EGG-M-11887

CONF-8704110--6

Received by OSTI

MAY 2 8 1987

EGG-M--11887

DE87 009716

# THE USE OF TRACERS TO ANALYZE THE EFFECTS OF REINJECTION INTO FRACTURED GEOTHERMAL RESERVOIRS

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## ABSTRACT

This paper discusses the use of tracers as a reservoir engineering tool in fractured geothermal reservoirs. The principle concern in injecting cooler spent fluids into a fractured reservoir is that the fluids may move through high permeability channels and return to the production wells after contacting a relatively small volume of rock. As a consequence of this rapid transport, the fluids will be only partially reheated and after a short period of time will effectively mine the heat from the limited volume of rock. The production wells will then experience a rapid and premature reduction in thermal output. Tracers can be used to infer the existence of high mobility conduits between injection and production wells and to monitor chemical changes of an injected fluid. Since tracer arrival precedes thermal breakthrough, tracer tests are a very useful forecasting tool.

Research into the development and use of tracers in geothermal reservoirs has been sponsored by the U.S. Department of Energy since 1981. Tracer research in support of this DOE program has been conducted by the University of Utah Research Institute, Stanford University and the Idaho National Engineering Laboratory. Investigations include the development of high performance tracers, the analysis of tracer flow through fractures and the interpretation of tracer return profiles. The status of these research efforts and discussion of recent accomplishments is presented.

Use of common groundwater tracers in geothermal fluids is inappropriate because of high halide backgrounds or thermal instabilities.

Derivatized hydrocarbons are a class of tracers that appear to be suitable for geothermal applications. The derivatives chosen by UURI for liquid-phase tracing were aromatic hydrocarbons with moieties of trifluoromethyls, sulfonates, methyls, fluorides or carboxyls. The derivatives chosen for gas-phase tracing were the perfluorinated alkanes. The tests for the liquid tracers consisted of heating the compounds in distilled water under nitrogen or oxygen at temperatures ranging from 125° to 300°C. At 200°C, 24 of the 39 liquid-tracer candidates survived for one week; at 250°C, 15 survived. The most stable compounds were the sulfonates, methylates and carboxylates. The perfluorinated liquid-phase tracers decayed completely at all temperatures tested.

The UURI gas-phase tracer research has proceeded through the phases of initial experimental design and tracer candidate selection to some initial hydrothermal tests. The perfluorinated short-chain alkanes have been chosen for the initial tests. This testing is currently underway.

Interpretation of tracer return profiles can indicate the speed of movement of the injected fluids through the reservoir and preferential flow between specific injection and production wells. Analysis of tracer transport is complicated by the fractured nature of many geothermal reservoirs. Standard reservoir engineering techniques can be used to evaluate pressure distributions and the effects of production and injection on a reservoir scale. However, the flow of injected fluids through high mobility channels in a reservoir and the evaluation of heat transfer and geochemical interactions along these channels requires more detailed investigation.

Several models have been developed at Stanford specifically to interpret geothermal tracer tests in fractured reservoirs. These models have been verified by experimental tracer tests conducted with core samples. The benefit of these tests is that the experiements can be closely controlled and reservoir parameters can be measured directly. Tests with unfractured core samples were used to confirm the reliability of laboratory procedures, data collection, and data analysis methods. Fractured core tests were designed to emulate geothermal reservoirs like Wairakei in which matrix permeability is responsible for only a small percentage of the total flow. The results of these tests were quite different from the unfractured core tests. The similarity between the laboratory results and tracer test data from Wairakei indicate that the experiments appropriately represent field conditions. Use of the Matrix Diffusion model was found to provide a very accurate match of the measured tracer data.

One of the objectives of the Stanford experiments was to verify the ability of tracer models to estimate fracture aperture. The aperture estimates were compared to physical observations of the fracture cast. Differences between the observed mean aperture of the core and the estimated apertures are due to the models' assumption that a uniform fracture aperture exists throughout the core and to tracer adsorption at low flow rates.

Recent studies at INEL on the nature of flow and tracer transport through fractured media have made simulation of complexly fractured reservoirs feasible. Two techniques have been developed as the basis for these investigations: dual

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permeability modelling and fluid front tracking. The dual permeability model, FRACSL, allows simulation of flow, tracer transport and heat transfer in discrete fractures and the permeable reservoir matrix. Particle tracking allows the fluid/tracer front to be tracked, in addition to the pressure front in a reservoir.

Laboratory model studies of fractures and matrix systems have been used by INEL to identify the important physical processes which affect fluid and tracer flow. These studies have also been used to validate numerical simulation techniques and to conduct sensitivity studies. The relationship of thermal breakthrough forecasts to detailed fracture system characteristics and to the interaction of fluid and tracers between fractures and the matrix has been investigated. Critical elements of fracture flow and tracer transport have been identified and incorporated into numerical models. Good agreement between tracer transport in a complex fractured reservoir and dual permeability simulations has been achieved. The relationship between the rate of advance of the thermal front and channeling in a reservoir has been demonstrated.

## INTRODUCTION

Reinjection of field and power station waste hot water is the most important problem facing the geothermal reservoir engineer. Reinjection is necessary in all but a few geothermal developments as a means of waste water disposal. Geothermal wells in liquid-dominated geothermal fields produce a mixture of steam and water under turbine inlet conditions, and the water must be separated and disposed of since only steam is useful in the turbine. Vapor-dominated reservoirs produce no water at the wellhead, and therefore have only power-station condensate to dispose of. Geothermal water can rarely be discharged into surface water conduits, since it is at high temperature and also contains dissolved materials (principally silica but frequently trace amounts of dangerous heavy metals, such as arsenic and mercury). The thermal and chemical pollution resulting from surface discharge would be unacceptable in most cases. Power-station condensate is practically free of chemical pollutants but is still above ambient temperature.

At the present time reinjection is the most readily available alternative to surface disposal. Despite its widespread use in the geothermally-generated electric power industry, reinjection is still subject to some serious engineering difficulties. These problems have become evident as the geothermal industry has accumulated reinjection experience in an increasing number of fields. However, the seriousness of these difficulties has only been fully appreciated since the early 1980s.

Reinjection may also be useful as a means of providing pressure maintenance and enhancing recovery by extracting heat left in the reservoir. Improvements in productivity as a result of reinjection have, for example, been observed at Otake (Kubota and Aosaki, 1975). Unfortunately reinjection can also have detrimental effects. As the thermal energy in the rocks along the reinjection path becomes depleted, the enthalpy of the water arriving at the production wells can drop. Such possible production losses are the most serious problem associated with injection. In highly fractured reservoirs this phenomenon can happen quite early in the life of the power-station, and is therefore a cause for serious concern. Unfortunately, many geothermal fields are in highly faulted and fractured volcanic rocks, and reinjected water moves through the formations with astonishing rapidity, sometimes in a matter of only a few hours. Such rapid reinjection performance was hitherto unexpected. As a result, several geothermal fields have experienced a loss in production due to thermal interference caused by reinjection (Horne, 1982). The problem faced by the reservoir engineer is to quantify the probable interference potential in a particular field and design a development scheme accordingly.

Tracers are particularly useful for the recognition and analysis of the rapid transport of reinjected fluid through fractures. When reinjection first begins, the reinjected water (carrying the tracers) is reheated by the time it reaches the production wells. Thus the arrival of a tracer front precedes the arrival of the subsequent thermal front, and is therefore a useful forecasting tool.

When the reinjection technology research program was initiated by the U.S. Department of Energy in 1981, there was comparatively little experience in the use of tracers in fractured reservoirs. There was also only a small amount of experience in the use of tracers in the high temperature geothermal environment. This paper summarizes progress to date in three areas of research associated with the use of tracers in fractured geothermal reservoirs. These three areas are: the development of more reliable, higher detectability tracers for high temperature geothermal use; the mechanisms of tracer flow through fractures and fracture junctions; the interpretation of tracer return profiles.

## TRACER DEVELOPMENT
(University of Utah Research Institute)

The tracers currently in use in high-temperature environments fall into three major categories: 1) radioactive isotopes; 2) salts of iodide, bromide, and chloride; and 3) organic dyes. Each of these classes of tracers has significant limitations. Radioactive isotope tracers such as $^{3}H$ and $^{36}Cl$ must not be used because they are natural-process tracers and will confuse interpretation of the unexploited state of the system. In addition, the half-life of the tracer must be chosen such that errors from decay corrections are not large. Furthermore, because of the toxicity of the radioactive tracers special precautions must be taken in their use. Iodide-131, despite being one of the more toxic radionuclides, has been used in the injection tests at the Wairakei and Broadlands geothermal fields. The salt tracers are limited by the high halide background in many geothermal systems, and must be used in large quantities for adequate tracer detection. High concentrations of salt increase the density of the injected solution, rendering interpretation of the results more difficult.

