TRACER TEST ANALYSIS FOR CHARACTERIZATION OF LAUGALAND GEOTHERMAL FIELD

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ABSTRACT

This paper presents the tracer data analysis obtained from the single-phase, conservative tracer experiments conducted during a two-year reinjection project at Laugaland geothermal field in N. Iceland. Three tracer tests were conducted during the two-year period (1997-1999). The tracers injected were sodium fluorescein in Test 1 and Test 3 and potassium iodide in Test 2. We concentrated on Test 1 only, the reasons for which are explained in the paper.

Axelsson et al. (2000; 2001) have conducted a comprehensive analysis of the Laugaland reinjection project tracer test data, including both qualitative and quantitative aspects using multi-flow-channel models. In this study, we focus only on the quantitative analysis of tracer test data using analytical interpretation methods. It has been proved extensively that the first temporal moment analysis leads to an estimation of the tracer swept pore volume in a closed boundary with a balanced injection/production rate scenario. But in this paper, we prove that the first temporal moment does give the swept pore volume, even for open boundaries with an unbalanced rate scenario such as existed at the Laugaland geothermal field. The produced tracer concentration history was used to estimate the interwell reservoir relative flow capacity versus storage capacity (F-C plot). The F-C plot is a simple and powerful semi-quantitative tool to evaluate the conceptual model’s relative flow and storage geometries. The relative flow and storage capacities calculated from the flow channel geometry obtained from multi-flow-channel modeling (Axelsson et al. 2001) for one production well LN-12 agreed well with the continuous F-C plot obtained from the tracer return data. The second temporal moment of tracer production history was used to derive an equivalent dispersion coefficient. The reservoir interwell heterogeneity was characterized using the Lorenz coefficient derived from the F-C plot. The Lorenz coefficient for well pair LJ-08/LN-12 was 0.509, indicating that it is moderately heterogenous.

Reservoir information was obtained for interwell LJ-08/LN-12 and, to some extent, LJ-08/TN-04. The tracer data for other wells could not be analyzed, since the streamlines were not constant, and deconvolution techniques need to be developed to do meaningful interpretation. Recommendations for possible future Laugaland reservoir modeling are offered in order to obtain a better description of the reservoir.

INTRODUCTION

Tracer testing for reservoir description has been applied in the petroleum and geothermal industries and in environmental applications. Tracers are a useful tool for understanding the flow of fluids through reservoirs and contain valuable information about the reservoir properties hidden in its production history. In order to obtain reliable estimates of these reservoir properties, proper quantitative analysis is required. The preliminary information obtained from a tracer contains the flow direction, presence of barriers to the flow, and the relative interwell connectedness. But the tracer data has valuable hidden information about the reservoir properties that can be obtained through quantitative analysis. Several researchers in the petroleum, environmental, and geothermal industries have developed methods to correlate tracer history with reservoir properties. Allison et al. (1991) determined such important reservoir characteristics as layer permeabilities, thicknesses, dispersion, and oil saturation, based on history matching the interwell tracer results using a numerical model. Abbaszedeh-Dehghani et al. (1984) developed techniques to determine reservoir layering and the individual layer’s porosity-thickness and permeability-thickness from well-to-well tracer flow.

The goal of tracer tests in geothermal reservoirs is to provide the reservoir operator with tools to better
understand the reservoir and to achieve optimal production/extraction of thermal energy from the geothermal rocks. Robinson et al. (1984) have developed methodologies for analyzing the internal flow characteristics of fractured geothermal reservoir using tracer-determined residence time distribution curves. Shook (1998) has shown that the moment method yields excellent approximations to the volume of a geothermal reservoir drained by the production well or supported by the injection well for closed boundary, single-phase heterogenous reservoirs. Shook (2003) has also demonstrated that the production tracer history could be used to obtain a flow capacity versus storage capacity plot, which serves as a simple and fast tool to aid in estimating fracture geometry. It indicates relatively what fraction of flow paths occur through what fraction of pore volume.

