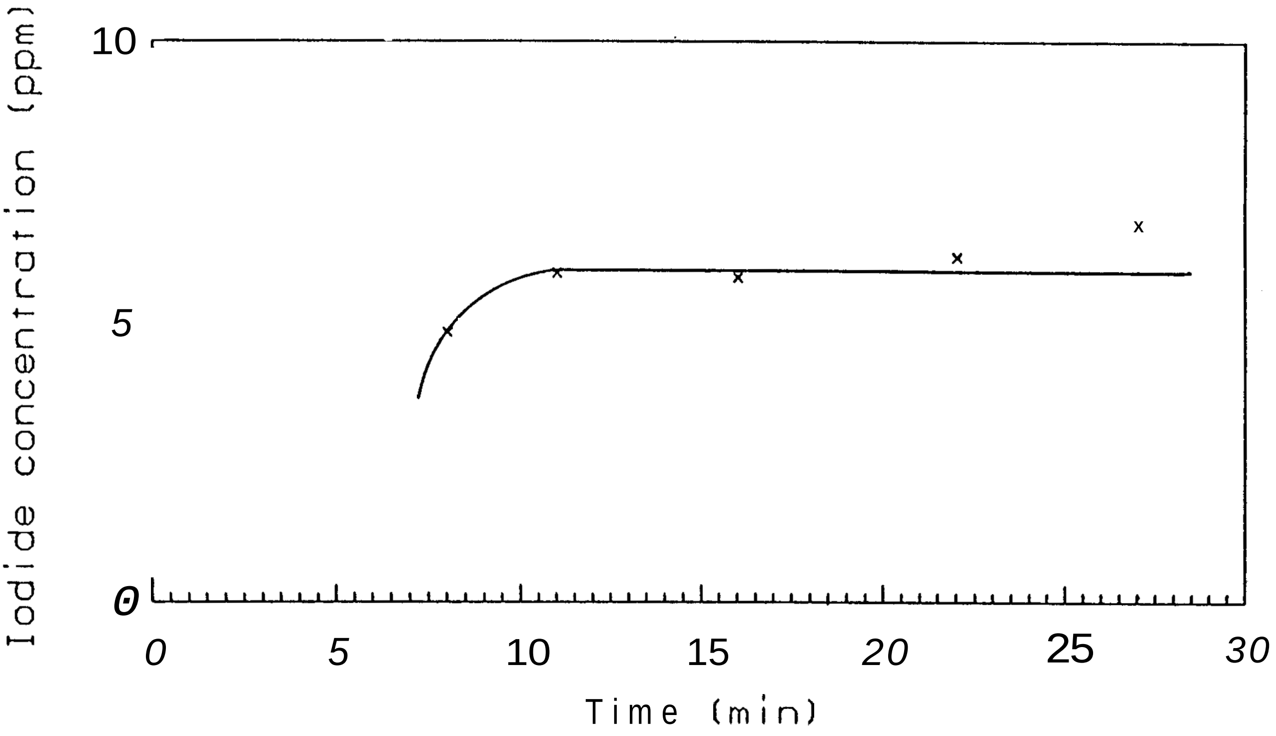


FIG. 6: Step Input of 7 PPM KI RUN #6

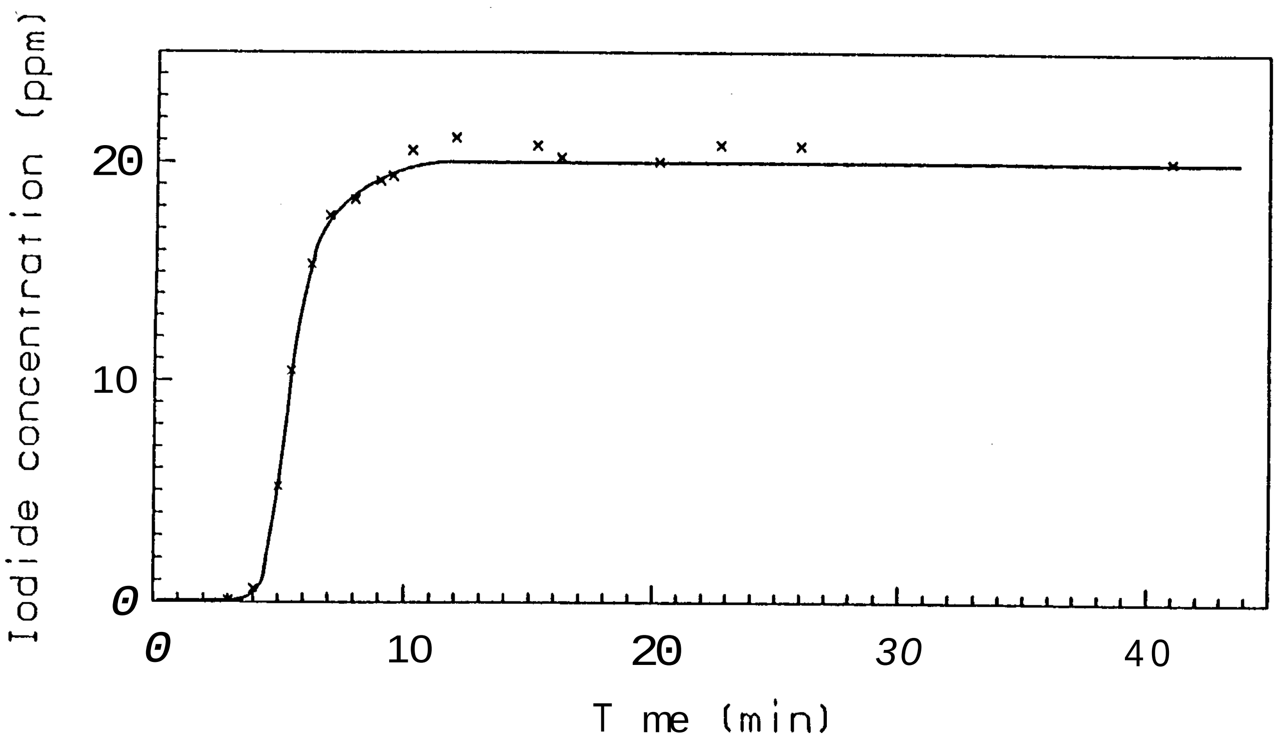


FIG. 7: Step Input of 20 PPM KI RUN #8

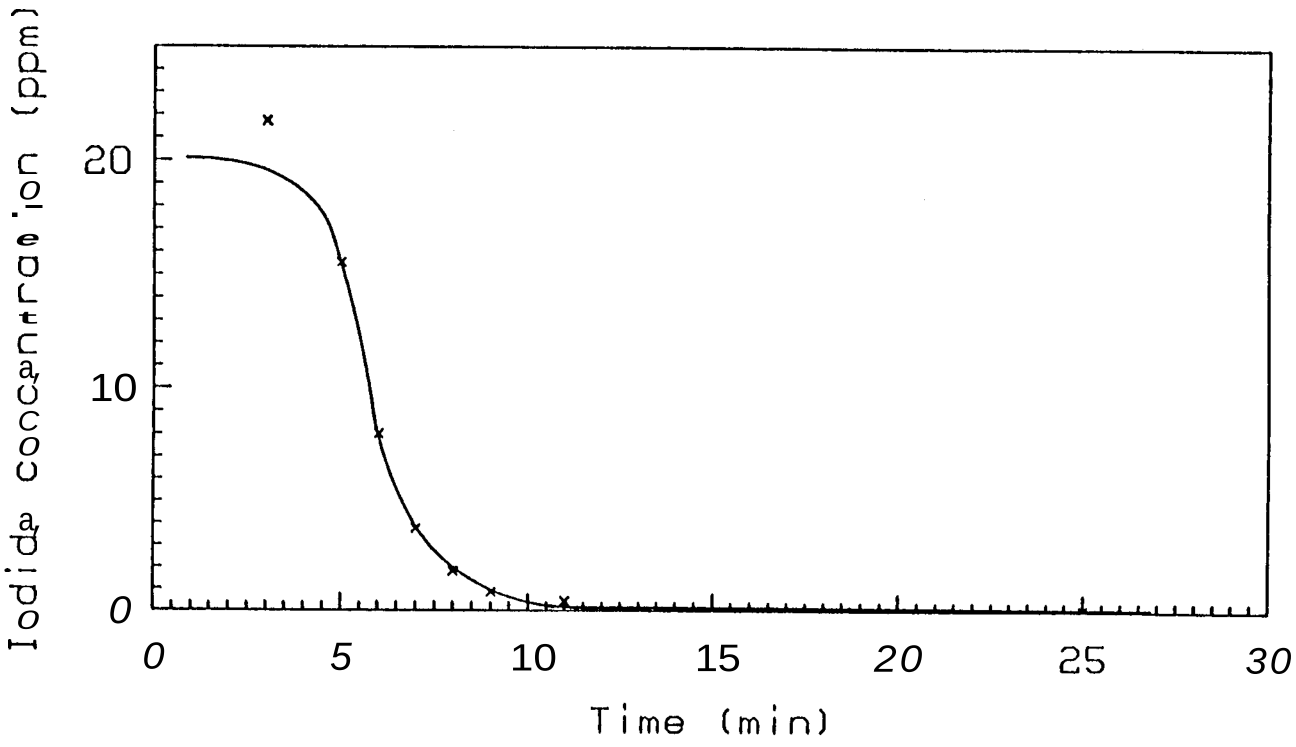


FIG. 8: Step Input of 20 PPM KI RUN #9

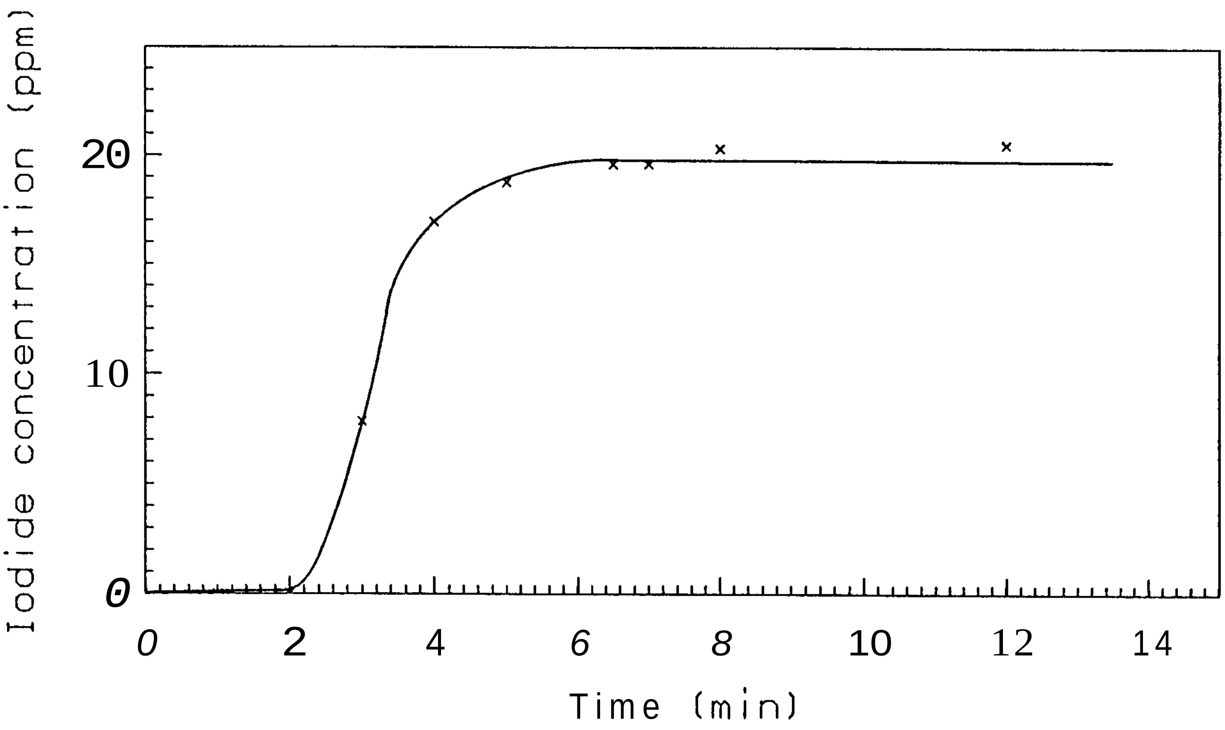


FIG. **9: Step Input** of **20** PPM KI RUN #10

SECTION 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 Walkup's model can be examined. The following are recommendations that could improve future 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 could be generated.

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

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SECTION 8: APPENDIX

RUN #3

Started tracer at 12:07 PM