An additional limitation of all the commonly used tracers is their lack of diversity, which restricts the number of wells that can be individually monitored in a producing field. Thus, in geothermal fields where many injection wells are in use, it is not yet possible to trace simultaneously the movement of fluid from all of the injection wells. Sequential tests using the same tracers run the risk of contaminating the reservoir with the tracers, which lowers the credibility of any interpretation.

Hydrocarbons and their derivatives are a new class of tracers now being tested that may meet all of the requirements of the ideal tracer, including the requirement of diversity. The hydrocarbons that were selected for testing are variations of aryl acids, or short-chain organic acids attached to a form of benzene. These compounds have been tested or used as groundwater tracers because they possess many of the characteristics of ideal tracers. They are negative ions at the pHs observed in natural waters and are therefore expected to be non-sorbing. They are low in toxicity, especially at trace concentrations, and are available as a large suite of similar species.

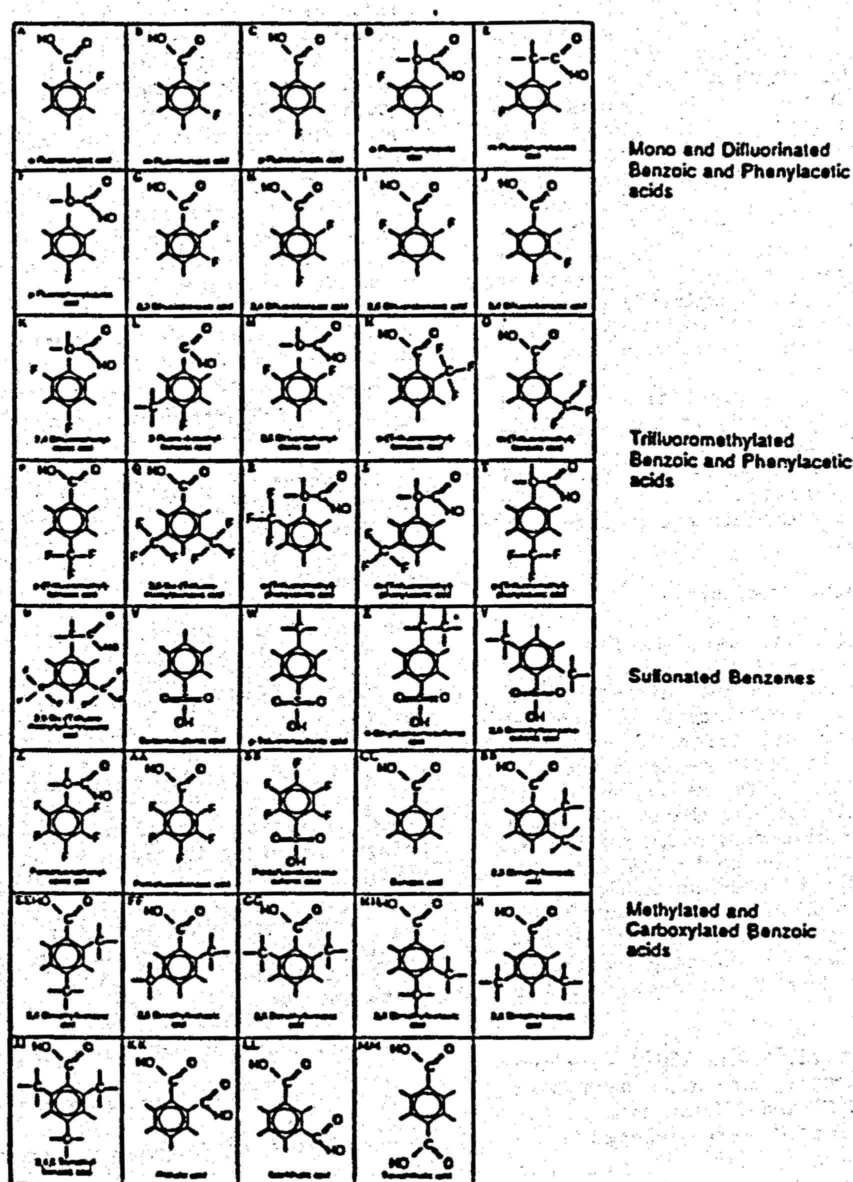


FIGURE 1
Chemical names and structures of hydrocarbon derivatives being tested.

## Tracer Selection

At the inception of our program, relatively little was known about the high-temperature behavior of derivatized hydrocarbons or of the organic dyes, fluorescein and rhodamine WT. Thus, the first step in our research program was to test a large number of compounds for simple thermal stability. The compounds selected for study can be divided into five groups on the basis of their compositions. The mono- and difluorinated benzoic and phenylactic acids (Fig. 1, A-M,) are resistant to bacterial decay and have been used as groundwater tracers. The degree of resistance is proportional to the amount of fluorine substitution. The trifluoromethylated benzoic and phenylacetic acids (Fig. 1, N-U) were selected because they are readily detectable using a high pressure liquid chromatograph (HPLC) and an electron capture detector. The sulfonated benzenes (Fig. 1, V-Y) are highly acidic and have a high molecular weight, which makes them the most soluble in the liquid phase. This makes them prime candidates as tracers for the liquid phase in two-phase reservoirs. The methylated and carboxylated benzoic acids (Fig. 1, CC-MM) while not as soluble as the other compounds were chosen for testing because they can be readily synthesized. The fifth group, (Fig. 1, Z-BB) are completely fluorinated analogues of the other groups. These compounds are completely protected from bacterial degradation and have been used in some harsh groundwater environments with success.

Tracers with high volatilities will be required for use in vapor-dominated systems. Potential gas tracers include the perfluorinated short-chain alkanes. Toward this end, perfluorinated methane was selected to calibrate the experimental techniques and equipment required for testing of gas tracers.

## Experimental Procedures

The experimental runs were designed to produce a rapid evaluation of the thermal stabilities of these compounds. In the initial set of experiments five groundwater tracers were tested at 125°C and 150°C to determine if any were thermally stable at even moderate temperatures. These were tested in the presence of an atmospheric as well as a nitrogen gas phase. Based on the success of these experiments, discussed below, 34 other compounds were added on to the next set of experiments, which were run at 250°C. The 250°C experiments were also run with an atmospheric or nitrogen gas phase. Subsequent experiments were run in the presence of only a nitrogen gas phase because of the rapid decay of the compounds in oxygen.

The experiments at 125°C and 150°C were run for one week each. Longer term runs have been performed at 200°C, 250°C, and 300°C. Five of the compounds initially selected were deleted from these experiments because it was felt that degradation products from their rapid decay were interfering with identification of the tracers during analysis. These compounds were the pentafluorobenzoic, pentafluorobenzenesulfonic, p-(trifluoromethyl)phenylacetic, 3,5-bis(trifluoromethyl)phenylacetic, and 2,6-difluorobenzoic acids.

Five experimental reaction vessels were put into operation during 1985. These vessels are housed at the University of Utah's Department of Metallurgy. One is capable of sustaining temperatures up to 350°C. The use of multiple reaction vessels makes it possible to perform experiments of relatively long duration on several different tracers or under different conditions simultaneously.

At the beginning of each experiment, 30 ml aliquots of the solutions containing the tracers are encapsulated in sealed quartz tubes. The solutions consisted of either distilled water or East Mesa geothermal brine, which has a total dissolved solids content of approximately 5000 ppm. The ampules are sealed in an oxymethane flame. Approximately two ml of the ampule are occupied by a gas phase during each experimental run. The gas phases used for these experiments are either pure nitrogen or ambient atmosphere (about 20 volume % oxygen). The solutions in the experimental runs with nitrogen as the gas phase are purged with nitrogen gas in the ampule for up to two hours. During sealing, the neck of the ampule is aspirated to prevent oxygen contamination from the oxymethane flame. Oxygen concentrations were measured for several solutions, and these averaged 6.9 ppm $O_2$ in the atmosphere-equilibrated solutions, and from .27 to .05 ppm in the nitrogen-equilibrated solutions, depending on the purge time.

Several experiments were run on the stability of fluorescein in the presence of altered rock. In these experiments, fluorescein was allowed to react with altered quartz diorite at 250°C for 112 hours. Rock/water weight ratios of 0.0, 0.07, 0.20, and 0.67 were used. The mineral assemblage consisted of quartz, illite, chlorite, and epidote. This assemblage is typical of a felsic intrusive rock subjected to hydrothermal alteration at 200°-250°C. Adsorbed oxygen was removed from the rocks prior to emersion in the tracer solution. This was accomplished by twice boiling the rock in distilled water under nitrogen until dry, and then adding the tracer solution. The tracer solution was also purged with nitrogen before and after it was added to the experimental vial.

