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THE ESTIMATION OF RESERVOIR PORE VOLUME FROM TRACER DATA

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ABSTRACT

Two methods for estimating the pore volume of a geothermal reservoir based upon tracer return-curve data are demonstrated. The first method uses a first-moment analysis of tracer return-curve data. It calculates the volume swept by a tracer between an injection region and a production region. For reservoirs with multiple regions of injection and production, the respective interwell volumes are calculated and simply added together to obtain an overall reservoir pore volume. The second method of estimating reservoir pore volume involves an analysis of the long tailing portion of a tracer return curve.

Tracer data from the Beowawe, NV and Dixie Valley, NV geothermal reservoirs were analyzed by the two methods and compared. A numerical simulation study was conducted in order to investigate the effect of interwell spacing on calculated volumes and to compare reservoir pore volumes calculated by the two methods. Application of both methods may serve to indicate the relative magnitude of an untapped resource adjacent to the exploited reservoir volume.

INTRODUCTION

Tracer data have long been used by engineers to study fluid flow within continuous flow systems such as pipes and chemical reactor vessels. Danckwerts (1953) introduced the concepts of F-C diagrams and age distribution functions to characterize flow in a variety of patterns ranging from piston (segregated) flow to complete mixing. In addition, he demonstrated the use of moment analyses of tracer-test data to determine reactor-vessel volumes (Danckwerts, 1958).

Robinson (1985) applied the concepts of Danckwerts and others to the study of flow through fractured media and recognized two basic ways of defining pore volume based upon residence time distribution (RTD) functions: modal volume and integral mean volume. The former corresponds to the maximum of the RTD curve and represents the volume of the primary (low impedance) fracture pathways. The latter is a more inclusive definition and represents the volume of all fractures, including both the low impedance and high impedance pathways.

Shook (2003) developed a proxy to true F-C diagrams based upon conservative-tracer data as a means of describing flow capacity and storage capacity in fractured media. He indicated that total pore volume could be obtained from the storage capacity proxy.

Another approach to the estimation of reservoir pore volume was introduced by Ito and coworkers (Ito et al., 1977; Ito et al., 1978). They showed that for relatively closed systems where there is little or no aquifer flow through the reservoir, it is possible to estimate the overall pore volume by a simple analysis involving the long-tailing portion of a tracer return curve. Rose and coworkers extended this method and showed in a numerical simulation study that approximations of the overall pore volume could be obtained even in reservoirs with some aquifer cross-flow (Rose et al., 1997).

In this paper, we compare two methods for estimating overall pore volume—one based upon a first-moment analysis of return curve data and the other based upon an analysis of the long-tailing portion of the return curve. We apply these two approaches to the analysis of tracer data from the Beowawe and Dixie Valley geothermal reservoirs.

PORE VOLUME ESTIMATES THROUGH FIRST-MOMENT ANALYSIS OF TRACER RETURN CURVES

Danckwerts (1953) used tracers in order to describe fluid flow in both open and packed-bed chemical reactors. A tracer was introduced at the reactor inlet stream and its concentration was subsequently measured at the reactor outlet. From an analysis of the tracer concentration measured over time at the outlet, it was possible to estimate the overall reactor fluid volume.

In his analysis, Danckwerts introduced the concept of exit age distribution E(t), which was defined as the fraction of fluid molecules in the reactor exit stream with residence time between t and t + dt. If a tracer was injected as a pulse into the reactor and measured at the exit stream then E(t) could be calculated as:

$$E(t) = \frac{Q \cdot C(t)}{m_p} \qquad (1)$$

where Q is the flow rate, C(t) is the concentration of the tracer at the reactor exit, and m_p is the mass of the tracer pulse.

Danckwerts (1958) later introduced the concept of the mean residence time τ as a tool for characterizing flow in chemical reactors. He used the following first-moment type formula to estimate the mean residence time, which is the average time spent by tracer particles within the reactor:

$$\tau = \int_0^\infty t \cdot E(t)dt \qquad (2)$$

For a steady state flow system, τ is directly related to the reactor volume, V and the flow rate:

$$\tau = \frac{V}{Q} \qquad (3)$$

The overall reactor volume could then be determined from tracer data by combining equations 1, 2, and 3:

$$V = \frac{Q^2}{m_p} \int_0^\infty t \cdot C(t)dt \qquad (4)$$

Equation 4 can be easily solved using standard numerical integration approaches. This is obviously a simplified method of estimating reactor volumes and Danckwerts (1953, 1958) advises caution in applying this method especially in the cases of significant fluid recycle and large fluid holdup due to stagnant zones. Nevertheless, the method provides a simple means of determining a first order estimate of reactor volume.