The Laugaland geothermal field is located in North Iceland. Axelsson et al. (2001) have comprehensively analyzed the tracer data obtained from the two-year reinjection experiment conducted at the Laugaland field. Based on the tracer analysis, their conceptual model produced the theory that the tracer traveled through the area bedrock by two modes: along high permeability and low porosity fractures, and dispersed through the large volume of the reservoir. The tracer recovered was assumed to be flowing through the modeled channels, and the rest of the tracer was dispersed through the large reservoir volume. Axelsson et al. (2001) have conducted cooling predictions that would take place due to long-term reinjection based on their multi-flow-channel model analysis of tracer tests data. Their predictions showed that the reinjection experiment would cause a temperature decline of only 1–3°C in 10 years.

The reinjection experiment included three tracer tests, of which we have reanalyzed the data from the first test only and estimated inter-well reservoir parameters using analytical interpretation methods. No thermal drawdowns were investigated in our analysis. The estimated interwell reservoir parameters could be used in the future for developing the integrated numerical model that is representative of the Laugaland geothermal reservoir.

**THE LAUGALAND GEOTHERMAL FIELD AND TRACER TESTS**

The well layout for the Laugaland geothermal field is shown schematically in Figure 1; and the well details are schematically depicted in Figure 2. The whole reinjection project was conducted for two years, but Test 1 was identified as about the first two-month period, or 67.0 days.

The first tracer test was started on September 25th, 1997 and continued for 67 days. The tracer used was sodium-fluorescein, which was injected into well LJ-08. Steady flow conditions were maintained during the Test 1 period, which would allow the streamlines from the injector to the producer during this period to be unaltered. The effect of temperature change on the mixing of injectate and in situ reservoir fluid may have a small effect on the change of streamlines, but for the purpose of this analysis, the flow conditions were considered as steady and controlled during the two-month period. The flow condition for tracer Test 1 was a constant injection rate maintained at 8.0 l/s in well LJ-08. The only production well on line during these two months was LN-12, at 41.0 l/s. The distance between these two wells, LJ-08 and LN-12, was 300 m.
Although LN-12 was the only production well online during the Test 1 period, the other production wells that had seen the injected tracer subsequently were LJ-05, LJ-07, and TN-04. The production data from well LN-12 during the 67 days was considered good because of the controlled and steady production conditions. Production from well LJ-05 was started only after the first 67 days, yet this well had produced the major fraction of the tracer at the end of two years (21%). The short distance from the injection well LJ-08 would imply that the tracer input function is not an impulse function. The interpretation could not be carried out with confidence for wells LJ-05, because the steady state flow regime was altered, implying the flow streamlines are being altered too. The tracer concentration history of well LJ-05 has to be deconvolved in some manner to be able to account for its dormant state within the first few months of nonproduction and subsequent rate variations and shut in periods during the two-year reinjection experiment. At present, the interpretation of tracer data from well LJ-05 has not been done, as information is insufficient about the distribution of tracer in the reservoir just before production of LJ-05.

An insignificant amount of tracer was produced from well LJ-07 (only 1% in two years) because the well was hardly used; hence, that tracer data was not interpreted. Approximately 6% of the injected tracer was produced during the 2-year period from well TN-04, which was 1800 m away from injection well LJ-08. Even in the case of well TN-04, the steady state flow regime was altered, and the injected tracer is no longer an instantaneous tracer concentration impulse function with respect to well TN-04. But the large distance between wells LJ-08 and TN-04 would allow the assumption that the perturbations in the flow conditions near the injector well are diminished in the larger scale. The declining portion of the tracer concentration was not captured in the time span of measurement for well TN-04, and, hence, extrapolation of the tracer tail was not possible. The tracer data from TN-04 was interpreted until the point of termination.

More detailed information about the tracer tests can be obtained from Axelsson et al. (2001).