Experimental work on gas tracers has required the fabrication of sample vials that can be filled and evacuated without atmospheric contamination. Sample vials that can be sealed under positive pressure and broken under vacuum have been designed and fabricated for this work.

## Analytic Methods

Analysis of hydrocarbon concentrations down to 20 ppb can be achieved by direct injection of up to 0.2 ml of sample into a high pressure liquid chromatograph. On-column enrichment techniques can be utilized to lower detection limits if needed (Stetzenbach et al., 1982). For high pressure liquid chromatograph analysis of the benzoic acids, the eluent buffer was prepared by adding sufficient phosphoric acid to reduce the pH to 1.9 with acetonitrile added in the 17-45% range. For analysis of benzenesulfonic acids, an ion-pairing reagent was added (tetrabutyl ammonium phosphate) and the pH adjusted to 6.0. A polymer-based column was used because it is more resistant to degradation than silica-based resins. Detection was by UV absorption at 200-205 nm. Fluorescein was analyzed using a colorimeter and a fluorometer for high and low concentrations, respectively.

Multiple determinations were performed on each sample to establish analytic errors. Standard deviations were calculated and ranged from 0.0 to 3.2%, averaging 0.94%. Recovery precision for these initial studies has tentatively been established at +/-15%, a standard precision for chromatographic techniques.

## Experimental Results

The experiments indicate that a large number of the organic compounds tested as tracers can be used in moderate to high temperature geothermal reservoirs. Of the 39 organic compounds tested, 24 have been shown to be stable for four weeks at 200°C and 15 for two weeks at 250°C. The number of compounds stable in each of the groups tested is shown in Table 1. The mechanisms responsible for the degradation of these tracers is discussed by Adams et al. (1986). The results of experiments conducted at 300°C are presently being interpreted. Our preliminary results indicate that only a few of the compounds tested are stable at these temperatures and that additional research will be needed to develop tracers for use at 300°C.

*Stable Compounds*

| Group | 200°C, 4 Weeks | 250°C, 1 Week |
|---|---|---|
| Methylated and Carboxylated Benzoic Acids | 11 | 8 |
| Benzenesulfonic Acids | 4 | 4 |
| Fluorobenzoic Acids | 4 | 2 |
| Trifluoromethyl-benzoic Acids | 2 | 0 |
| Fluorophenylacetic Acids | 2 | 0 |
| Perfluorinated Acids | 0 | 0 |
| Fluorescein | 1 | 1 |
| TOTAL | 24 | 15 |

TABLE 1

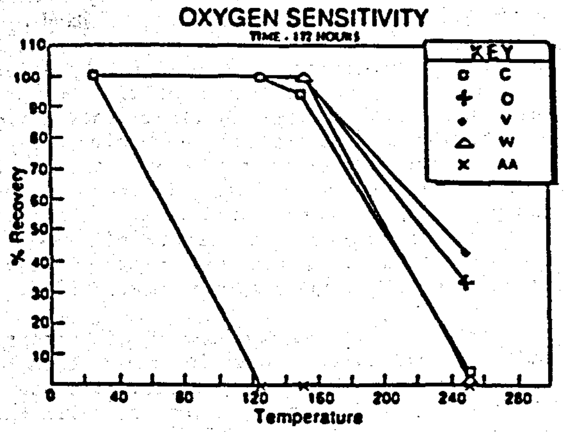


FIGURE 2

Recovery vs. temperature for five hydrocarbon derivatives in the presence of atmospheric oxygen. See Figure 1 for chemical names.

Significantly, all of the compounds tested showed high rates of reaction in the presence of molecular oxygen. Figure 2 shows the concentrations of five representative compounds after being heated in the presence of atmospheric oxygen for approximately one week. It is obvious from this figure that the concentration of oxygen in the injected fluid will have to be considered in any field tracer test over 150°C. To our knowledge, however, all injection processes attempt to exclude oxygen in order to avoid precipitation and to protect the well casing.

The recovery ratios for fluorescein in experiments with quartz-diorite ranged from 0.89 to 0.86. These recovery ratios are identical to those obtained in control experiments that did not involve rock. The 10% loss is thought to result from residual oxygen in the autoclave equipment. These experiments indicate that adsorption at high temperatures is not a significant factor in controlling the behavior of fluorescein.

Fluorescein was also tested at 300°C. At this temperature fluorescein decays rapidly with a half-life of approximately one day. Analysis of the data indicates that the reaction is first order with respect to fluorescein. The decay rate was not affected by the presence of quartz diorite.

## Planned Research

The research we have conducted to date has clearly demonstrated the potential of derivatized hydrocarbons as geothermal tracers in low-salinity geothermal fluids. While a large number of compounds appear to be stable up to temperatures of 250°C, and are thus suitable for most geothermal systems, additional experimentation is required to develop tracers for use in higher-temperature environments. The testing of additional tracers will be initiated after analysis of the recently conducted experiments is completed.

Although low- to moderate-salinity brines do not appear to affect the stability of the hydrocarbons, preliminary data suggest that the analysis of the tracers may be adversely affected by hypersaline brines typical of the Salton Sea geothermal field. Laboratory experiments designed to establish these effects are planned. In addition, the effects of rock-tracer interactions require evaluation. Loss of tracer due to adsorption is not anticipated to be significant, but must be tested. A variety of rock types commonly found in geothermal systems will be tested to document any possible interactions.

Field testing and development of appropriate handling, preservation, and injection techniques for the liquid tracers are required. Because most of the fluorinated tracers, which are resistant to bacterial degradation, did not prove to be stable in the geothermal environment, biodegradation of the tracers between the sampling point and the laboratory may be a problem. Potential preservation techniques include the addition of acid, base, or bactericides. The suitability of these methods requires investigation.

The perfluorinated short-chain alkanes hold particular promise as gas-phase tracers. Additional experiments are required to establish the stability of these tracers to temperatures of at least 250°C.

The development of tracers that will partition into both the liquid and vapor phase is required for two-phase geothermal systems. Thermodynamic data on liquid-vapor distribution coefficients of organic compounds at geothermal temperatures is lacking. Suitable experimental techniques remain to be developed and tested before the necessary data can be obtained.

All of the liquid hydrocarbon compounds being investigated are well suited for on-site analysis using standard techniques on a high pressure liquid chromatograph. Appropriate sampling methods for high-temperature fluids must still be developed. Additional rapid and simple methods designed to screen for the presence of hydrocarbon tracers also require investigation.

## ANALYSIS OF FLOW IN FRACTURES
(Stanford University)

In order to quantitatively interpret tracer tests, a reservoir flow model is required to model the mechanisms controlling tracer transport. Due to the extensive fracturing occuring in many geothermal reservoirs, conventional convection/dispersion models for flow in uniform porous media were not considered applicable. Field test results were also far different than those seen before in more uniformly porous reservoirs. These test results confirmed the need for a model which considers the extreme contrast between fracture and matrix properties in these reservoirs.

In response to this need, several models have been developed at Stanford specifically to interpret these tracer tests. Generally, these models relate the test response to fracture aperture and tracer dispersivity. However, some of the model parameters are difficult to measure and when matching field tests, the accuracy in predicting reservoir properties cannot be verified. This uncertainty turns out to be critical in any further quantitative predictions. For example, thermal breakthrough calculations are extremely sensitive to the fracture width used in forecast models. This indicates the importance of assessing the models accuracy in estimating fracture properties.

To validate the accuracy of the tracer model, a test must be conducted where reservoir characteristics are known precisely. The heterogeneity and uncertainty found in nature makes field scale verification of the tracer flow models impractical. However, the models can be verified by experimental tracer tests conducted in a closely controlled laboratory environment where reservoir parameters can be directly measured on the core sample. Flow models verified in this way can then be applied to interpret field tests, generating reliable reservoir property estimates for use in thermal breakthrough calculations.

Thus, the objectives of the work carried out were divided into five tasks, namely; (1) Develop experimental techniques to simulate field tracer tests in a laboratory environment, (2) Conduct tracer tests on fractured cores, (3) Analyze test results with analytical models to evaluate the models ability to match experimental results, (4) Measure core properties and compare with model estimates from model match parameters, and (5) Modify existing models and/or propose new ones to accurately estimate core properties from tracer test results.

Several experiments with an unfractured core were conducted first. The unfractured core tracer response is well known and thus it served as a test of the experimental procedures and tracer detection techniques employed. The tests also provided an estimate of rock permeability to distilled water when fully saturated with water and a method of determining the tubing volume between the measurement electrodes. After evaluating the testing procedures using the unfractured samples, fractured cores were tested next. The fractured core tracer response, which is not as well known as the response of unfractured samples, could then be determined with confidence. Potassium iodide was used as the tracer in these tests.