If a geothermal reservoir can be thought of as a large flow vessel such as the ones analyzed by Danckwerts, and if flow rates, tracer mass, and tracer return-curve data are known, then equation 4 can serve to estimate the pore volume between the tagged injection well and the monitored production well within such a reservoir.

PORE VOLUME ESTIMATES THROUGH THE ANALYSIS OF TAILING PORTIONS OF TRACER RETURN CURVES

Rose and coworkers extended the method of Ito et al. (1977, 1978) to show that the long tailing portions of tracer return curves could be used to estimate overall reservoir pore volume (Rose et al., 1997). In a numerical-simulation study, a conservative tracer was introduced into a geothermal reservoir modeled loosely after the Beowawe, NV reservoir.

In the first example, closed boundary conditions were imposed. The produced fluids were reinjected continuously over a period of 2000 days. Since the produced and injected fluids contained tracer, it was evenly mixed throughout the reservoir, eventually attaining a steady-state concentration, F_t. The pore volume, V was easily calculated from the following relationship:

$$V = \frac{m_p}{F_t} \qquad (5)$$

If constant-pressure boundary conditions were imposed and an aquifer flow was allowed to flow into the reservoir, the overall pore volume could be estimated through a similar analysis of the tracer return-curve tail. In this case, the mass fraction F_t is the intersection of the linear long-tailing portion of the return curve with the ordinate. Likewise, the rate of aquifer flow through the reservoir could be estimated from the slope of the long tailing portion of the return curve (Rose et al., 1997).

FIELD EXAMPLES

Tracer tests were initiated several years ago at the Beowawe and Dixie Valley geothermal reservoirs. Data from these long-term tracer tests can be used to determine reservoir pore volume according to the two methods described above.

Beowawe

The Beowawe geothermal reservoir (see Figure 1) is a relatively simple system with one injection well and three production wells. The production wells are located in close proximity to each other and through weighted averaging can be treated as a single well. Thus, the four active wells within the Beowawe reservoir can be effectively reduced to a doublet.

On July 13, 1994 91 kg (200 lbs.) of the sodium salt of fluorescein was mixed with about 23m^3 (6000 gal) of reservoir water. The solution was injected as a slug into injection well 85-18 at a rate of about 220 L/sec (3500 gpm). The production flow rate at Beowawe was assumed to be 254 L/s (4,020 gpm). Water samples were collected at the three production wells Ginn 1-13, Ginn 2-13, and 77-13. The samples were analyzed for fluorescein using a Waters 2690 HPLC with a Waters 474 scanning fluorescence detector.

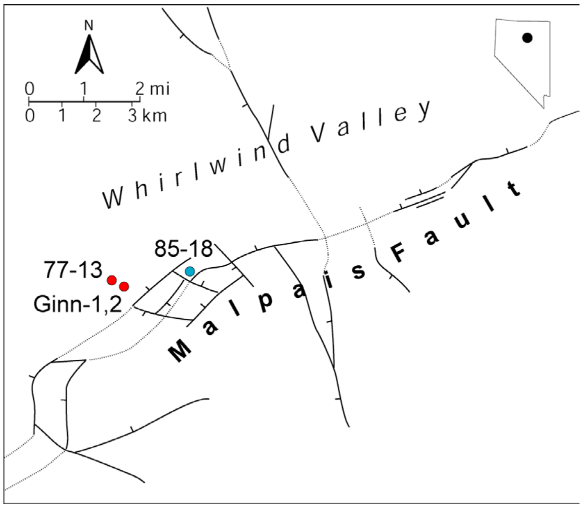

Figure 1. Plan view of the Beowawe geothermal reservoir showing the injection well 85-18 and the three production wells Ginn-1, Ginn-2 and 77-13.

Plots of fluorescein concentration versus time for each of the three production wells are shown in Figure 2.

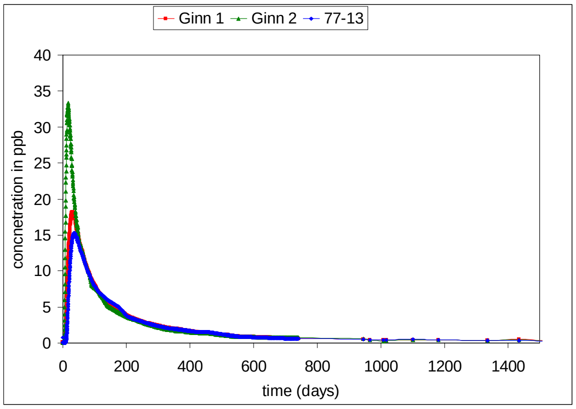

Figure 2. Fluorescein return curves from 1994 Beowawe tracer test.