Started collection at 12:12 PM

TOTAL ELAPSED **TIME** (MIN)	IODIDE CONCENTRATION (PPM)
5	0.007
11	0.007
13	0.043
15	0.311
17	1.132
27	4.378
29	4.246
31	4.581
33	4.890
35	5.103
37	5.355
41	5.474
43	5.088
45	4.614
51	4.579
53	4.352
55	5.099
57	5.242
63	5.360

RUN #4

Started tracer at 4:20 PM
Started collection at 4:35 PM

TOTAL ELAPSED **TIME** (MIN)	IODIDE CONCENTRATION (PPM)
15	6.248
16	6.177
17	5.965
17.5	6.463
18	6.656
19	7.092
20	6.930
21	6.659
22	5.948
24	6.274

RUN #5

Started water at 8:37 PM
Started collection at 8:45 PM

TOTAL ELAPSED TIME (MIN)	IODIDE CONCENTRATION (PPM)
8	2.360
9	0.882
11	0.501
13	0.199
15	0.245
21	0.000

RUN #6

Started tracer at 10:15 PM
Started collection at 10:22 PM

TOTAL ELAPSED TIME (MIN)	IODIDE CONCENTRATION (PPM)
8	4.800
11	5.860
16	5.782
22	6.144
27	6.711

RUN #8

Started tracer at 4:09 PM
Started collection at 4:11 PM

TOTAL ELAPSED TIME (MIN)	IODIDE CONCENTRATION (PPM)
3	0.105
4	0.624
5	5.163
5.5	10.424
6.5	15.377
7	17.575
8	18.294
9	19.148
9.5	19.360
10.5	20.520
12	21.083
15.5	20.741
16.5	20.220
20.5	20.020
22.5	20.767
26	20.734
41	20.043

RUN #9

Started water at 6:30 PM
Started collection at 6:31 PM

TOTAL ELAPSED TIME (MIN)	IODIDE CONCENTRATION (PPM)
3	21.716
5	15.518
6	7.976
7	3.738
8	1.789
9	0.838
11	0.412
25	0.080

RUN #10 Started tracer at 2:39 PM Started collection at 2:40 PM	
TOTAL ELAPSED **TIME** (MIN)	IODIDE CONCENTRATION (PPM)
1	0.000
2	0.012
3	7.827
4	16.915
5	18.726
6.5	19.572
7	19.593
8	20.290
12	20.500