RESERVOIR INVESTIGATIONS ON THE HOT DRY ROCK GEOTHERMAL SYSTEM, FENTON HILL, NEW MEXICO: TRACER TEST RESULTS.

Timothy J. Callahan
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

ABSTRACT

A closed-loop circulation test was conducted from 10 May to 14 July 1995 on the Hot Dry Rock (HDR) reservoir at Fenton Hill, New Mexico after a hiatus of nearly two years. Changes in heat transfer and reservoir volume were investigated and compared to previous circulation tests. Chemical tracers can be used to measure the volume of flow paths in hydrologic systems. Usually, tracers are used in low temperature situations, but the application to high temperature systems has been established for certain tracer compounds. During the 1995 flow testing at Fenton Hill, both a conservative and a non conservative tracer were injected into the reservoir in each of two separate experiments. The purpose was to determine the volume of the most direct flow paths and to estimate the total volume of fractures in the system. The results indicate a relatively static reservoir volume between June and July, yet with an increase in flow dispersion. It can be assumed that channeling of flow did not occur in the main body of the reservoir due to continuous operation. However, a new flow path adjacent to the injection well did develop, and its affect on reservoir flow was investigated using tracer technology. The tracer data collected during that period shows that there is a minor contribution of flow from a previously under-developed region of the HDR reservoir.

INTRODUCTION

The goal of the recent circulation test at Fenton Hill was to show that heat can be extracted from a Hot Dry Rock reservoir for an extended period of time without greatly reducing the temperature of the produced fluid. Furthermore, it was hoped that by injecting certain chemical tracers, a better understanding of the spatial characteristics of the reservoir would be obtained, especially concerning fluid flow paths.

Table 1: Reservoir conditions for tracer tests of the HDR reservoir at Fenton Hill, NM.

<table>
<thead>
<tr>
<th>Date of test</th>
<th>Average injection press. (kg/cm²)</th>
<th>Average production flow rate (kg/s)</th>
<th>Average production press. (kg/cm²)</th>
<th>Average water loss rate (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/18/92</td>
<td>273</td>
<td>6.21</td>
<td>99</td>
<td>0.85</td>
</tr>
<tr>
<td>4/12/93</td>
<td>279</td>
<td>5.72</td>
<td>99</td>
<td>0.47</td>
</tr>
<tr>
<td>5/15/93</td>
<td>271</td>
<td>7.70</td>
<td>99</td>
<td>-0.25*</td>
</tr>
<tr>
<td>6/06/95</td>
<td>279</td>
<td>6.62</td>
<td>99</td>
<td>1.13</td>
</tr>
<tr>
<td>7/11/95</td>
<td>279</td>
<td>5.87</td>
<td>155</td>
<td>0.52</td>
</tr>
</tbody>
</table>

*the negative water loss was due to the increased fracture expansion during tests conducted after the LTFT proper.
Volume parameters determined from these tracer tests are shown in Table 2.

**EXPERIMENTAL PROCEDURE**

For the tracer tests conducted at Fenton Hill in June and July 1995, both sodium fluorescein and para toluene sulfonic acid (p-TSA) were used to study the flow path characteristics of the HDR reservoir. Fluorescein is considered a non conservative tracer compound for reasons discussed below, yet it can be measured easily in the field, thereby providing a fairly accurate first-arrival time.

**Test 1 (6 June 1995)**

A solution containing 200 g of fluorescein and 200 g of p-TSA was injected into the make-up water at 0700 hours on 6/06/95. The make-up water was then added to the circulating fluid which was subsequently injected into the reservoir. The production water was sampled every 30 minutes, starting at 1200 hours, until the tracer was detected at 1400 hours, at which time the sampling interval was adjusted to every 15 minutes. At each sampling time, about 20 ml of unfiltered production fluid was collected in plastic vials for dye analysis, and about 75 ml of unfiltered production fluid was collected in glass bottles for later p-TSA analysis. The fluorescein dye was analyzed on-site, according to the methods outlined in LANL memo EES-4-92-124. The p-TSA samples were analyzed in the EES-1 chemistry laboratory in Los Alamos.