The measured tracer concentrations at each production well were weighted according to their individual flow rates in order to create a common tracer return curve. This curve is the same as would be obtained if the tracer samples were taken after the water from the three producers was first mixed into a common production line. Thus, the reservoir at Beowawe can be reduced to an injector-producer doublet.

Fluorescein Thermal Decay at Beowawe is Negligible

The decay kinetics for fluorescein under geothermal conditions has been studied and documented (Adams et al., 1991). Since the fluid temperatures at Beowawe are less than 200^{o}C, the thermal decay of fluorescein was expected to be negligible. To verify this, the fluorescein concentrations measured at the production well were temperature-corrected according to laboratory-determined decay kinetics. Shown in Figure 3 are the original and temperature corrected return curves for the 1994 tracer test at Beowawe. The figure indicates that the two curves are almost coincident and that the fluorescein tracer has decayed very slightly over the first 1500 days of the tracer test.

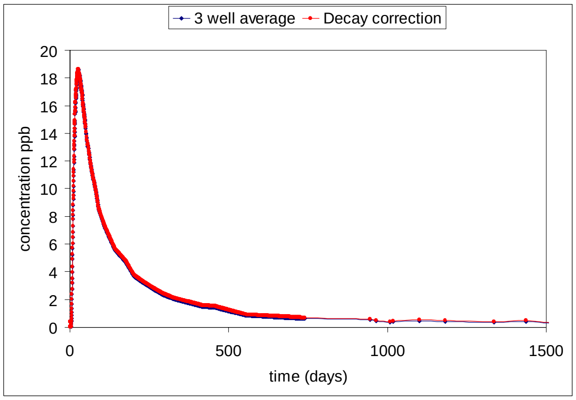

Figure 3. Fluorescein return curve for the 3-well average and the decay correction for the 3 well average.

Beowawe Pore Volume Calculation through First-Moment Analysis

Using the first-moment analysis approach described above, it is possible to estimate the pore volume of the reservoir swept by the tracer. Since the produced tracer is reinjected, the tracer return curves shown in Figure 3 must be 'deconvoluted' before the moment analysis pore-volume calculation can be done. The deconvolution calculation corrects for the reinjected tracer, resulting in a single-pass tracer return curve. This is the curve that would have resulted if all of the produced tracer could have been removed from the produced fluids before those fluids were reinjected.

The measured return curve, $C_m(t)$, can be corrected to create the deconvoluted return curve $C_{adj}(t)$:

$$C_{adj}(t) = C_m(t) - (1 - F_{loss})\int_0^t C_m(t-\tau)C_m(\tau)d\tau \qquad (6)$$

where $C_{adj}(t)$ is the recycle-adjusted concentration at time t (Robinson, 1985). F_{loss} is the fractional production loss or:

$$F_{loss} = \frac{Q_p - Q_i}{Q_p} \qquad (7)$$

where Q_p is the production rate and Q_i is the injection rate. At Beowawe, F_{loss} has had an average value of approximately 0.16 over the duration of the tracer test. Using equation 6, a recycle-corrected return curve was generated for the first 1500 days of the 1994 Beowawe tracer test (Figure 4).

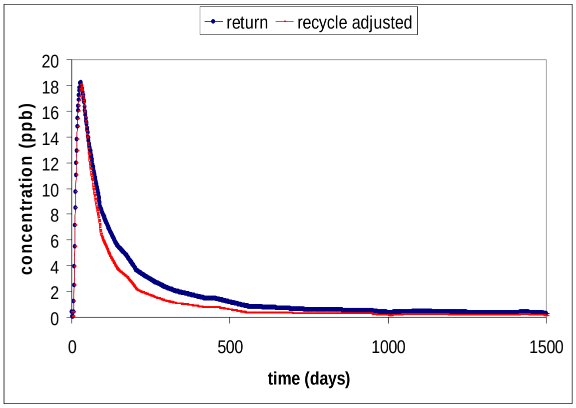

Figure 4. Beowawe 1994 measured return curve and the recycle-adjusted return curve.