### Unfractured Core Samples

The unfractured core tests were conducted with the original distilled water pump and pressurized tracer vessel which Pulskamp (1985) had used. The core permeability was calculated from Darcy's law, where

$$k = 14.7 \frac{q}{A} \frac{L}{p_i - p_o} \qquad (1)$$

where

$$k = \text{core permeability} \quad \text{darcy's}$$

$$q = \text{flowrate} \quad \frac{cm^3}{sec}$$

$$A = \text{core cross sectional area} \quad cm^2$$

$$L = \text{core length} \quad cm$$

$$p_i = \text{core inlet pressure} \quad psia$$

$$p_e = \text{core exit pressure} \quad psia$$

Average permeability was found to be 13 md with good agreement between all the cases. The equivalent slug test responses for four of these cases are plotted in Figure 3. The data is plotted on a pore volume basis to allow for a direct comparison of results on a dimensionless time scale. As the plots show, the curves are almost symmetrical and effectively collapse to one curve indicating that the response is independent of flow velocity. In this plot the symmetrical tracer concentration profile reflects a common property of dispersion often found for uniform porous media. This property is reflected in the dimensionless dispersion coefficient, the Peclet number.

The Peclet number is defined as

$$P_e = \frac{D_p}{u\,l} \qquad (2)$$

where

$$P_e = \text{dimensionless Peclet number}$$

$$D_p = \text{porous media dispersion coefficient} \quad \frac{cm^2}{sec}$$

$$u = \text{flow velocity} \quad \frac{cm}{sec}$$

$$L = \text{flow length} \quad cm$$

It has generally been observed for porous media that the medium dispersion coefficient increases linearly with flow velocity and can be calculated ignoring molecular diffusion effects. Thus, the ratio of the dispersion coefficient to the flow velocity, termed the medium dispersivity, is a constant for a uniform porous medium. This constant media dispersivity has been observed to remove flow velocity as a system variable when test results are displayed in dimensionless form. The experimental data from this study exhibits this property and therefore agrees with these observations. This result is a good indication that the laboratory procedures, data collection and data analysis methods used are reliable.

The unfractured test results were further examined to obtain a direct measurement of the tubing volume between the inlet and outlet electrodes. The slug response in Figure 3 should reach a peak value at a pore volume of one. The volume used in generating these plots, corresponding to both pore and tubing volume, can be treated as a variable to adjust the x-axis. By shifting this curve slightly to the right, the correct combined core and tubing volume can be estimated as 13.6 cc. The 11 cc core pore volume is then subtracted from the 13.6 cc used to shift the test data so the peak coincides with a pore volume of one. This leaves 2.6 cc for the tubing volume

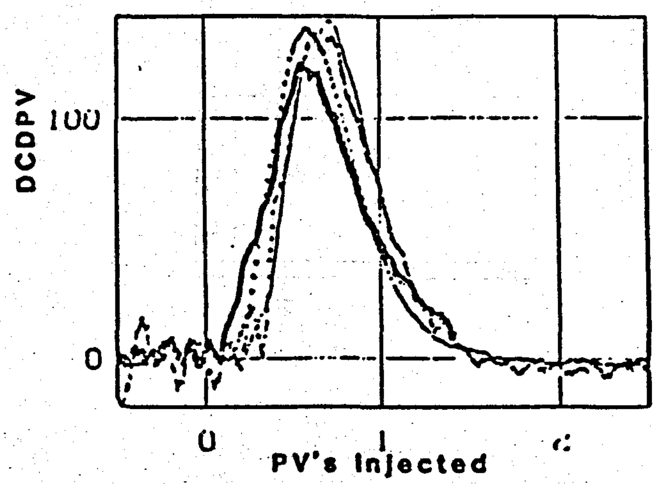


FIGURE 3

Pore volume plots for unfractured core tests. (-)=3 cc/min (+)=4 cc/min (*)=7.6 cc/min (#)=0.5 cc/min

which agrees well with calculations made from equipment drawings.

## Fractured Core Tests

The initial fractured core tests were conducted with an 80-100 mesh sand as a fracture proppant. The volume of proppant was deliberately kept as small as possible to minimize any flow restrictions within the fracture. Unfortunately this proppant was only partially effective in keeping the fracture open. The equivalent slug test response for this core (Figure 4) shows the response indicative of two flow paths.

This is probably the separate response of the fracture and core matrix. A total flow rate of 4.5 ml/min was measured at a 185 psi pressure drop. This indicates that the total core permeability has been enhanced from 13 to only 20 md. Matrix flow at this pressure drop is calculated to be 3.0 cc/min leaving 1.5 cc/min as fracture flow. This degree of matrix flow agrees with the two peak concentration profile where the low storage fracture responds first and the matrix later. Although these results are interesting, the core is obviously not representative of flow in most geothermal reservoirs. For example, at Wairakei matrix permeability is responsible for only a small percentage of total flow directly into wells and fractures are the dominant flow corridors. This type of system could be better emulated if the fracture size (and thus permeability) were increased substantially so the flow through the core matrix is negligible.

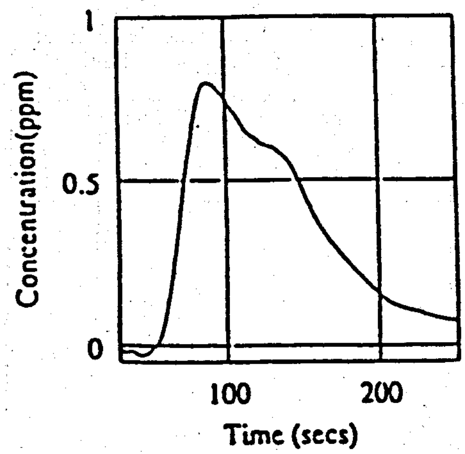


FIGURE 4

First fractured core test with
both fracture and matrix response.

To increase the fracture width, a 20-40 mesh sand was chosen as proppant and inserted liberally in a new fractured core sample. Only one layer of proppant was inserted into the fracture as two layers would be unstable under overburden pressure. The initial flow tests using this new core indicated that the larger proppant was effective. The fracture totally dominated the flow through the core and calculated average permeability increased to 7800 md. Matrix flow was estimated at only 0.1% of the total flow. The tracer response profiles later confirmed the lack of matrix flow as no secondary matrix pulse was seen in the core effluent tracer concentration curves. This sample was subsequently used in all fractured core tests.

As examples of the tracer concentration data handling procedures, the entire suite of tracer profiles generated for the 3.7 cc/min test are shown in Figures 5 through 10. This includes the actual measured voltage data, the corresponding tracer concentration profiles and also the equivalent slug test response. The voltage responses measured during the step change injection tests for both the "step up" and "step down" tests are in Figures 5 and 8, respectively. The "step up" refers to the stabilized flow of distilled water as the background fluid followed by a switch to tracer solution. This case is representative of a continuous injection test in an actual reservoir. The "step down" is the reverse case resulting when flow of tracer as the background fluid is followed by a change back to distilled water. The voltage data of Figures 5 and 8 was then used to convert to tracer concentration generating Figures 6 and 9. These tracer concentrations are in response to continuous tracer injection and they were differentiated to yield the equivalent slug test responses shown in Figures 7 and 10. This entire series of plots was generated for each test, however they are not all shown here in the interest of brevity.

In general, the resolution of the data was good. Repeat tests were conducted at similar flowrates and near identical results were observed, indicating the repeatability of the test. Test reversibility was evaluated by comparing the step up and step down data in Figures 5 through 10. Although the curve shape and peak values are similar, the plots are not mirror images of each other. This suggests some hysteresis in the tracer transport mechanism. However, the remainder of the analyses in this report centered on the reservoir equivalent slug test data (the "step up" slug tests) and the reverse test results are left as a subject for further study.

The results of the fractured core slug tests are significantly different than those obtained on the unfractured core. The slug test response, the highest resolution plot, shows a great degree of asymmetry, similar to the field results observed in Wairakei. These responses show the same early steep rise and late time "tails" characteristic of the field test responses. The similarity between the laboratory and field test results indicates that the experimental geometry adequately emulates reservoir conditions. It was therefore considered justifiable to begin quantitative analysis of the experimental results.