**QUANTITATIVE ANALYSIS**

The quantitative analysis performed on the tracer data is described as follows:

1. **Flow Capacity – Storage Capacity**

   Information about relative fraction of flow paths versus swept pore volume (Shook, 2003)

   \[
   f_i = \frac{k_iA_i}{L_i} / \sum_{j=1}^{n_{frac}} k_j A_j / L_j
   \]

   \[
   c_i = \frac{V_j}{\sum_{j=1}^{n_{frac}} V_j}
   \]

   \[
   F_i = F_{i-1} + f_i \quad \text{for } i = 1, \#frac
   \]

   \[
   C_i = C_{i-1} + c_i
   \]

   \[
   C(t) = \frac{\int c_{out} \tau d\tau}{\int c_{out} t dt}
   \]

   \[
   F(t) = \frac{\int c_{out} dt}{\int c_{out} t dt}
   \]

   Lorenz Coefficient, \(L_C = 2\left\{ \int_0^\infty F dC - \frac{1}{2} \right\}\)

   \[
   2. \text{Zero}^{th} \text{Temporal Moment} = \int C_{out} \cdot dt
   \]

   Mass of tracer recovered = \(q_{ext} \int_0^\infty C_{out} dt\)

   \[
   3. \text{First Temporal Moment}, \bar{t} = \frac{\int_0^\infty t \cdot C_{out} \cdot dt}{\int_0^\infty C_{out} \cdot dt}
   \]

   Mean Swept Pore Volume, \(V_p = q_{inj} \cdot \bar{t} \cdot \left( \frac{m_{rec}}{M_{inj}} \right)\)

   \[
   4. \text{Second Temporal Moment}, \bar{t}^2 = \frac{\int_0^\infty \bar{t}^2 \cdot C_{out} \cdot dt}{\int_0^\infty C_{out} \cdot dt}
   \]
A more detailed description of the flow capacity versus storage capacity can be obtained from Shook (2003). A brief description is given here. The flow capacity of any given fracture is proportional to the volume of fluid it carries and the fracture length itself. The incremental flow capacity of the $i^{th}$ fracture is the ratio of that fracture’s flow capacity to the total network’s flow capacity. The fractional storage of the $i^{th}$ fracture is pore volume of that fracture divided by the total fracture pore volume. The flow capacity, $F$, and storage capacity, $C$, are simple summations of the individual fracture $f_i$ and $c_i$.

The equivalent dispersion coefficient (Neretnieks, 1983) was calculated from the second temporal moment. This is equivalent to the case when the tracer spreading has taken place in a one-dimensional infinitely long homogenous system between the injection and extraction points. The equivalent dispersion coefficient serves as a means of quantifying the tracer spreading.

**Testing the Validity of First Temporal Moment for Unbalanced Rates, Open Boundary Porous Media**

The hypothesis to be tested is that the first temporal moment of a producer tracer concentration history leads to the determination of inter-well swept pore volume in the case of unbalanced rates and an open boundary reservoir. A simple synthetic model was set up to test the validity of first temporal moment analysis for these conditions. In order to compare the tracer-deduced swept volume, the swept volume is also determined geometrically from the tracer concentration (binary data) contour and streamline velocity vector contours. The analysis of the binary tracer concentration data and streamline velocity vector contour are subject to interpretation error and therefore considered to give only approximate estimates. The schematic diagram of the 2D synthetic model with the well placement, rates, and boundary conditions is shown in Figure 3. The streamline velocity vector contour for this synthetic model is shown in Figure 4. The results of comparison of the swept pore volume calculated from tracer concentration contour (282.0 m$^3$) with the temporal moment method (280.1 m$^3$) shows a difference of 0.7%, while the swept pore volume calculated from streamline velocity vector contour (245.6 m$^3$) with the temporal moment method shows a difference of 14.0%. Hence, it is proved for the simple case that the first temporal moment gives the swept pore volume, even for unbalanced rates and open boundary system. Various other geometries, boundary conditions and flow rates were studied as well. All results confirmed that swept volume could be determined for tracer tests using Equation 8.

**ANALYSIS OF LJ-08/LN-12 TEST1 TRACER DATA**

We analyzed and interpreted the tracer data from well LN-12 in Test 1. The measured tracer concentration history for the first 67.0 days is shown in Figure 5. The assumptions of steady-state flow and pulse injection hold good during the first couple of months. The validity of applying the temporal moment analysis to an open boundary, unbalanced injection/production rate scenario was proved before proceeding to interpret the LJ-08/LN-12 tracer data. At 67.0 days, numerical integration shows the swept pore volume was 850.0 m$^3$ and the tracer recovery was 4.7%.

![Figure 3. 2D synthetic model schematic diagram showing well locations and boundary conditions.](image-url)
The tracer concentration data from 26.0 to 37.0 days were matched with an exponential curve, as shown in Figure 6, to obtain the parameters describing the curve fit. Using the last available concentration measured at 67.0 days, the tail was extrapolated as shown in Figure 7.