The mass of the pulse of tracer must be known in order to solve for the pore volume using equation 4. But if there is less than complete return of a conservative tracer, then it may be assumed that some of the missing tracer was advected away from the reservoir through aquifer cross-flow or that some has diffused into relatively stagnant zones adjacent to the forced-convection region. This lost mass must therefore not be used in determining the swept volume and it is the mass of tracer *returned* rather than the mass of tracer *injected* that should be entered into equation 4.

The amount of tracer that is returned was calculated from the numerical integration of:

$$m_{pr} = Q\int_0^t C(t)dt \qquad (8)$$

where m_{pr} is the mass of tracer returned, Q is the flow rate and C(t) is the deconvoluted return curve. Using this approach, m_{pr} was found to be 47 kg.

The pore volume for the fraction of the Beowawe reservoir swept by tracer from the 1994 test was determined by numerically integrating equation 4, where m_p was replaced by m_{pr} and the recycle-corrected return curve in Figure 5 was used in the place of the measured return curve. Using this approach, the pore volume was calculated to be approximately 6.78 billion L or 1.78 billion gal.

Beowawe Pore Volume Calculation through Analysis of Tailing Portion of Tracer Return Curve

As described above, the long tailing portion of a return curve can be used to estimate the reservoir pore volume. The intersection of the extrapolation of the linear portion of the return curve with the y axis was determined to be 0.689 ppb. Using a value of 47 kg for m_p in equation 5 results in a reservoir volume of approximately 68.2 billion L or 18.0 billion gal. There is a difference of approximately a factor of 10 (1.8 vs. 18) in the estimated pore volume at Beowawe depending on the method used.

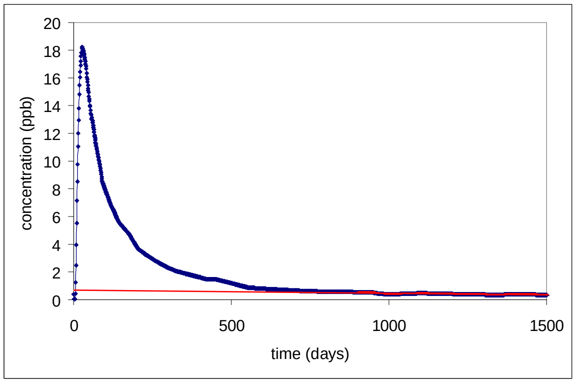

Figure 5. Linear extrapolation of the long tailing portion of the 3-well-average return curve from the 1994 tracer test at Beowawe.

<u>Dixie Valley</u>

Fluid flow patterns at the Dixie Valley (see Fig. 6) geothermal reservoir have been extensively studied in a series of tracer tests between 1996 and the present. These tracer data were used to estimate the reservoir pore volume.

Shown in Figure 6 is a plan view of the wellhead locations. Injection wells 41-18 and 65-18 were tagged in a concurrent set of tracer tests starting in 1998 (Rose et al., 2000). Injection wells 25-5 and 45-5 were tagged in tracer tests starting in 1999 and 2001, respectively (Rose et al., 2001a; Rose et al., 2002). Injection well 27-32 was tagged in a tracer test starting in 1999 (Rose et al., 2001a). Details of these tests are reported in the cited papers.

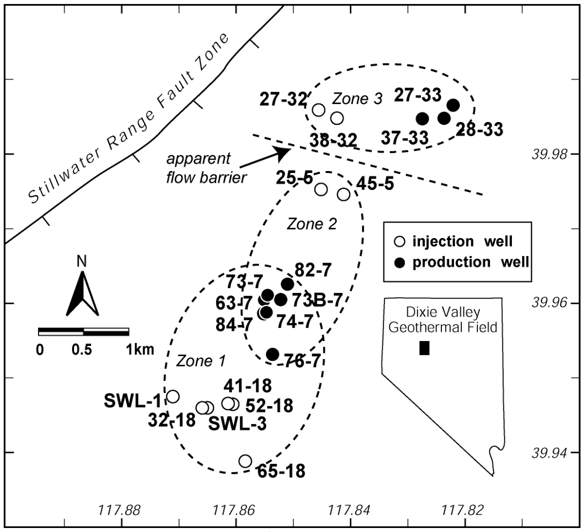

Figure 6. A plan view of the Dixie Valley geothermal reservoir, showing the injection and production wellhead locations. Also shown are the three zones that the reservoir was divided into in order to calculate the overall pore volume using the moment-analysis method.

