

Numerical Simulation of a Tracer Test at Dixie Valley, Nevada

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Abstract

A tracer test was conducted at the Dixie Valley, Nevada, geothermal reservoir using fluorescein. Four of 9 production wells showed fluorescein breakthrough during the first 200 days of the test. Reconstructed fluorescein return curves are presented that correct for the thermal decay of the tracer assuming an average reservoir temperature of 227°C. In order to examine the feasibility of using numerical simulation to model tracer flow, we developed simple, two-dimensional models of the geothermal reservoir using the numerical simulation programs TETRAD and TOUGH2. By fitting model outputs to measured return curves, we show that numerical reservoir simulations can be calibrated with the tracer data. Both models predict the same order of elution, approximate tracer concentrations, and return curve shapes. Using these results, we propose a method for using numerical models to design a tracer test.

Introduction

With the increased use of reinjection in geothermal reservoirs, tracers have become an important tool in developing reservoir management strategies. If injectors are positioned too close to producers, a risk of short circuiting develops, resulting in the possibility of premature thermal breakthrough. If injectors are placed too far away, the injected water will not provide sufficient pressure support to the reservoir. Since chemical breakthrough is more rapid than thermal breakthrough, a tracer test can provide important interwell flow data that can be used to optimize injection well placement and injection flow rates.

In tracing the flow of geothermal water along injection-production flow paths, a chemical compound is typically injected as a pulse into a selected well. The tracer enters the reservoir and is diluted as it is connected through fractures and diffuses into the pore matrix. The surrounding production wells are then

sampled over an appropriate duration in order to determine the arrival times and concentrations of the tracer produced at each well. From an analysis of the tracer-return curves, it is possible to derive valuable information concerning the potential for thermal breakthrough between injection and production wells.

Perhaps the most challenging aspect of tracer test design is the determination of the appropriate quantity of tracer required for a test. The use of an insufficient quantity results in no detected tracer at the production wells, and no flow path information is obtained. The use of excessive quantities of tracer, which is often done in order to insure breakthrough, is not only expensive, but leads to the use of even greater quantities of that chemical for any subsequent tests in order to overcome the induced high background levels.

An accurate estimation of the quantity of tracer required for a tracer test requires a knowledge of reservoir well spacing, well fluid-entry positions, injector and producer flow rates, fluid temperatures, matrix and fracture porosity, and reservoir volume. Such information is contained in the input data file of a calibrated reservoir simulation model. The simulator uses this input information to calculate flow patterns, production well pressures, and produced fluid temperatures. It follows that the simulation model might be a valuable tool in tracer test design. In addition, the tracer return curves can be used to provide constraints that will aid in model calibration. The recalibrated model might then be used to improve tracer-return predictions for subsequent tracer tests.

Our objective is to demonstrate the feasibility of using numerical simulation to model the flow of tracer throughout a geothermal reservoir. Models of the geothermal reservoir at Dixie Valley, Nevada, were developed using the two finite difference simulators, TOUGH2 and **TETRAD**. Predicted tracer return data are compared to those measured in a recent tracer test conducted at the Dixie Valley geothermal reservoir,

Using these data and results, we developed a method for estimating the minimum quantity of tracer required to obtain reliable interwell tracer-breakthrough data.

Geology of Dixie Valley

Dixie Valley, located in west-central Nevada, is an asymmetric Basin and Range graben. It is bounded on the west by the Stillwater Range and on the east by the Clan Alpine Mountains. The Dixie Valley geothermal field is located on the west side of the valley. Production in the geothermal field is defined primarily by fracture permeability associated with the Stillwater range front fault and related secondary faults (Fig. 1).