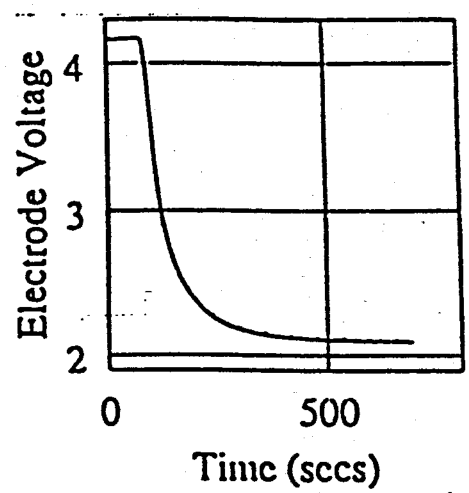


FIGURE 5
Voltage profile for step up at 3.7 ml/min.

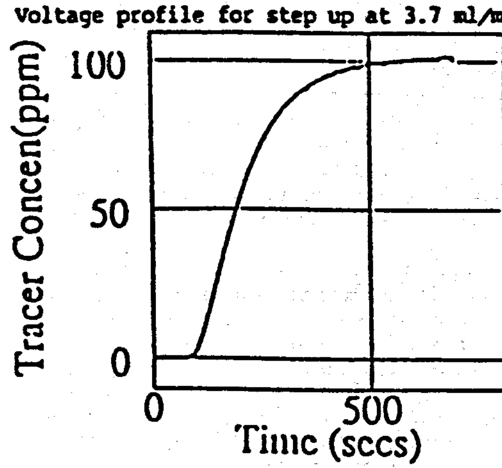


FIGURE 6
Concentration profile for step up at 3.7 ml/min.

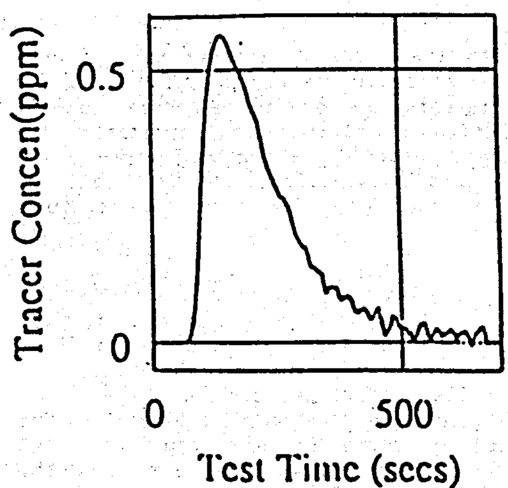


FIGURE 7
Equivalent slug test for step up at 3.7 ml/min

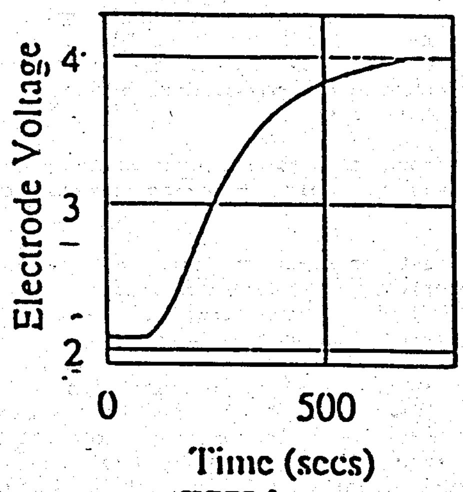


FIGURE 8
Voltage profile for step down at 3.7 ml/min.

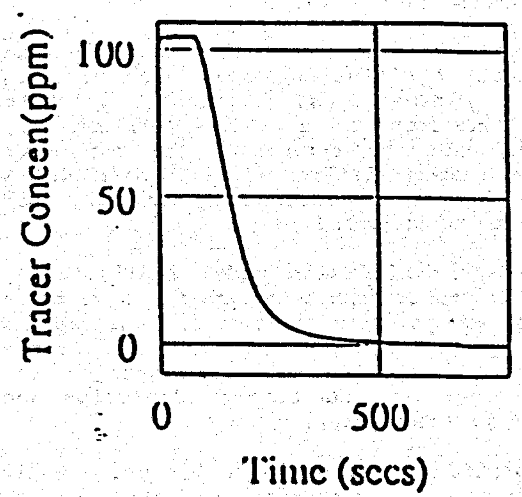


FIGURE 9
Concentration profile for step down at 3.7 ml/min.

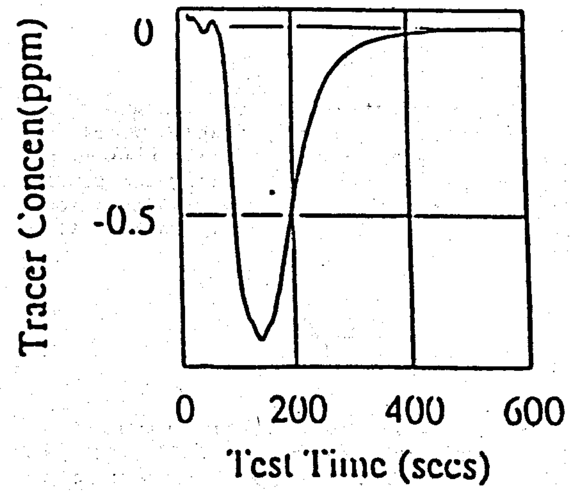


FIGURE 10
Equivalent slug test for step down at 3.7 ml/min.

Before any further analysis of the data was possible, it was necessary to adjust the time datum of the measured response to reflect the actual time of tracer entry into the core. It is important to note the time scale for Figures 5 through 10 reflects the start of the data collection clock and it is NOT time measured from when the tracer entered the core. Thus, a shift of time datum by 20-200 seconds was required depending on the flow rate. This time datum correction was estimated using the inlet electrode response as follows:

$$t_{dc} = t_{ie} + \frac{V_t}{q} \tag{3}$$

where

$t_{dc}$ = calculated time datum correction secs

$t_{ie}$ = measured inlet electrode first tracer arrival time secs

$V_t$ = tubing volume between electrodes $cm^3$

$q$ = flowrate $\frac{cm^3}{sec}$

This time datum correction was then subtracted from the measured times correcting the plots to a true time scale.

$$t_a = t_{oe} - t_{dc} \tag{4}$$

where

$t_a$ = actual test time relative tracer entry into the core secs

$t_{oe}$ = measured clock time at outlet electrode secs

These shifted plots were later used for developing pore volume plots and in model analyses. In fact, model analyses were found to be sensitive to the actual test start time and the shift parameter was often used as a system variable.

## Results

One of the objectives of the study was to verify the accuracy of the tracer model in estimating fracture aperture. Three estimates of the fracture aperture were made during the course of this work. Fracture permeability calculations were made using the following cubic fracture flow equation:

$$q = \frac{W^3}{12} \frac{p_i - p_o}{L} \quad (5)$$

The results of these calculations provided an estimate of the fracture aperture (0.012 cm). An estimate of the fracture aperture was also available from physical observations of the fracture cast. The fracture cast, created with epoxy resin, indicated a mean aperture of 0.08 cm. Finally, the tracer model match parameters were used to obtain two fracture aperture estimates. Fracture aperture estimated from the breakthrough time was 0.025 cm, with an 85% standard deviation. Using both match parameters, an average aperture of 0.047 cm with a 45 % standard deviation in the data was calculated. The differences between the estimates and the variation in the tracer model estimates can be explained by comparing the physical conditions of the tests to the assumptions inherent in the models used to evaluate the fracture aperture.

The aperture estimate determined using flow rate and pressure drop measurements in the cubic fracture aperture equation assumes that a uniform fracture exists throughout the core. In reality, proppant within the fracture creates substantial restrictions impeding flow. It is not surprising, then, that a lower value is predicted using this simple equation. The equation could be adjusted to account for the fracture proppant by modifying the flow area to reflect this flow restriction. This roughly works out to a 25% increase in fracture aperture for a 50% reduction in flow area. Using this order of magnitude approximation and the visual observation that as much as 80-90% of the fracture area is blocked by sand grains in the epoxy cast, a fracture aperture on the order of 0.05 cm is more likely. Another unknown, influencing the fracture permeability estimate of fracture aperture, is the pressure drop in the laboratory flow system. The low pressure drops across the fracture were not initially anticipated and the 0.2 to 0.5 psi head losses in the flow system were considered negligible. In retrospect, this factor would lower the actual pressure drop occurring within the core, increasing the aperture estimate by as much as 50%. The actual pressure drop is, however, difficult to quantify due to the complex mixing heads used in the core holder. For this reason, a quantitative impact of flow system head losses is not possible.

The fracture aperture indicated by the epoxy is probably a good estimate of the true fracture aperture. The low standard deviation of the measured values suggests little error in the measurements. However, the error in this estimate is not due to the physical measurement system. The main uncertainty is whether the fracture cast actually represents the overburden core conditions, or, if the fracture cast indicates the aperture once released from overburden pressure. Considering this possibility, the core cast is most likely a good upper bound on the fracture aperture.