Dixie Valley Pore Volume Calculation through Analysis of Tailing Portion of Tracer Return Curve

Shown in Figures 7 through 10 are plots of the tracer return curves for the section-7 production wells for these four tests. Also shown in each figure is a line extrapolating the long tailing portion of the return curve to its intersection with the y axis. Using the return-curve-tail method described above, the pore volume was estimated in each case. The pore volumes calculated using this method are reasonably close in value (see Table 1).

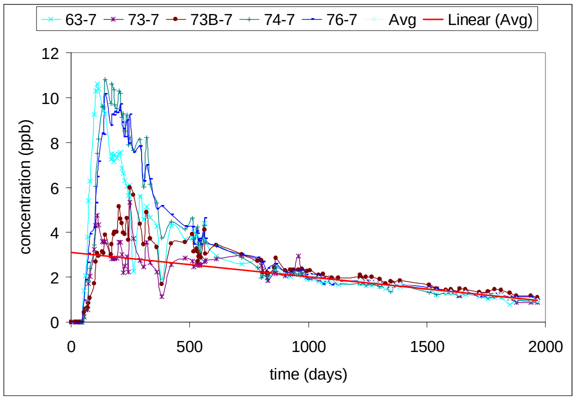

Figure 7. Return curves for the tracer 1,5-nds that was injected into Dixie Valley well 41-18 and measured at the section-7 production wells (Rose et al., 2000).

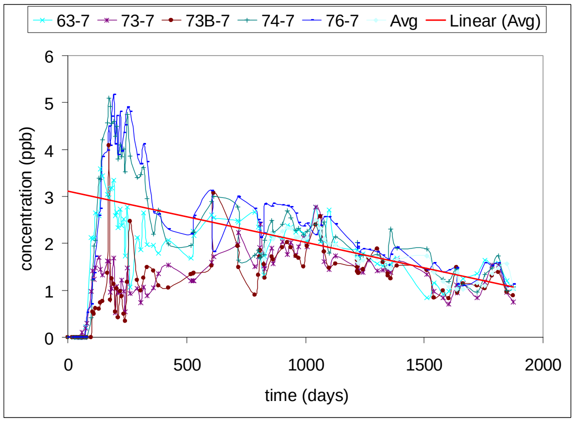

Figure 8. Return curves for the tracer 1,3,6-nts that was injected into Dixie Valley well 65-18 and measured at the section-7 production wells (Rose et al., 2000).

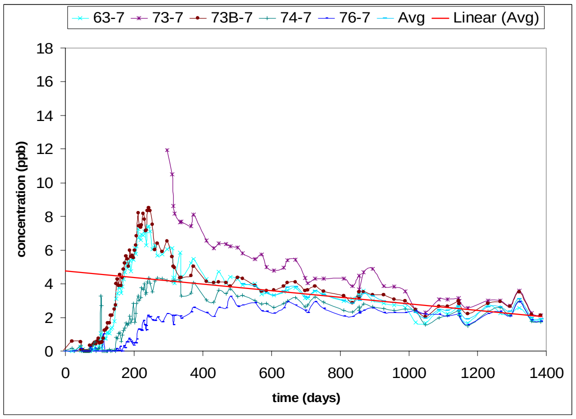

Figure 9. Return curves for the tracer 2-ns that was injected into Dixie Valley well 25-5 and measured at the section-7 production wells (Rose et al., 2001a).

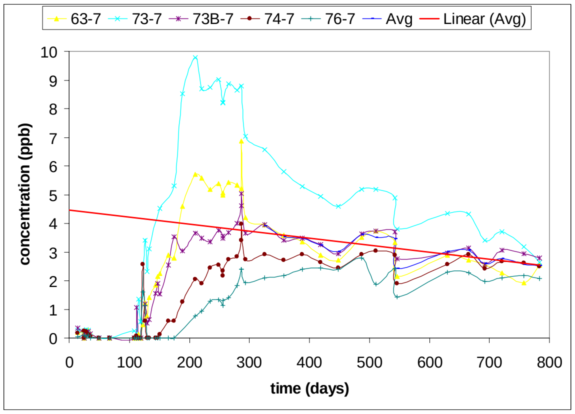

Figure 10. Return curves for the tracer 1-ns that was injected into Dixie Valley well 45-5 and measured at the section-7 production wells (Rose et al., 2002).

Table 1. Dixie Valley reservoir pore volume calculated from the long-tailing portions of four tracer tests.