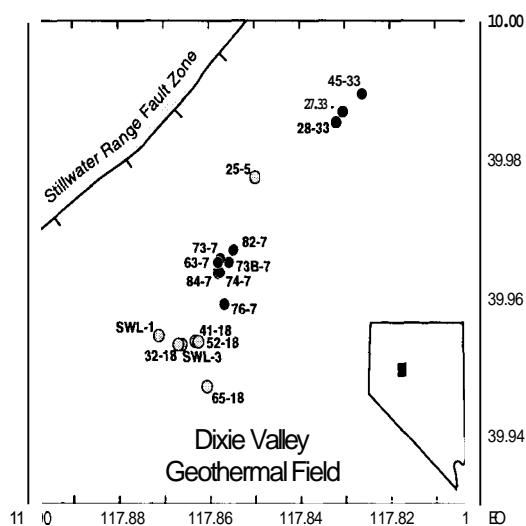


Figure 1. Wellhead locations in Dixie Valley, Nevada, geothermal field. Injection wells shaded grey, production wells shaded black. Approximate location of Stillwater Range normal fault zone, dipping 52-54° to the southeast, is shown in upper left.

Seismic data indicate that the young NNE-striking normal faults that presently define the structural topography of Dixie Valley are high angle, planar, and may extend to depths of 14 km. In the vicinity of the Dixie Valley Geothermal Field, the Stillwater range front fault is known to dip 52-54° to the SE with a roughly planar geometry to depths of 3 km (Benoit, 1995).

Sibson (1977) and Chester and Logan (1986) developed a conceptual fault zone model consisting of a fault core and damage zone surrounded by relatively undeformed protolith (see also Caine et al., 1996). In

any individual fault zone segment, the fault core and damage zone can be spatially heterogeneous, and either may be absent. Fault cores, which accommodate most of the fault displacement, typically consist of fine-grained gouge and cataclasite. Associated damage zones are typically faulted and fractured. Fractures and faults in the damage zone oriented sub-parallel to the main fault increase the permeability in the plane of the fault (Forster and Evans, 1991). As Caine et al. (1996) suggest, permeability in the fault core may be limited by the fine grain size, whereas it is the hydraulic properties of faults and fractures in the damage zone which control permeability there.

The Tracer Test

On May 29, 1996, 169 kg of a 50% by weight aqueous solution of the dipotassium salt of fluorescein and 100 kg of the disodium salt of 7-amino-1,3-naphthalene disulfonic acid (amino G acid) were mixed with approximately 3000 kg of produced reservoir brine and pumped into injector 25-5 over a period of about 20 minutes. The 9 production wells were sampled weekly and the samples were analyzed for fluorescein using a Perkin Elmer LS-30 luminescence spectrometer at excitation and emission wavelengths of 475 nm and 510 nm respectively.

The mean temperature of the brine at the Dixie Valley reservoir was recently shown to be between 225°C and 230°C (Adams and Davis, 1991). For the purposes of this exercise, it is assumed that the mean brine temperature is 227°C, which is within the range of this recent measurement. Adams and Davis (1991) showed that, at 227°C, fluorescein has a half-life of about 95 days. At about 300 days, when the first return-curve maxima are expected, more than 90% of the originally injected fluorescein will have thermally decayed. From a knowledge of fluorescein decay kinetics, it is possible to correct for thermal decay and to reconstruct "conservative" fluorescein return curves. Of course, after the fluorescein has decayed below the detection limit of the spectrofluorometer, it will not be possible to correct for decay, and the tracer test will necessarily end.

The decay-rate constant, k , varies with temperature according to the Arrhenius relationship:

$$k = A e^{-E_a/RT} \quad (1)$$

where E , is the activation energy, A is a pre-exponen-

al factor and R is the gas constant. Based upon arameters obtained in the study by Adams and Davis 991), the rate constant at 227°C was found to be:

$$k = 7.92 \times 10^{-3} da^{-1} \quad (2)$$

he concentration of fluorescein in the reservoir varies with time according to the first-order rate expression:

$$C = C_0 e^{-kt} \quad (3)$$

here C is fluorescein concentration, C_0 is initial fluorescein concentration, and t is time. By substituting equation 2 into equation 3, the rate expression for decay at 227°C becomes:

$$C = C_0 e^{-0.00792t} \quad (4)$$

inally, by correcting the measured fluorescein return-curve concentrations using expression 4, it is possible to construct conservative tracer return data. Figure 2a shows the uncorrected return curves for all of the wells where fluorescein appeared, and Figure 2b shows the return curves after correcting for thermal decay. Since the minimum measurable concentration was approximately 10 parts per trillion (ppt), only the return curves for wells showing fluorescein concentrations greater than 10ppt are shown in Figure 2b.