**Test 2 (11 July 1995)**

A similar procedure was followed for the second tracer test. The two tracers were injected at 0724 hours on the morning of 7/11/95. During this second test, the flow from the annulus of the injection well (EE-3A) was also sampled every 30 minutes, beginning at 1315 hours, to monitor the arrival and response curve of the tracers from the injection well annulus.

**RESULTS AND DISCUSSION**

By studying the tracer recovery patterns from the reservoir, we are able to infer changes in flow path characteristics. For example, Figures 1 and 2 illustrate the tracer response curves of p-TSA for five different tracer tests conducted at Fenton Hill. These graphs show the data corrected for the redundant tracer response caused by re-injection of the produced fluid during the closed-loop flow test. The corrections were made using the computer code tracer_reduce, a program that determines the concentration of fluorescein and p-TSA relative to the production fluid mass flow rate and the fluid density (Robinson, 1992a). The corrected data is displayed here as the residence time density (distribution) versus total produced fluid during each test. The residence time density is a function of the time required for any one fluid pulse to travel across the reservoir. It is plotted against produced volume, rather than elapsed time, in order to compare tracer tests run at different production flow rates.
Table 2: Results of tracer tests of the HDR reservoir at Fenton Hill, NM.

<table>
<thead>
<tr>
<th>Date of test</th>
<th>Fluorescein</th>
<th>p-TSA*</th>
<th>p-TSA</th>
<th>Fluorescein</th>
<th>p-TSA</th>
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<th>p-TSA</th>
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<tbody>
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<td>5/18/92</td>
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<td>320</td>
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<td>2246</td>
<td>79</td>
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<td>4/12/93</td>
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<td>658</td>
<td>6579</td>
<td>2034</td>
<td>124</td>
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<tr>
<td>5/15/93</td>
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<td>n.d.</td>
<td>358**</td>
<td>3558</td>
<td>n.d.</td>
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<td>6/06/95</td>
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<td>610</td>
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<td>1789</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>7/11/95</td>
<td>478</td>
<td>357</td>
<td>743</td>
<td>8376</td>
<td>1630</td>
<td>111</td>
<td></td>
</tr>
</tbody>
</table>

n.d.: no data collected
*p-TSA: para-toluene sulfonic acid

The p-TSA data from the 1995 tests gives an integral mean volume of 1789 m³ for June and 1630 m³ for July (Table 2). Unfortunately, these values are only estimates of the total volume of the reservoir flow paths because of the inaccuracy in predicting the "tail" of the tracer response curve. At face value, the response curves indicate that the volume of the reservoir has increased between June and July 1995. However, the program tracer_reduce estimates the amount of tracer remaining in the reservoir to calculate the remaining tracer response curve. During the July test, the flow rate out of a known leakage path through the injection well annulus was 1.58 kg/cm², substantially higher than during any of the past tracer tests. Therefore, the 200 grams of each tracer did not reach the reservoir. This annulus flow was monitored to determine the amount of tracer lost and the corrected amounts were used in tracer_reduce to calculate the distribution curves for the July test. Nonetheless, this change in injection conditions for the July experiment caused uncertainty in tracer behavior within the reservoir.

The p-TSA data shows a decrease in integral mean volume between June and July, whereas the fluorescein data indicates an increase. Because fluorescein degrades under moderate to high temperatures (Adams and Davis, 1991), p-TSA, as a conservative chemical, is considered to be a more reliable tracer in the HDR reservoir. It has been shown (Adams and Davis, 1991) that under certain reservoir conditions (e.g., in flashed geothermal waters, where pH increases), there is minimal fluorescein degradation. However, the pH of the Fenton Hill reservoir is slightly acidic, which may cause reaction of fluorescein with dissolved oxygen. Furthermore, fluorescein may be adsorbing onto rock surfaces within the reservoir (Adams and Davis, 1991), thus indicating an apparently longer residence time. A more bold assertion is that higher temperatures were encountered during the July test, thus causing more fluorescein degradation. Further investigation is needed to argue for or against this inference.

A separate analysis of the tracer response curve gives the modal volume for each test. The modal volume represents the volume of produced fluid from the time of the tracer injection to the moment the maximum tracer concentration is recovered. This is the volume of low-impedance fracture connections which follow the most direct routes from the injection well to the production well, as discussed by Robinson and Tester (1984). Comparing the modal volume from one test to another may be a more accurate way to examine flow path changes in the reservoir over time, as opposed to comparing the integral mean volumes of different tests. As shown in Table 2, the modal volume is larger for the June 1995 test than the July test. The difference in the modal volumes may be due to the presence of more direct flow paths in the reservoir. The modal volume determination is semi-
quantitative, because in most cases, an estimation of the center of the peak tracer response is used as the direct flow path volume.