The fracture aperture estimate from the tracer flow model is the main reason for this study. The errors apparent when using the first breakthrough time alone to estimate fracture aperture actually are responsible for the majority of the uncertainty in the model estimates. The variation in apertures arising from both match parameters is really not that extreme and the range of estimates is well within the magnitude of the average value. Reviewing the uncertain adsorption characteristics observed at the lower flowrates suggests a greater weight be given the higher rate cases. This result would suggest the aperture is roughly 0.045 to 0.08 cm, which agrees extremely well with the physical observations made with the fracture cast.

Based upon the experience gained in the study, it was possible to reach several conclusions:

1) Tracer tests on fractured cores were conducted in the laboratory resulting in tracer response profiles similar to those observed in fractured geothermal reservoirs such as Wairakei.

2) Laboratory tracer tests were analyzed with two analytical flow models. The Taylor Dispersion model was found to be inappropriate for matching the data even after adjusting the model for experimental conditions. The Matrix Diffusion model was found to match the test data reasonably and, once modified for the tracer dispersion in the inlet of the equipment, gave a very accurate match of the measured data.

3) Parameters arising from the match of the data to the Matrix Diffusion model were used to estimate core properties. Estimated fracture apertures were found to be 0.025 - 0.05 cm which, agrees well with other estimates. The tracer/rock adsorption characteristics were also defined. A value of 20 for the dimensionless partition coefficient was estimated.

4) The Matrix Diffusion model realistically reflects tracer transport mechanisms in fracture dominated, low porosity reservoirs. The model's parameters can be used to provide reliable estimates of reservoir properties such as the fracture aperture and tracer adsorption and diffusion characteristics.

5) Adsorption effects, even for very weakly sorbing tracers, are significant and these effects should be included in fracture aperture estimates.

6) Further studies of the reverse tracer tests should be conducted to gain valuable insight

into the diffusion/adsorption of tracer in field slug tests.

7) Future tests in laboratory samples should use a longer core length (50-60 cm) to minimize the effects of tracer mixing prior to entering the core. Samples of lower matrix porosity and permeability will be more representative of flow rates, pressure drops, and fracture widths observed in the field.

8) Tracer test models which can provide a unique fracture estimate in field tests should be used to model the laboratory tests from this study. The uncertainty in the effects of diffusion and adsorption effects on tracer transport could thus be eliminated.

9) Until a proven model which eliminates diffusion and adsorption is available, the Matrix Diffusion can be used to give a good estimate of fracture aperture. When estimating the fracture width, reservoir adsorption properties should be considered due to the strong coupling of these two terms in the model solution.

MECHANISMS OF TRACER FLOW IN FRACTURED RESERVOIRS
(Idaho National Engineering Laboratory)

In geothermal reservoirs which are highly fractured, or which have significant matrix as well as fracture permeability, the transport of injected fluids is influenced by interactions between fractures and between fractures and the matrix. Heat transfer in a reservoir is a function, in part, of the thermal conductivity of the rock, the surface area contacted by the fluids, the temperature gradient and the fluid mass flux. While a few large fractures may be the primary controlling factors in fluid flow in a reservoir, secondary fractures and a permeable matrix can represent a much greater surface area for heat transfer and rock-water interactions. Highly fractured or porous reservoirs may also support convective as well as conductive heat transfer. Thus, a realistic interpretation of tracer transport data and forecasts of thermal breakthrough must account for reservoir complexity.

Researchers at the Idaho National Engineering Laboratory (INEL) have been investigating the significance of fracture systems and the influence of the matrix in fluid migration, tracer transport and heat transfer. This research has been based on an integration of analytical, laboratory, numerical and field studies. Physical model tests in the laboratory have proven particularly useful in studying detailed transport mechanisms. The tests have permitted validation of numerical codes under controlled conditions where the basic reservoir parameters can be defined.

The emphasis of the INEL research program is on reservoirs where both fractures and the matrix play roles in flow distribution and tracer transport. The basic dual permeability numerical simulation approach is an improvement on homogeneous porous matrix approximations and discrete fracture representations. Porous matrix approximations require that the system be sufficiently large that the effects of individual fractures cannot be distinguished. Discrete representations provide substantial detail about individual fractures, but due to computational limitations are restricted to sparsely fractured reservoirs. In the dual permeability approach to reservoir-scale simulations, primary fractures are modeled discretely and secondary fractures and the matrix are modeled using representative elements. Representative elements provide the basis for simulating the effect of fracture and matrix permeability. Hydraulic and transport characteristics of each element are determined from stochastic analyses of physical parameters. Unlike equivalent porous media models, homogeneity of the representative elements is not required. The use of representative elements in dual permeability models has proven to be a powerful tool in modelling complex reservoirs and significantly reduces the cost and complexity of large-scale simulations (Clemo, 1985). The dual permeability approach allows evaluation of fractured reservoirs which cannot be effectively represented by a porous media approximation (Hull and Clemo, in press). The influence of smaller fractures and fracture-matrix interactions on tracer return, and on heat transfer and rock-water interactions in the reservoir, is preserved.

A series of physical models of fracture systems and dual permeability reservoirs have been used at INEL to study tracer transport mechanisms. The models for the fracture network studies consist of a set of orthogonal fractures oriented diagonally in non-porous or polyethylene. Constant head boundary conditions are maintained at the upstream and downstream ends of the model, with no-flow boundaries along the sides.

A common assumption in solute transport studies is that complete mixing of the solute occurs at fracture intersections. This assumption effectively decouples the tracer transport from the velocity profile in the fracture and the tracer front is assumed to move at the average speed of the fluid. An alternate approach bases tracer transport on streamline flow under laminar flow conditions, with no diffusion across streamlines.

A series of tracer tests was conducted in the laboratory using the fracture network model shown in Figure 11 to evaluate these assumptions and to validate transport algorithms contained in the dual permeability code, FRACSL. This code can be used to simulate transient and steady-state flow in porous, fractured and dual permeability reservoirs, the transport of conservative tracers, and advective transport between fractures and matrix. As such, the code provides a useful tool in studies of tracer transport in fractured reservoirs. FRACSL computes fracture and matrix flows using a common head distribution for both. Tracer dispersion is treated mechanistically, combining Poiseuille profile advection with transverse diffusion. Dispersion in the matrix is calculated using the random walk approach. The code employs a particle tracking routine in which individual particles, tagged with specific amounts of tracer, are driven by the flow distribution, dispersion and diffusion. This approach avoids the numerical problems which are inherent in direct solutions to the transport equation (Hull, et al., in press).

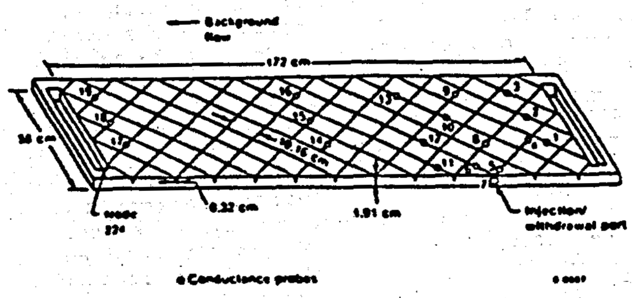


FIGURE 11
Fracture network physical model.

The FRACSL code was used to generate 2-D simulations for comparison to the fracture network tracer data under a range of flow assumptions. The best fit to the laboratory data is based on streamline transport with transverse mixing by diffusion, both in the fractures and in fracture junctions. Chi square values for the fit between measured and simulated data were 15.5, 3.6 and 80.3 for the respective cases of streamline flow, streamline with diffusion, and complete mixing (Miller and Hull, 1986).

Figure 12 shows predicted tracer breakthrough using the assumptions of streamline flow or complete mixing. These tracer profiles can be compared to the base case tracer return porfile in Figure 12 which represents the best fit to the laboratory data. It is evident that assuming streamline tracer transport through the fracture system is not warranted and results in underestimating dispersion and the time to tracer breakthrough. The laboratory test results show that diffusion in the fractures and in fracture junctions spreads the tracer laterally in the fracture system and tracer reaches points in the model which would not be possible under streamline flow alone. This lateral dispersion of the tracer retards migration through the reservoir, resulting in a broader tracer return profile.

The tracer return shown in Figure 12 for the assumption of complete mixing has a narrower profile than the base case. This profile indicates that, using this assumption, the injected tracer would move through the system as a plug. The dispersion which actually occurred in the laboratory tests is not represented. It is this dispersion that demonstrates more contact between the injected fluids and the formation, resulting in more heat transfer potential.