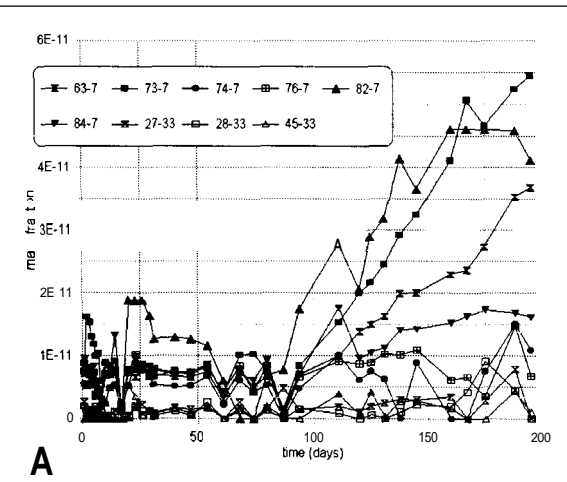


Figure 2. (a) Fluorescein mass fractions measured at 9 production wells.

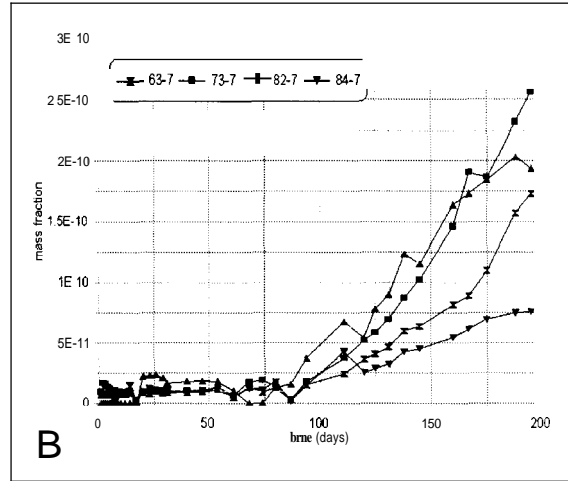


Figure 2. (b) Fluorescein mass fractions at 4 production wells after correcting for thermal decay.

The Reservoir Models

Models of the reservoir at Dixie Valley were developed using the finite difference, numerical simulation programs TOUGH2 (Preuss, 1991) and TETRAD (Vinsome, 1995). The models were configured to simulate the flow of a short pulse of tracer injected into well 25-5 (Fig. 1). The model outputs were then fit to the actual tracer production data by adjusting reservoir thickness, permeability and porosity, within reasonable limits.

Both TOUGH2 and TETRAD allow for the separate tracking of two aqueous components. The “first water” represents all of the water initially present in the reservoir as well as essentially all of the water that is reinjected. The “second water” is injected into an appropriate injection well over a very short period of time at the beginning of the simulation. It represents the pulse of tracer that is used to trace the flow of injectate. After the injection of the tracer pulse, the injector is immediately switched back to injection of the first water. Although the two aqueous components mix thoroughly as they are convected throughout the reservoir, the second water emerges as dispersed pulses in the production wells.

TOUGH2 is a numerical simulation program that was developed for the purpose of modeling the multiphase and multicomponent flow of fluid and heat through porous and fractured media. Among the specific applications for which the code was designed are geothermal reservoir engineering, nuclear waste disposal and unsaturated zone hydrology. Its architecture and

method of implementation are detailed elsewhere (Preuss, 1991).

TETRAD is a three dimensional numerical simulation computer program that was developed to model the multiphase, multicomponent flow of heat and fluid through porous or fractured media. The name "TETRAD" refers to the code's four available application modes: black oil, multicomponent, thermal and geothermal flow modeling. Details of the structure and implementation of the program are provided elsewhere (Vinsome, 1995).