Injector	Tracer Mass (kg)	Y-Intercept (ppb)	Reservoir Volume (x 10^9 gal)
41-18	100	3.10	8.5
65-18	100	3.11	8.5
25-5	200	4.76	11.1
45-5	143	4.47	8.5
		average	9.1

Dixie Valley Pore Volume Calculation through First-Moment Analysis

An estimation of the tracer-swept pore volume at the Dixie Valley reservoir using the first-moment analysis approach is a challenging calculation due to the ever-changing number of injection and production wells on line and the variations in injection and production flow rates. Using some simplifying approximations, however, a reasonable estimate is possible.

As shown in Figure 6, two injection wells are located in section 5 northeast of the section-7 production wells. Six injectors are located in section 18, which is southwest of section 7. Tracer test data obtained over several years of testing have shown that water injected in the two sections flows only to section 7 (Rose et al., 2001b). Likewise, injection wells 27-32 and 38-32 have each been tagged with tracers. Injection fluids from these two wells flow exclusively to section 33.

We therefore can divide the reservoir into the regions between sections between sections 18 and 7 (Zone 1 in Figure 6), 5 and 7 (Zone 2), and 32 and 33 (Zone 3). We can then use the first-moment analysis approach to calculate the tracer-swept volumes within each of these three regions. By adding together the volumes calculated for each zone, we can obtain an overall volume for the tracer-swept regions of the Dixie Valley reservoir.

We have made the simplifying assumption that the production rate from section 7 has averaged 7,000 gpm since the mid-1990's and that the production flow rates were evenly distributed between the five producers 63-7, 73-7, 73B-7, 74-7, and 76A-7. We also assumed that the injection rate into sections 18 and 5 has averaged approximately 6,300 gpm over that same duration and that approximately 60% of the injectate was pumped through Zone 2, with the remaining 40% being pumped through Zone 1. Finally, we assumed that the production rate from section 33 has averaged 4,000 gpm evenly distributed among the operational wells in that section and that the injection rate into section 32 was approximately 3,600 gpm.

To estimate the volume swept by tracer through Zone 1, we used data from the tagging of well 65-18. This injector is further away from the section 7 wells than any other section-18 injector and therefore its use in the calculation will serve to maximize the calculated volume within this region. The tracer data produced from the tagging of 65-18 were averaged as shown in Figure 11. Also shown in Figure 11 is the deconvoluted curve, which is the curve that would have been obtained if all tracer were removed from the produced fluids after only one pass through the reservoir.

Substitution of the deconvoluted C(t) data into equation 4, followed by numerical integration led to a calculated volume of 4.0 billion liters (1.0 billion gal).

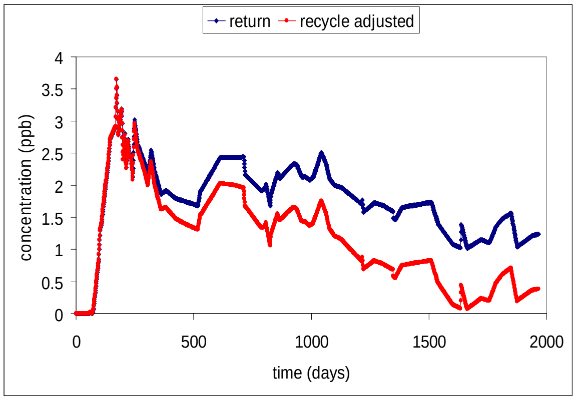

Figure 11. Averaged and recycle-adjusted return curves for the tracer 1,3,6-nts that was injected into Dixie Valley well 65-18 and measured at the section-7 production wells (Rose et al., 2000).

To estimate the volume swept by tracer through Zone 2, we used data from the tagging of well 25-5. Figure 12 shows the averaged return from that injector to the section-7 producers as well as a deconvoluted return curve. Substitution of these deconvoluted C(t) data into equation 4, followed by numerical integration led to a calculated volume of 4.8 billion liters (1.3 billion gal).

To estimate the volume swept by tracer through Zone 3, we used data from the tagging of well 27-32. Figure 13 shows the averaged return from that injector to the section-7 producers as well as a deconvoluted return curve. Substitution of these deconvoluted C(t) data into equation 4, followed by numerical integration led to a calculated volume of 5.5 billion liters (1.4 billion gal).

The combined volume of the regions swept by the tracers from the three tracer tests described above was obtained by adding the volumes of Zone 1, Zone 2, and Zone 3. That volume was 14.3 billion liters

(3.7 billion gal). This is approximately 40% of the volume of the Dixie Valley reservoir as calculated by the return-curve-tail method (see Table 1).