Further data analysis provides the dispersion volume; that is, the volume (width) of the tracer response curve at 3/4 the maximum peak height. Like the modal volume, this value is semi-quantitative, yet it can allow comparisons of the varying tracer dispersion in tests conducted under different operating conditions (Table 2). The July 1995 test shows a higher degree of dispersion than for the June test.

Figure 3 is a plot of the cumulative tracer recovered from the production well for the June and July 1995 experiments. For the July test, the amount of tracer lost in the short circuit of the injection well was subtracted from the initial amount of 200 grams for each tracer placed into the make-up water line, as explained in the procedural section above (it was assumed that all 200 grams of each tracer was injected into the reservoir during the June test). The lower recovery of fluorescein compared to p-TSA is most likely due to thermal effects, as explained above. The noticeable difference between the two fluorescein data sets may also be due to the tendency for fluorescein to decay under high temperatures. This leads to the assumption that higher reservoir temperatures were encountered during the July test.

To investigate the flow characteristics in the reservoir region accessed by the injection well annulus, the outflow from the injection well annulus was sampled for fluorescein dye during the July 1995. The annulus flow rate was markedly higher during the July test, an average of 1.58 kg/cm² compared to 0.32 kg/cm² during the June test. The results for fluorescein are discussed for the annulus flow rather than for p-TSA because more data were collected for fluorescein, and it can be assumed that there is less fluorescein decay in this cooler region of the reservoir. The flow was sampled every 30 minutes, beginning 8 hours after tracer injection. First arrival of the fluorescein was measured as 19 ppb nearly 13 hours after injection of the tracer. The concentration after 13.5 hours jumped to 2000 ppb (Figure 3), and then gradually decreased to 23 ppb by t₀ + 20 hours.

Figure 4 illustrates the re-injection of tracer recovered from the production well. This shows that a new flow path within the reservoir developed between the time of the first and second tracer tests of 1995. Because the tracer response occurred in a short amount of time, it can be assumed that this new flow path is of relatively small volume. The flow from the annulus during the June test indicates a more tortuous history in this region. However, the total volume of this region of the reservoir may be substantial (Table 3).

In early June 1995, the pressure on the annulus outflow port was about 10.6 kg/cm² and increased steadily until it reached 21.2 kg/cm² on 6 July, when the valve was opened to release the back pressure. The flow rate increased quickly to 1.89 kg/cm² and the resulting pressure drop no doubt reflected the
opening of a flow path in the reservoir near the injection well. Because operating conditions were normal during the June test, this annulus flow was only sampled twice during the June 1995 test. The fluorescein concentration at 1 hour + 7.5 hours was 120 parts per billion (ppb), twice as much as the peak concentration measured from the production well. In the following three weeks, the annulus fluid was monitored for fluorescein on a weekly basis (Table 3) and the concentration decreased continuously over that time. This data indicates that the main flow pattern is similar to that seen in the main body of the reservoir. However, Figure 4 shows that there is apparently a "short circuit" path from the injection well to the inner annulus that developed over the course of the 1995 flow test. This figure also shows that the second peak of tracer response in the annulus fluid closely resembled the dispersion in the reservoir. The circulation test at Fenton Hill was a closed-loop system, therefore the dispersed tracer was re-injected, causing an apparent duplication of the dispersion pattern.

CONCLUSIONS

Only the p-TSA data are discussed below (with one exception) due to the conservative (non reactive) nature of this chemical at high temperatures. The analysis of the recent tracer test data provides three general conclusions on the state of the Fenton Hill reservoir.