For simplicity, a two-dimensional Cartesian grid was used to represent the reservoir (Fig. 3). This is justified since the reservoir is defined largely by a set of fractures closely associated with the Stillwater Fault, which possesses remarkably constant dip and strike angles within the Dixie Valley geothermal field and which therefore can be reasonably approximated as a plane. In addition, all of the wells except one are completed within this highly fractured fault zone.

The 442-element grid that was used in both the TOUGH2 and TETRAD models is shown in Figure 3. This figure shows the locations of the completion intervals of the seven injection wells and nine production wells that were active during the tracer test. Tracer was injected only into well 25-5. With a flow rate of about 284 kg/sec, this well alone accounts for over half of the total injection into the field. The remaining injectors are distributed between shallow and deep completion intervals in section 18. Six of the nine production wells are clustered in section 7; the remaining three are located in the northeast end of the reservoir in section 33.

The top of the grid was positioned 1676 m below the ground surface, and the initial pressure within the grid was hydrostatic. The initial temperature was set at 227°C uniformly throughout the reservoir, whereas the reinjected water had a temperature of 100°C.

In the case of the TOUGH2 model, Neumann (no-flow) boundary conditions were maintained on all surfaces except for the uppermost blocks at either end of the reservoir. At these blocks, the elements were given Dirichlet (constant temperature and pressure) boundary conditions. In the case of the TETRAD model, the columns of blocks at either end were designated as steady-state aquifer elements, which allow for flow into the reservoir. Such conditions were chosen because only about 82% of the produced water is returned as injectate. If the boundaries were entirely

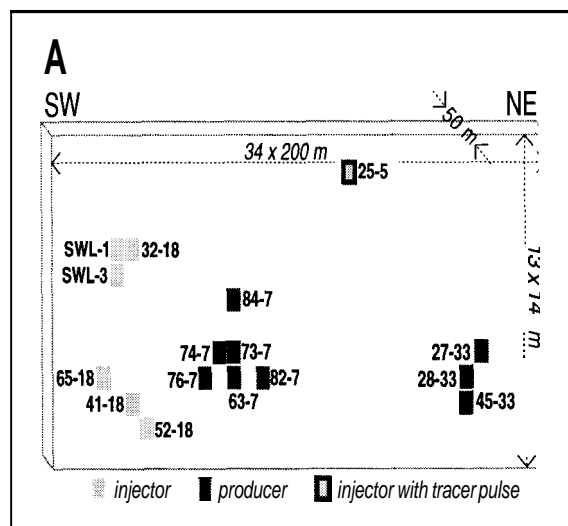


Figure 3. (a) Schematic grid used in both TETRAD and TOUGH2 numerical simulations. Well positions (based on wellhead location) are projected onto the assumed planar fault zone. Completion intervals for production wells (black) and injection wells (grey) are shown.

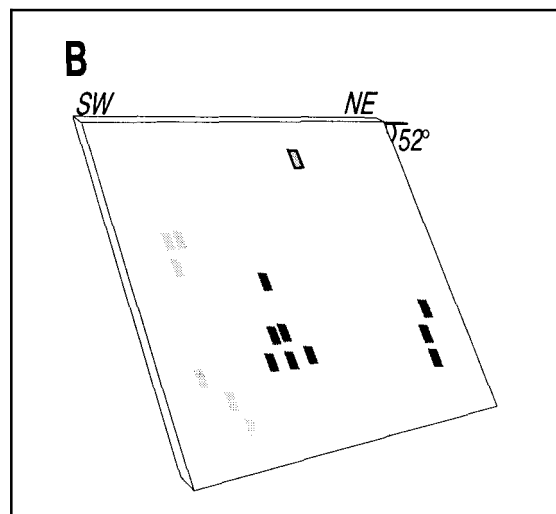


Figure 3. (b) In both simulation models, we rotated the gravity vector to simulate the planar fault zone dipping 52° to the southeast. Well symbols are the same as in Figure 3a.

closed, two-phase conditions would soon develop in the reservoir and likewise in the model. The choice of these boundary conditions allows for flow throughout the reservoir to be dominated by the injection and production wells, while allowing for make-up flow into the reservoir as needed to maintain single-phase (liquid) conditions.