At 23 months, the analysis based on the extrapolated tracer tail curve shows a total swept pore volume of 3181.6 m$^3$. At infinite time, the swept pore volume did not change significantly and was 3181.9 m$^3$, and the mean injectate residence time was 62.0 days. The cumulative tracer recovery history from the zero$^{th}$ temporal moment is given in Figure 8. At the end of 23 months, the cumulative tracer recovered was 7.3%, whereas the analysis done by Axelsson et al. (2001) estimated 8.0 % recovery. The variance of the tracer concentration history was calculated to be 3801.0 day$^2$, the equivalent dispersion coefficient 1438.0 m$^2$/day, and the equivalent dispersivity 297.0 m.

Axelsson et al. (2001) developed a three-channel flow model connecting wells LJ-08 to well LN-12 whose simulated tracer production history was in excellent agreement with the measured tracer concentration history. Based on the channel flow geometry, the discrete flow capacity and storage capacity values of the fractures were calculated, as shown in Table 1. The discrete fractional flow and storage capacity points were plotted on the continuous tracer-derived F-C curve. We were encouraged to see these discrete points fall closely on the F-C plot (shown in Figure 9), constructed from the production tracer history of well LN-12. The heterogeneity of the inter-well reservoir was characterized using the Lorenz coefficient. The Lorenz coefficient (Lake 1989) is one of the commonly used measures of reservoir heterogeneity and is defined as the area between the F-C curve and a 45$^\circ$ line (homogenous F-C curve) and normalized by 0.5, as given in equation (4). The extremes of the Lorenz coefficient

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**Figure 4.** Streamline velocity vector contour from the synthetic model.

**Figure 5.** Tracer concentration history produced from well LN-12 during Test 1.

**Figure 6:** Tracer concentration data matched with an exponential curve.

**Figure 7:** Extrapolated LN-12-produced tracer concentration history curve.

**ANALYSIS OF LJ-08/TN-04 TEST 1 TRACER DATA**

Well TN-04 is at a distance of 1.8 km from the injection well and, therefore, the perturbations in the flow field near the injector well are considered to be negligible. The tracer concentration history from well TN-04 is given in Figure 10. The tracer history in TN-04 had not begun declining, and hence could not be extrapolated to infinity.

The temporal analysis on the available data gave the following results. At the end of 23 months, the calculated mean residence time was 521.0 days, mean flow velocity $4.0 \times 10^{-5}$ m/s, tracer recovery 5.6 %, injectate/tracer swept pore volume 20,475 m$^3$, and equivalent dispersivity 109.6 m. Axelsson et al. (2001) developed a single flow-channel model connecting wells LJ-08 to well TN-04 whose simulated tracer production history was in excellent agreement with the measured tracer concentration history until the point of termination. The single flow-channel model analysis gave the results of mean flow velocity $3.5e-5$ m/s, flow-channel cross-sectional area 360 m$^2$ (assuming a porosity of 7%), dispersivity 97 m, tracer recovery 6.0% at 23 months and 7.2% at infinite time. In the single flow-channel model, the mean tracer residence time calculated from the interwell distance and mean flow velocity was 595.2 days and the flow-channel pore volume was 45,360 m$^3$. Axelsson et al. (2001) results agree reasonably well with our analysis results other than the tracer swept pore volume as compared to the single flow-channel pore volume. The reason for this difference could be explained due to the different approaches and the different time scales used. Our analysis was based on an analytical method (Equation 8) while Axelsson et al. (2001) adopted a channel-flow model approach that could be non-unique. Also, we used the tracer data only until the point of termination at which point the tracer concentration had not even begun declining, whereas the channel model would simulate the produced tracer concentration history beyond the point of termination until infinite time. Because our analysis truncates the tracer history prematurely, our pore volume estimate

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**Table 1: F-C parameters calculated from the channel geometry data (Axelsson et al. (2001)).**