1.) The modal volume decreased slightly for p-TSA between June and July 1995 (Table 2), whereas the first arrival volume and the dispersion volume increased. This indicates that there may have been an increase in flow dispersion within the reservoir. The modal and first arrival volumes are less than those measured in April 1993 during the LTFT, yet greater than at the beginning of that flow test (May 1992; see Table 1). There was also a more dispersed flow in the July test than in April 1993, which indicates that the HDR reservoir, under the right operating conditions, can be shut in for a long period of time with no decrease in flow dispersion. This is a positive characteristic in terms of heat extraction. In May 1993 (just after the end of the LTFT, but before the reservoir was shut in) a tracer test was conducted on the HDR reservoir using only fluorescein. The modal volume was 314 m$^3$; the first arrival volume was 105 m$^3$. The tracer data collected during the LTFT of 1992-93 illustrates the gradual change of the HDR reservoir, at first with a substantial proportion of large volume flow paths, to one with more small volume flow paths. Yet in May 1993, it seems as though a reversal of this effect occurred. A large increase in production flow occurred; in fact, the production flow rate exceeded the injection flow rate (Table 1). It seems as though new, large volume flow paths were opened by tests on the HDR reservoir after the end of the LTFT proper. Even though the reservoir was on stand-by for nearly two years, the reservoir flow appeared to be as diverse, if not more so, in the summer of 1995 than in April of 1993.

If this were the case during the LTFT, the increase in modal volume and first arrival time during the 1995 flow test seems to follow a pattern similar to that measured up through April 1993. In late June 1995, surge flow tests were run on the reservoir for four hours per day for a span of 6 days. Such experiments may be the cause of the increase in modal volume and first arrival time as the reservoir was inflated. It is uncertain what effect continuing the surge tests would have on the nature of the flow paths in the reservoir. Future modeling work is scheduled to examine the fluid flow processes that cause changes in dispersion within reservoir systems like that at Fenton Hill, New Mexico.
2.) The integral mean volume of the reservoir (the volume of all paths contributing to flow) decreased only marginally between June to July 1995. The amounts of tracer recovered in both the June and July tests for p-TSA are almost identical, and the integral mean volume varied by less than 10 percent. The change in integral mean volume between May 1992 and April 1993 was also only a 10 percent decrease for p-TSA. This variance is considered to be within standard error for the integral mean volume measurement. On the other hand, there was a large decrease (for fluorescein) as determined in the May 1993 tracer test. As mentioned above, it is believed that a more direct flow path network was opened due to increased reservoir stimulation. Generally, these tracer tests show that under controlled conditions, a relatively constant volume of rock is accessed by introduced fluid for continuous heat extraction.

3.) There was a large discrepancy in fluorescein recovery between the two tracer tests (Figure 3). The recovery patterns for the non reactive tracer (p-TSA) during the two tests were nearly identical. Because fluorescein reacts thermally and temporally, it may be inferred that either higher reservoir temperatures were encountered, or that the reservoir flow was more circuitous during the July test. The latter explanation can be discounted because the modal volumes and integral mean volumes were relatively constant between June and July. Another possibility concerns the chemistry of the operating fluid in the HDR reservoir. Due to the CO₂ (aq) concentrations, the water is slightly acidic. Adams and Davis (1991) have shown the effects of pH on fluorescein degradation. Nonetheless, this hypothesis can be ruled out also, as there was no significant change in water chemistry during the 1995 flow test. The only remaining explanation for a decrease in fluorescein recovery is temperature effects. Therefore, the fluorescein recovery during a tracer test may be used as a qualitative assessment of heat extraction fluctuations in geothermal reservoirs.

4.) The flow out of the injection well annulus was monitored continuously for tracer concentration during the July 1995 test. Figure 4 shows that a pulse of fluid with a high concentrations of fluorescein traveled in a relatively straight path down the injection well and back up the annulus. The second pulse of tracer in the annulus flow resembles the main response out of the production well due to re-injection of the tracers. It is possible that there was a contribution of tracer from the reservoir adjacent to the injection well, but it is more likely that the concentration in this flow was less than that in the re-injected flow, and thus the two are indistinguishable. Only 30% of the total flow sampled from the injection well annulus was recovered during the “short circuit” (this volume contained most of the tracer mass accounted for in the annulus flow), therefore the other 70% of the annulus flow was re-injected water over the course of the test or was from the reservoir accessed by the injection well annulus. Thus, the new flow path accounts for only a small proportion of the fracture volume within this region of the reservoir. Consequently, heat extraction from the main reservoir was not hindered substantially from this increase of annular flow.

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REFERENCES