Although the Dixie Valley reservoir consists of a complex network of faults and fractures extending throughout a heterogeneous rock matrix, it was defined for the purposes of this modeling exercise as an isotropic and homogeneous porous medium

Results and Discussion

Using the input parameters and boundary conditions described above, the TOUGH2 and TETRAD models were run for a period of three years. Plots of tracer concentration vs time for all of the wells showing return are shown in Figure 4. It is apparent that both models predict the same order of elution and approximate relative tracer quantity for the section-7 production wells, although the TETRAD returns are all slightly greater than the TOUGH2 returns. Both models predict that the section-7 wells show return well in advance of the section-33 wells. Interestingly, the relative quantity of returning tracer is reversed for the section-33 wells, with the TOUGH2 model showing a greater return than the TETRAD model. The differences between the model predictions are slight, however, as revealed by a plot of cumulative tracer production vs time in Figure 5. Figure 6 shows the first 200 days of tracer-return data, corrected for thermal decay, and simulation results from TOUGH2.

Although the match is imperfect, the simulated curves reflect the general order of elution, position, size and shape of the measured curves. The match is particularly good for the producer 82-7, which shows the strongest return, whereas the simulated returns underpredict to varying degrees the measured returns for the remaining section-7 wells.

Figure 7 shows the return-curve data in combination with the simulation results for the TETRAD model. Again, the simulated curves reflect the general order of elution, position, size and shape of the measured curves. The TETRAD-generated curves bracket the measured data, with two curves (wells 82-7 and 84-7) being overpredicted and two curves (wells 73-7 and 63-7) being underpredicted. Since both models represent a two-dimensional, homogeneous and isotropic porous medium and the reservoir is doubtlessly a three-dimensional, anisotropic, heterogeneous, and fractured medium, the similarity between both the TOUGH2 and TETRAD modeled results and the data is remarkable.

Tracer Test Design

In designing a tracer test, the reservoir engineer must estimate the minimum quantity of tracer required for