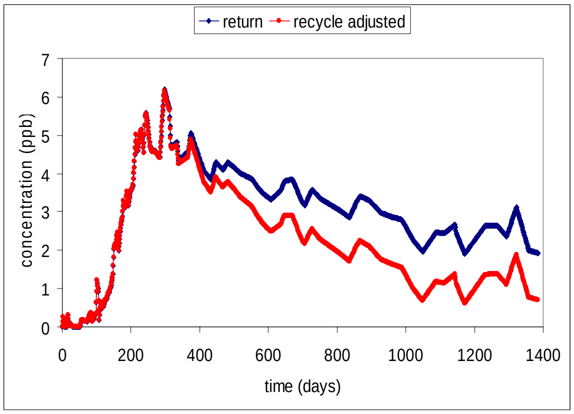

Figure 12. Averaged and recycle-adjusted return curves for the tracer 2-ns that was injected into Dixie Valley well 25-5 and measured at the section-7 production wells (Rose et al., 2001a).

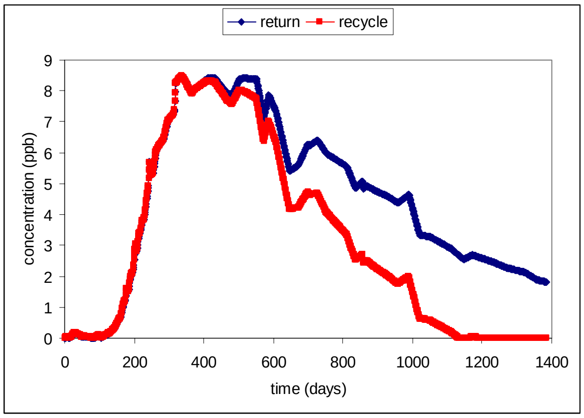

Figure 13. Averaged and recycle-adjusted return curves for the tracer 2,7-nds that was injected into Dixie Valley well 27-32 and measured at the section-33 production wells (Rose et al., 2001a).

NUMERICAL SIMULATION EXAMPLES

At both Beowawe and Dixie Valley, the pore volume calculated using the first-moment-analysis method is less than the pore volume calculated using the return-curve-tail method. In order to explain these differences, we conducted numerical simulation experiments of tracer tests in a highly idealized geothermal reservoir that consisted of an injector/producer doublet. We altered the spacing between the injection and production well while holding the overall reservoir volume constant in order to determine the relative effect of well spacing on the calculated tracer-swept volume.

The grid was designed to simulate the damage zone around a sub-vertical fault. It was 5 km long, 2 km deep, and 100 m thick. This reservoir/grid was buried by a 1-km deep overburden. Three pairs of injector/producer well doublets with interwell spacings of 1, 3, and 5 km were placed in the reservoir at a depth of 2.5 km.

The code used to develop the model was TOUGH2 (Preuss, 1991), version 2 with the EOS1 module and the PetraSim (Swenson and Hardeman, 2003) user interface. Permeability, porosity, and injector-producer flow rates were held constant at 0.025 Darcy, 0.025, and 180 kg/s, respectively. No-flow boundary conditions were enforced.

We used TOUGH2's two-waters option, with the tracer designated as the second water. The tracer was injected as a pulse and none was recycled to the reservoir after its production.

In order to test the effect of interwell spacing on the measured tracer-swept pore volume, the numerical simulation experiment was run for each of the three well pairs. The first model run involved the injector/producer well pair having an interwell spacing of 1 km; the remaining 4 wells were shut in. A pulse of tracer was injected into the injection well and its passage through the reservoir and subsequent production were monitored. The well pairs with 3-km and 5-km interwell spacings were successively flowed in similar fashion. Figure 14 shows tracer pulses flowing through a cross-section of the reservoir for each of the three cases.

Figure 15 shows the return curves resulting from each of the three cases shown in Figure 14. Using the first-moment-analysis technique described above, the volume swept by the tracer was calculated for each case. Shown in column 2 of Table 2 are the fractional pore volumes swept as the well spacing was increased.

As expected, the swept pore volume increases with the interwell spacing, finally equalling the overall reservoir pore volume for the well pair with the injector and producer positioned at either edge of the reservoir. In a previous numerical simulation study, we showed that the overall pore volume can be approximated by an analysis of the long-tailing portion of the return curve, as described above (Rose et al., 1997). Thus, the two methods converge when the wells are placed at the edges of the reservoir (see Table 2), but the first-moment analysis underestimates the overall reservoir pore volume when the wells are placed away from the edges of the reservoir.