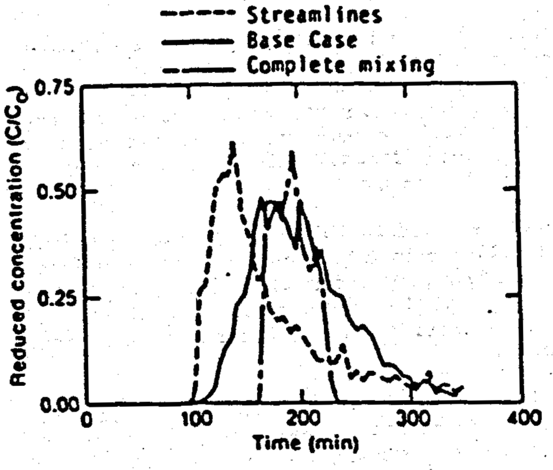


FIGURE 12

Tracer breakthrough profiles at node 224 in the fracture network model, comparing assumptions that (a) tracer follows streamlines with no mixing or (b) tracer travels at the average fluid speed in a fracture with complete mixing at fracture junctions, and (c) the base case of streamline flow with diffusion.

Complete mixing of tracer at fracture intersections is not warranted for all conditions, but will depend on the fracture system geometry and local flow rates in the reservoir (Hull, et al., in press). Although the laboratory data have demonstrated that little mixing occurs at fracture junctions under Darcy flow, in systems where the fracture velocities are low (low Peclet numbers) and diffusion dominates, advection can be reasonably simulated assuming complete mixing.

A dual permeability physical model, consisting of a fracture network in a porous polyethylene matrix, was used to study the interaction between fractures and the matrix and its influence on tracer transport. The test data were also used to validate specific tracer transport algorithms in FRACSL. Of particular interest was the algorithm which simulates advective and diffusive transport across the fracture-matrix interface. Some dead-end fractures were included in the physical model to emphasize this fracture matrix interaction. The fracture apertures were determined by matching computer simulations to head distributions from a series of hydraulic tests (Hull and Clemo, in press). In the tracer tests, tracer was injected into a matrix block with a background flow field across the model and withdrawn from a fracture near the downstream end of the model.

The tracer tests illustrated the influence of individual fractures in the reservoir and demonstrated significant fluid and tracer movement between fractures and the matrix. The correlation between simulated and measured pressure gradients in the model was, by design, excellent. The match between the spatial distribution of tracer in the physical model and the simulations was very good (Figure 13). Comparisons of the tracer breakthrough profile at two points in the model are shown in Figure 14. Some uncertainty in fracture apertures resulted in a less exact match to the laboratory profiles. Given the complexity of the model, the dual permeability features of the code which allow fracture-matrix transport did a good job of matching the laboratory data, indicating that the basic transport assumptions are appropriate. The results also illustrate that while the pressure response to injection was well-defined, it was not sufficient to analyze actual fluid movement in the system.

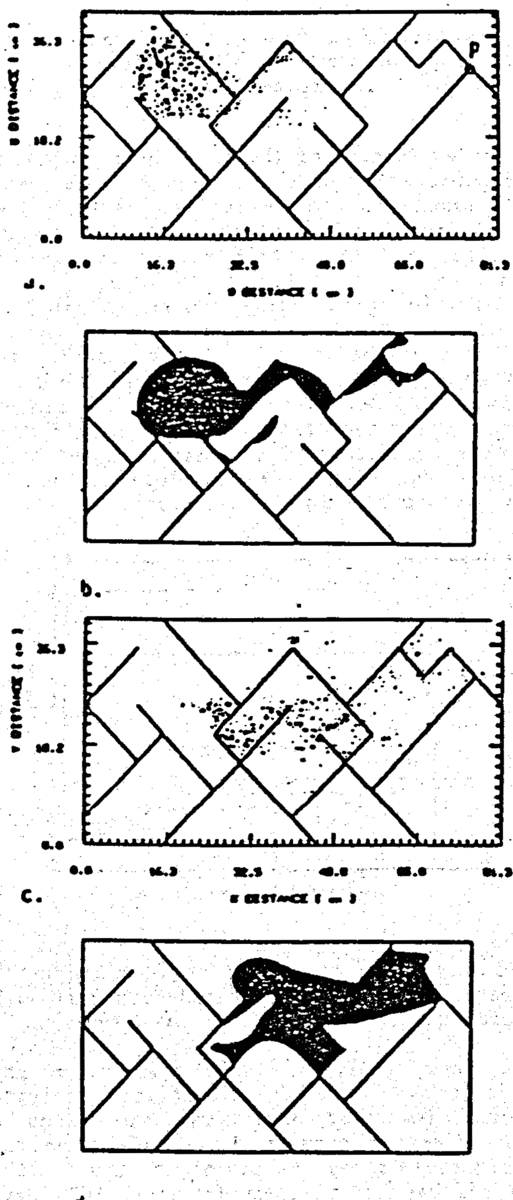

FIGURE 13
Comparison of simulated tracer dispersion (a,c) with dual permeability laboratory model observations (b,d) after 75 minutes and 270 minutes (plan view). Tracer injection ceased after 76 minutes.

Once the transport capability of FRACSL had been successfully validated, the code was used for a series of studies to assess the sensitivity of tracer/thermal breakthrough forecasts to simplifying assumptions commonly used in simulations of fracture systems (Hull and Clemo, 1987). The studies were based on a production and injection well doublet in a fractured, liquid-dominated reservoir. The wells were spaced 1200 m apart, with a 90-m injection interval. This base case reservoir consisted of 22 fractures, some of which connect both wells (Figure 15).

Tracer and thermal breakthrough for this complex fracture system were compared to simulations of hydraulically equivalent reservoirs in which progressively more of the smaller fractures in the reservoir were replaced by a porous media representation. In the extreme, the entire reservoir was simulated as an equivalent porous media. A single fracture connecting the two wells was also simulated. A correlation of the pressure profiles for each of the simulations indicates that incorporating a few of the dominant fractures is all that is required to achieve a good match to the pressure response in the reservoir (Hull and Clemo, 1987).

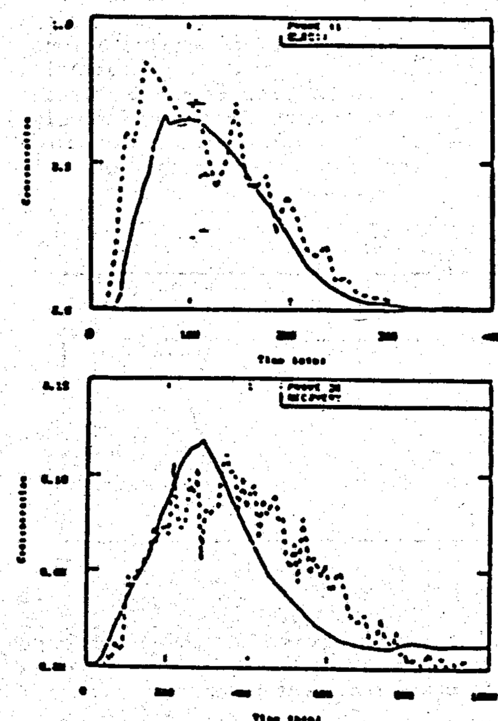

FIGURE 14
Comparison of predicted tracer breakthrough (dashed line) to tracer breakthrough measured in dual permeability laboratory studes (solid line).

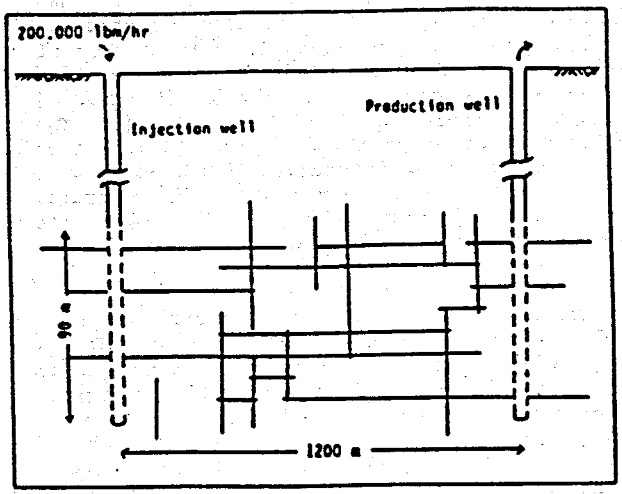


FIGURE 15
Fracture distribution between injection well and production well used as the base case for sensitivity studies.