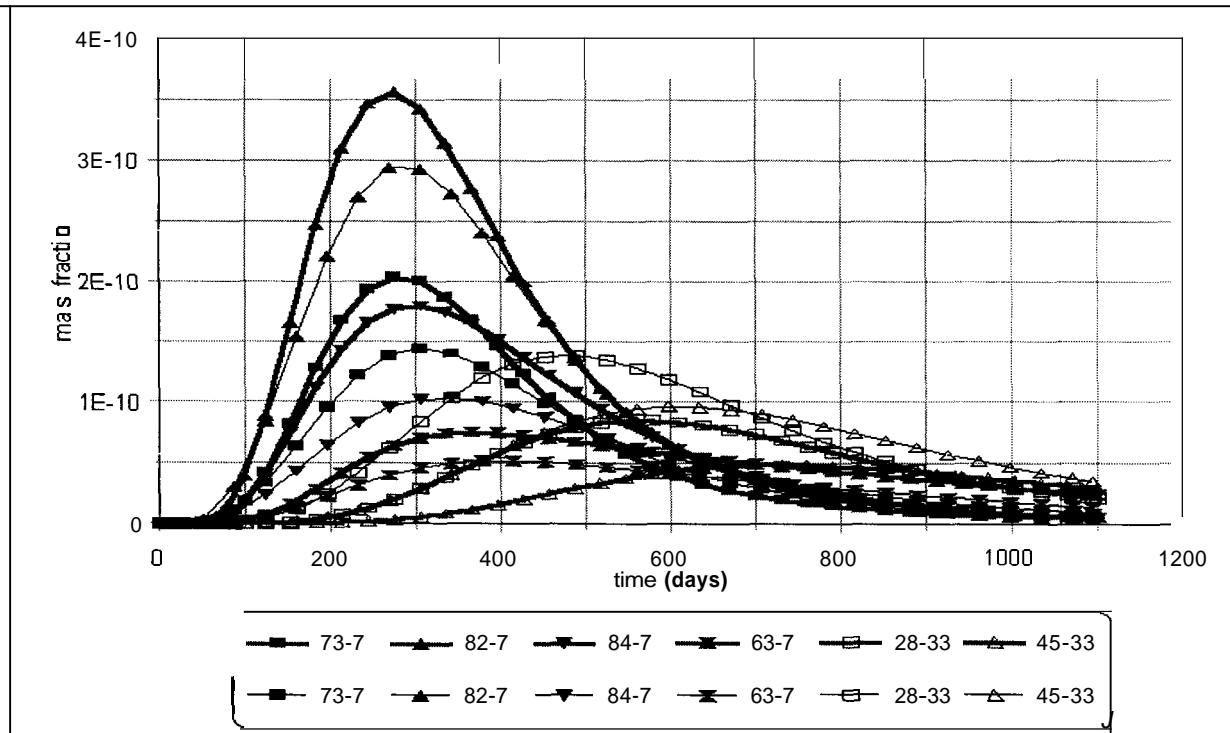


Figure 4. Simulated tracer return curves for TETRAD (thick lines) and TOUGH2 (thin lines).

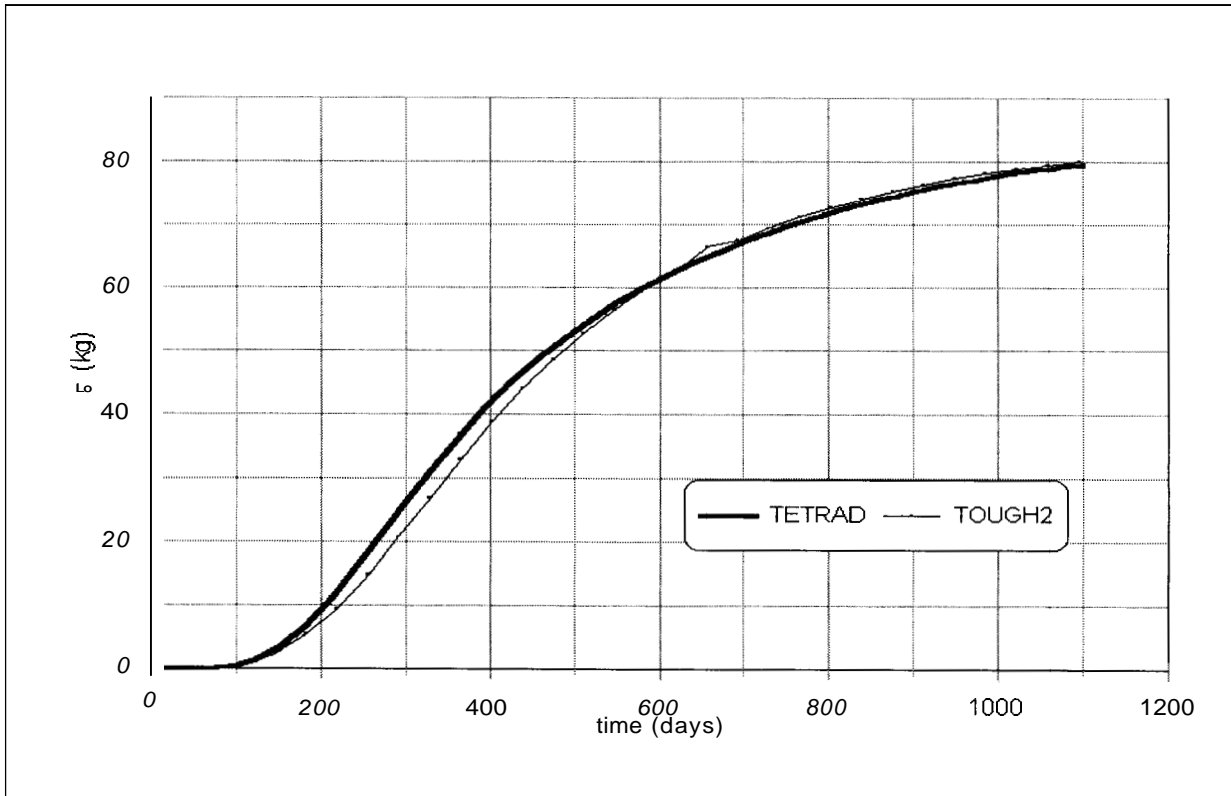


Figure 5. Cumulative tracer returns for TETRAD and TOUGH2.