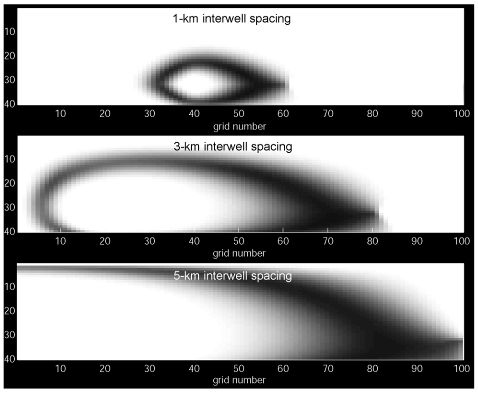

Figure 14. Cross section of the simulated tracer pulse flowing through the reservoir. Not shown are the injection and production wells, which are spaced 1 km, 3 km, and 5 km for the three images respectively.

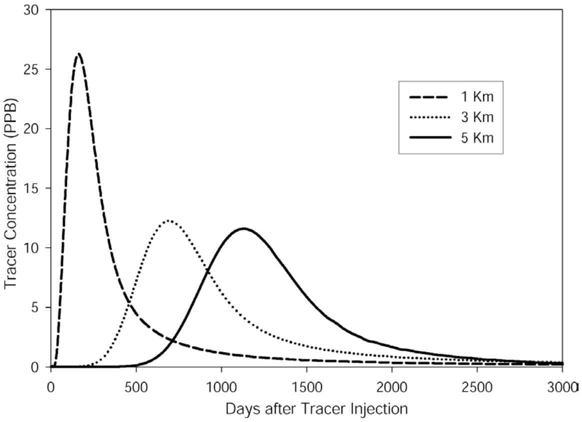

Figure 15. Return curves from the numerical simulation experiment for wells spaced 1, 3, and 5 km, respectively.

Table 2. The fractional pore volume approaches the overall pore volume as the injection and production wells are placed closer and closer to the edges of the reservoir.

Interwell Spacing	**Fractional Pore Volume Based Upon First-Moment Method**	**Fractional Pore Volume Based Upon Return-Curve-Tail Method**
1 km	0.38	1.0
3 km	0.81	1.0
5 km	1.0	1.0

DISCUSSION

The two methods of estimating reservoir pore volume produced different results for both the Beowawe and Dixie Valley tracer-test data. In the case of Beowawe the difference was large (1.8 vs. 18 billion gal). In the case of Dixie Valley, however, the difference was less but still significant (3.7 vs. 9.1 billion gal).

Differences in the estimation of pore volume were expected, however, as indicated by the numerical simulation study. That study showed that if the wells are near the natural boundaries of the reservoir then the two methods converge to the same value. If the wells are far from the reservoir edges, then pore volumes calculated by the two methods differ considerably, indicating that there is a significant volume available for the natural convection and/or diffusion of tracer away from the active forced-convection loops between the injectors and producers.

It is worthwhile to apply both methods, however, since a comparison of values may indicate something about the untapped reservoir. Again, as shown by the numerical simulation study, if the difference between values calculated by using the two methods is large then there may exist a large untapped reservoir adjacent to the exploited reservoir.

SUMMARY AND CONCLUSIONS

Two methods for estimating the pore volume of a geothermal reservoir based upon tracer return-curve data were demonstrated. The first method used a first-moment analysis and calculated the volume swept by a tracer between an injection and production region. For reservoirs with multiple regions of injection and production, the respective interwell volumes are calculated and simply added together to obtain an overall reservoir pore volume. The second method of estimating reservoir pore volume involved an analysis of the long tailing portion of a tracer return curve.

Tracer data from the Beowawe, NV and Dixie Valley, NV geothermal reservoirs were analyzed by the two methods and compared. In both instances, the overall reservoir pore volume calculated from an analysis of the long-tailing portions of return curves indicated a larger volume than the tracer-swept volume calculated using the first-moment-analysis approach, although the difference between the two approaches was less for the Dixie Valley tracer data than for the Beowawe tracer data. A numerical simulation study was conducted in order to investigate the effect of interwell spacing on calculated volumes and to compare reservoir pore volumes calculated by the two methods. The return-curve-tail method should be used with caution, since as seen from the Beowawe data, it seems to greatly overestimate the overall reservoir volume, However, the simultaneous application of both methods may serve to indicate the relative magnitude of an untapped resource adjacent to the exploited reservoir.

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