<table>
<thead>
<tr>
<th>Fracture #</th>
<th>Length (m)</th>
<th>Porosity</th>
<th>$u$ (m/s)</th>
<th>A (m$^2$)</th>
<th>$C_l$ - Frac Vp</th>
<th>$F_l$ - Frac Vp</th>
<th>$F_l$ - Frac Vp</th>
<th>R</th>
<th>C</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>0.07</td>
<td>7.3E-04</td>
<td>1.49</td>
<td>23.4</td>
<td>1.02E-03</td>
<td>3.48E-05</td>
<td>0.021361</td>
<td>1.48E-01</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>500</td>
<td>0.07</td>
<td>4.6E-04</td>
<td>7.57</td>
<td>295</td>
<td>3.63E-03</td>
<td>1.37E-05</td>
<td>0.214303</td>
<td>6.40E-01</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1000</td>
<td>0.07</td>
<td>1.70E-04</td>
<td>15.43</td>
<td>1080</td>
<td>2.62E-03</td>
<td>2.48E-06</td>
<td>1.10E+00</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
is low. The extent it is low cannot be inferred from the analysis. The extent to which Axelsson et al. (2001) obtain a good match of the tracer data suggests their model captures the character of the LJ-08 - TN-04 flow zone.

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**SUMMARY AND CONCLUSIONS**

The first tracer test period extended from September 25 to November 30, 1997 (about a 2-month period). Controlled and stable conditions were maintained in the reservoir. Analysis of the tracer concentration history using the temporal moments was conducted and useful reservoir information was obtained, which included the inter-well mean residence time, swept pore volumes, equivalent dispersion coefficients, flow-storage capacity plot, and Lorenz coefficient.

The flow-storage capacity plot obtained from tracer data for well LN-12 agreed well with the discrete F-C points calculated from the channel geometry estimated by Axelsson et al. (2001). The F-C data can be used to constrain a numerical model.

Well LJ-05 did not have steady flow conditions in the reservoir, as was maintained for LN-12, because of the unsteady production flow rates beyond the first two months. After two months, the flow streamlines would have changed, since the other wells started producing too. Hence, the tracer data were not interpreted using the moment analysis method.

No tracer concentration history data were available for well LJ-07.

Tracer breakthrough in well TN-04 occurred about May 1998. The declining portion of the tracer concentration history for well TN-04 was not measured, and, hence, the tail could not be extrapolated. The tracer data from TN-04 was interpreted until the point of termination. The mean residence time, mean flow velocity, and equivalent dispersivity estimates obtained from the temporal analysis agreed reasonably well with the single flow channel model analysis by Axelsson et al. (2001).

The possible direction for future Laugaland reservoir description would be to develop a complex reservoir model based on data from all available sources, such as interwell tracer data, pressure tests, well logs, seismic data, and core analysis. This modeling approach would involve history matching of all production tracer histories even at unsteady state conditions. This numerical model could be used as a tool to predict the temperature drawdown history due to long-term reinjection.
NOMENCLATURE

\( A_i \) Mean cross-sectional area of the \( i^{th} \) fracture

\( c_i \) Incremental storage capacity of the \( i^{th} \) fracture

\( C \) Storage capacity

\( C_{out} \) Produced tracer concentration

\( D_t \) Equivalent dispersion coefficient

\( f_i \) Incremental flow capacity of the \( i^{th} \) fracture

\( F \) Flow capacity

\( F_i \) Cumulative flow capacity function of the fracture network

\( k_i \) Permeability of the \( i^{th} \) fracture

\( L_c \) Lorenz coefficient

\( L_i \) Length of the \( i^{th} \) fracture

\( m_{rec} \) Mass of tracer recovered

\( M_{inj} \) Mass of tracer injected

\( q_{ext} \) Production flow rate

\( q_{inj} \) Injection flow rate

\( t \) Time

\( \bar{t} \) First Temporal Moment (Mean Residence Time)

\( \tilde{t} \) Second Temporal Moment

\( \bar{U} \) Mean Flow Velocity

\( V_p \) Swept pore volume

\( V_{pi} \) Pore volume of the \( i^{th} \) fracture

\( x \) Distance in flow direction

\( \alpha \) Dispersivity

\( \sigma^2 \) Variance

\( \sigma_i^2 \) Injection tracer function variance

\( \sigma_{in}^2 \) Produced tracer function variance

REFERENCES


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