Figure 16 shows a comparison of the tracer breakthrough curve for the base case reservoir to predicted tracer breakthrough using equivalent porous media and single fracture approximations. It can be seen that the method of representing permeability has a significant effect on tracer transport. Figure 17 demonstrates that including at least some of the dominant fractures in a simulation will provide a better forecast of

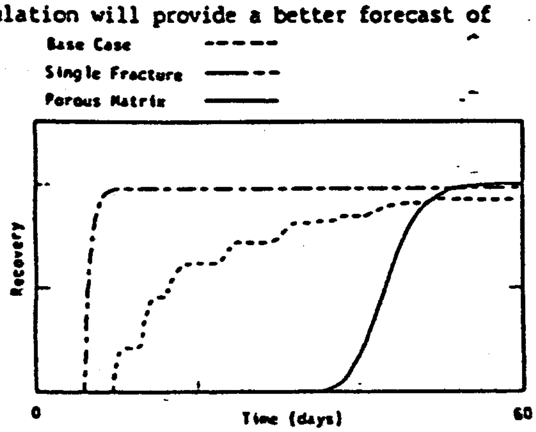


FIGURE 16
Tracer breakthrough curves for the base case fractured reservoir compared to the porous matrix and single fracture representations.

tracer breakthrough. It is critical, however, that the simulation still preserve the influence of smaller fractures and the matrix on heat transfer and rock-water interactions.

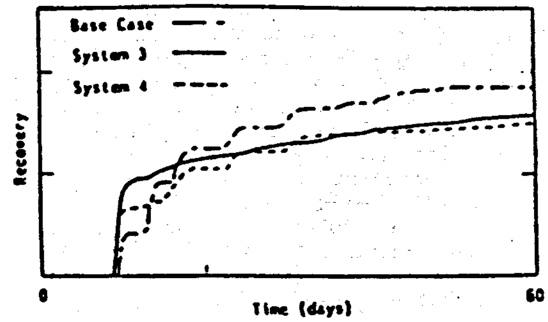


FIGURE 17
Tracer breakthrough curves for the base case fractured reservoir compared to systems where smaller fractures are replaced by representative matrix.

Further evaluation of the case where only the 10 most dominant fractures in the reservoir were explicitly simulated can be used to assess this effect. Figure 18 shows tracer distribution in the fractures and the matrix after 10 days of injection. Preferential migration paths are evident, both in the fracture system and in the matrix. The largest fractures are shown to transport much of the injected fluids and are the basis for much of the preferential migration into the matrix. Single fracture simulations cannot account for the retardation which occurs in the matrix, while equivalent porous matrix representations cannot represent the channeling due to fractures which occurs in the reservoir.

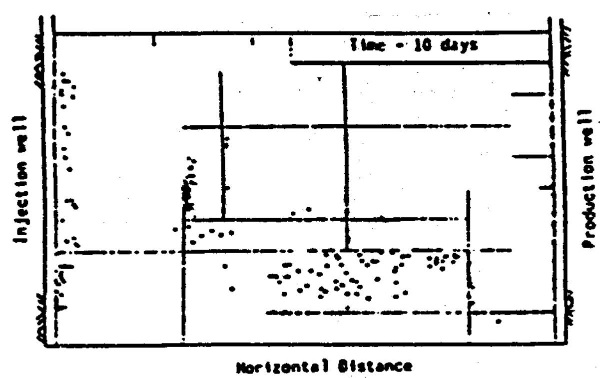


FIGURE 18
Spatial distribution of tracer between injection and production wells in a fractured reservoir with matrix permeability after 10 days in injection.

Preliminary analyses of the movement of the thermal front based on these simulations indicate the potential impact of simplifying assumptions on decisions affecting geothermal wellfield operations. Figure 19 shows the advance of the cooling front in the base case reservoir after 2000 days of injection. Figure 20 shows the predicted position of the thermal front if a single fracture connection is assumed between the wells. According to the prediction, thermal breakthrough has occurred. Well placement decisions based on this prediction would be conservative, possibly unreasonable so. In the porous media approximation, the thermal front advances very slowly between the wells and use of these results would greatly over estimate the time to thermal breakthrough period. A more realistic representation of a fractured reservoir can provide a more reasonable basis for analyzing tracer data and forecasting thermal breakthrough and would result in more efficient reservoir development.

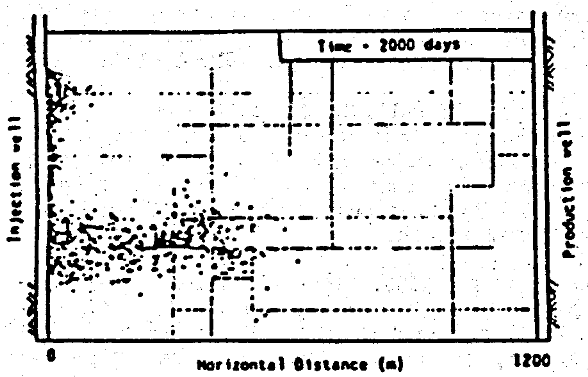


FIGURE 19
Extent of cooling between injection and production wells in the reservoir after 2000 days of injection.

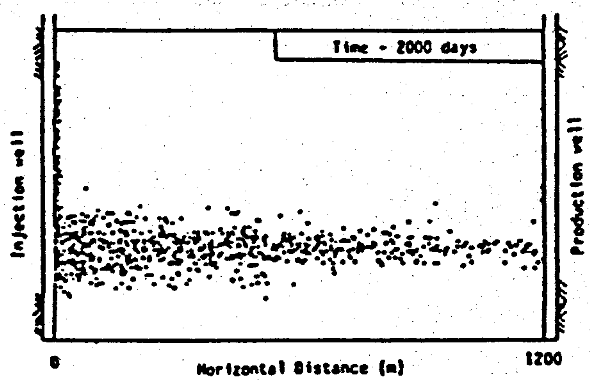


FIGURE 20
Predicted extent of cooling after 2000 days based on assuming a single fracture connection between the injection and production wells.

Future research at INEL is aimed at additional sensitivity studies of fracture location and the assumptions which form the basis for heat sweep models; the development of more streamlined and cost-effective reservoir simulation techniques; and the incorporation of kinetics-based rock-water chemical interactions in reservoir simulations. Field testing to verify application of these analytical techniques is planned. Publication of a 2-D version of the FRACSL reservoir code is planned for early 1988, in conjunction with cooperative analysis efforts with industry.

In conclusion, the study of tracer transport provides a basis for more realistic assessments of the effects of injection in complex fractured reservoirs. Much of the research at INEL has emphasized the influence of fractures and fracture-matrix interactions on the spatial and temporal distribution of a tracer in a reservoir, and on the shape of the tracer return profiles. With this basic understanding, analyses of tracer return profiles can then be used to provide information on hydrodynamic and thermal processes in geothermal reservoirs.

## Conclusions

The use of tracers in geothermal reservoirs provides a unique method to track the migration of injected fluids, to study heat transfer and chemical interactions in the reservoir, and to forecast thermal breakthrough between injection and production wells. This information is critical to effective well placement and to efficient resource extraction. The objectives of studies sponsored by the U.S. Department of Energy are to develop tracers which can be used in geothermal environments and to develop techniques to interpret tracer data and to relate tracer breakthrough to thermal breakthrough.

The stabilities of 39 derivitized hydrocarbons and fluorescein have been experimentally investigated at the University of Utah Research Institute. The data indicate that many of the compounds tested can be used as tracers in moderate- to high-temperature geothermal reservoirs. Of the 39 hydrocarbons tested, 15 are thermally stable at 250°C while 24 are stable at 200°C. The large number of stable compounds will make it possible to monitor many injection wells simultaneously. UURI is currently conducting thermal stability experiments on perfluorinated alkanes for use as gas-phase tracers.

Laboratory tracer tests using unfractured and fractured core samples have been conducted by Stanford University to evaluate models of transport in fracture dominated, low porosity reservoirs. Stanford's Matrix Diffusion model provides a realistic representation of tracer transport in a fracture and can be used to provide reliable estimates of reservoir properties. Experiments have shown that consideration of tracer adsorption in the reservoir is important in estimating fracture appertures using this model.

Studies of fluid flow, tracer transport and heat transfer have been conducted at INEL to investigate these processes in complex reservoirs where both fracture and matrix permeability may be significant. Validation of the dual permeability code FRACSL, using laboratory data has demonstrated its ability to simulate these processes. Sensitivity studies were used to investigate the uncertainty in the interpretation of tracer data which is introduced by simplified reservoir assumptions. Streamlined simulation techniques allow more complex reservoirs to be modeled and improve the capability to provide realistic forecasts of thermal breakthrough in geothermal reservoirs.

Acknowledgements

Funding for this work was provided by The Department of Energy, Division of Geothermal Technology, under contract numbers: DE-AC07-76ID01570 (INEL), DE-AS07-84ID12529 (STANFORD), and DE-AC07-85ID12489 (UURI).

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