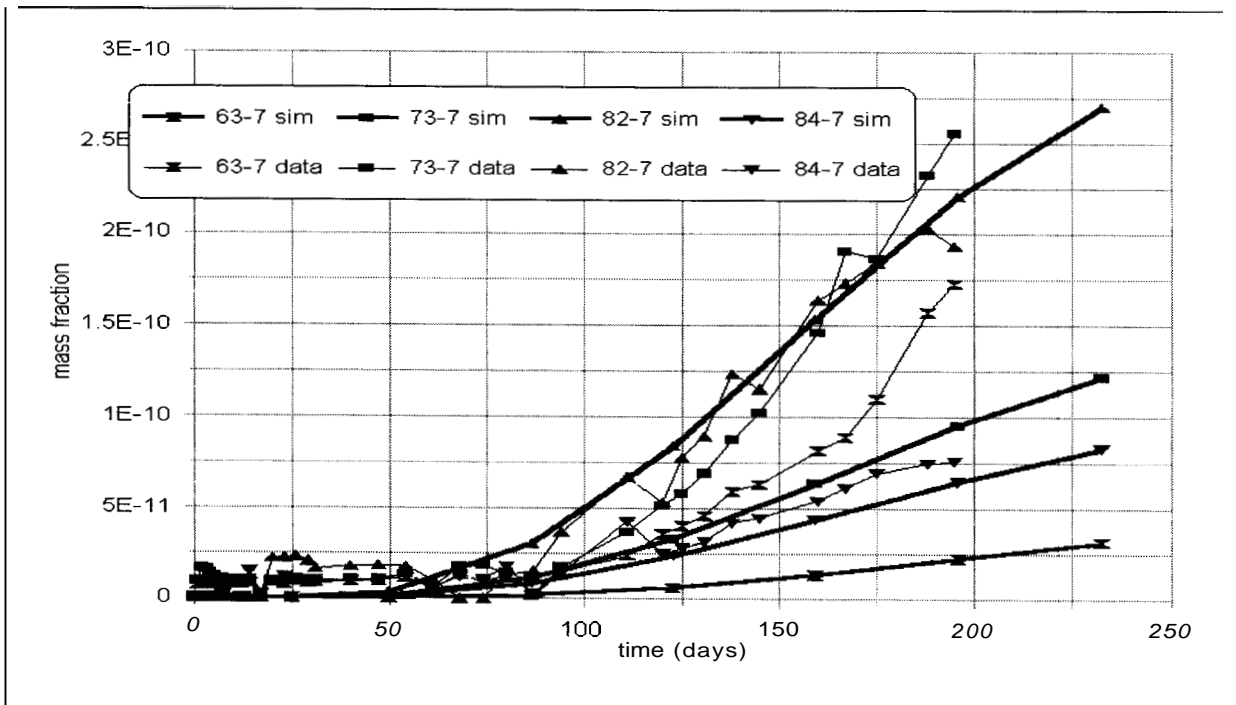


Figure 6. Measured return curves (thin lines) and simulated return curves using TOUGH2 (thick lines)

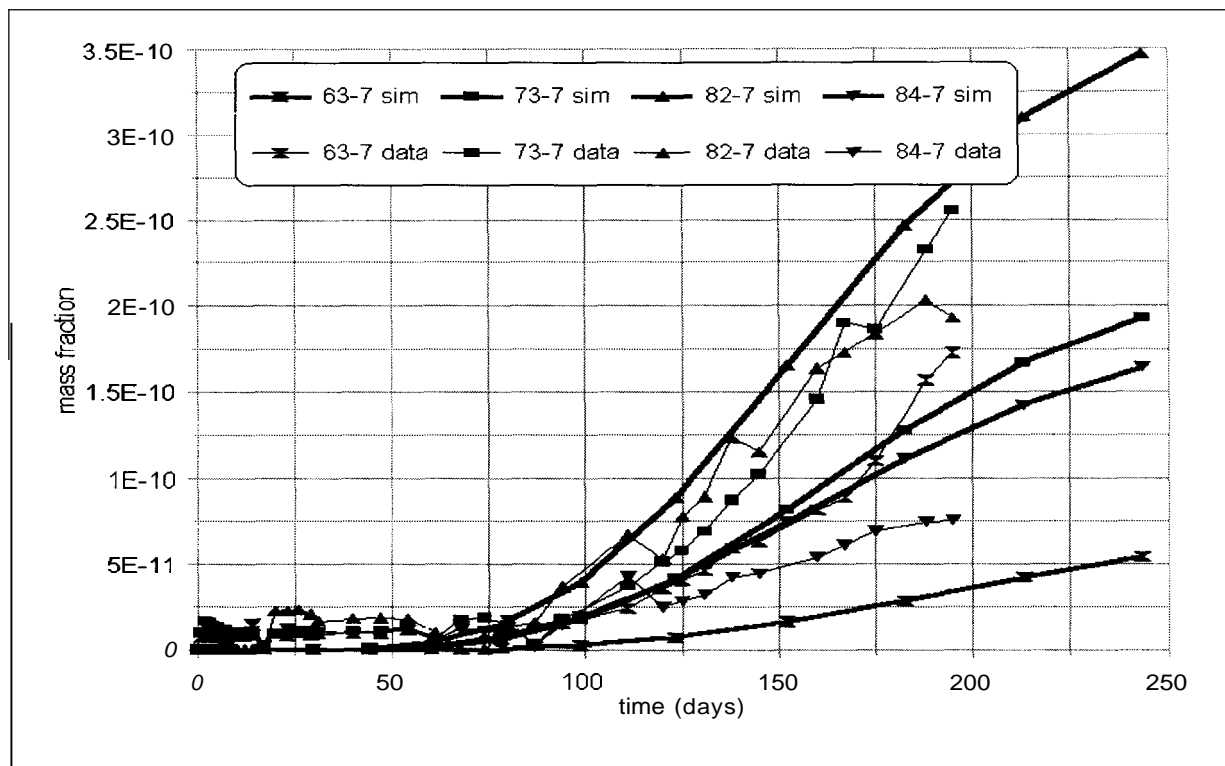


Figure 7. Measured return curves (thin lines) and return curves simulated using TETRAD (thick lines).

breakthrough at the producers and the probable injection flow patterns. A knowledge of flow patterns is required in order to estimate the first arrival times and peak arrival times of tracer, which in turn are used to determine appropriate sampling locations and sampling frequency. In order to estimate the minimum amount of tracer, the reservoir engineer needs only to minimize the duration of the simulated tracer-injection pulse, since, for a constant flow rate, the pulse duration is directly proportional to the mass of tracer injected. The minimum pulse duration occurs when enough tracer has been injected to result in return curve concentrations at the production wells that exceed the minimum measurable concentration of the detector by a comfortable margin. Of course, if thermally unstable tracers are used, the tracer decay kinetics must be determined and accounted for.

Summary and Conclusions

A tracer test was conducted at the Dixie Valley, Nevada, geothermal reservoir in order to determine the destiny of reinjected reservoir fluids. Fluorescein breakthrough was evidenced at 4 of the reservoir's 9 production wells. Using TOUGH2 and TETRAD, relatively simple two-dimensional models of the tracer

flow patterns were developed by fitting model outputs to measured return curves. Since fluorescein decays rapidly at the average reservoir temperature of approximately 227°C, it was necessary to correct the return curves for tracer decay, using kinetics developed under conditions that simulate the geothermal environment. Both models were equally successful at simulating the return curve shapes and elution order as well as the approximate concentrations of produced tracer. We have proposed a method for using numerical models to design a tracer test.

Acknowledgements

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