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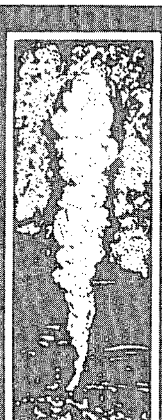

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RESPONSE OF EAST MESA AND RAFT RIVER RESERVOIRS TO INJECTION-BACKFLOW TESTING

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ABSTRACT

Analysis of tracer recovery curves from injection-backflow testing at two geothermal reservoirs reveals large differences in response between the two. The East Mesa reservoir is in a layered sandstone matrix, and tracer behavior can be adequately described by porous media theory. As the volume of water injected into the reservoir increases and, consequently, the depth of penetration into the formation, the ratio of dispersive flux to advective flux decreases, indicating the increasing importance of advective transport. This effect can be seen in normalized tracer recovery curves that become more symmetrical with greater injection volume. At the Raft River site, the reservoir is dominated by a single major fracture zone. Injecting larger volumes of water into the fracture does not change the shape of the normalized tracer recovery curves. This indicates that the dispersion coefficient increases proportionally to the distance traveled by the injection front. Differences in the shape of tracer recovery curves are related to fundamental differences in reservoir characteristics. Long tails on the tracer recovery curves at Raft River suggest a dual porosity reservoir with a secondary fracture network connected to the major fracture. Such findings may considerably affect calculations of secondary heat recovery using injection wells.

INTRODUCTION

Injection of spent geothermal fluids to maintain reservoir pressure may have the undesirable side effect of lowering the enthalpy of production fluids. Because of the fractured nature of many geothermal resources, they are frequently difficult to characterize. Without adequate characterization, it is difficult to predict the effects of injection. Tracer breakthrough tests (Horne, 1982; Fossum and Horne, 1982) have been used to study interconnections between wells where tracer travel times are on the order of days to a few weeks. Since breakthrough does not always occur within this time frame, alternative reservoir evaluation techniques have been proposed.

One such alternative under development is injection-backflow testing. This type of test consists of injecting water labeled with tracer(s) into a well for a predetermined period of time and then, immediately or after a quiescent period, withdrawing this labeled water through the same well. Tracer concentration is monitored to quantify the degree of mixing between injected and reservoir fluids. This type of testing provides enhanced ability to evaluate fracture-dominated geothermal systems and can assist in addressing concerns associated with long-term thermal breakthrough.

Methodology for interpretation of interwell tracer tests is well established (Lenda and Zuber, 1970; Grove and Beeten, 1971; Vetter and Zinnow, 1981). Single-well injection-backflow tests have been used to study the dispersion and adsorption characteristics of porous media reservoirs (Sternau et al., 1966; Drever and McKee, 1980; Pickens et al., 1981). Recently, methods have been developed to study interwell tracer tests in fractured reservoirs where well connections are along one or a few major fractures (Fossum and Horne, 1982; Horne and Rodriguez, 1983). Most of these techniques are based on an analytical solution to the advection-dispersion equation. The equation derived by Ogata and Banks (1961) for continuous injection and one-dimensional flow, in either porous media or in a single fracture, is:

$$C = \frac{Co}{2}\left\{\operatorname{erfc}\left(\frac{1-\tau}{2\sqrt{\xi\tau}}\right) + \exp(\xi^{-1})\ \operatorname{erfc}\left(\frac{1+\tau}{2\sqrt{\xi\tau}}\right)\right\} \quad (1)$$

where

C = measured tracer concentration

Co = injected tracer concentration

erfc = complementary error function

τ = reduced time = t/t_0

t_0 = x/v

x = distance to measurement point

v = average linear velocity

ξ = D_L/vx = ratio of dispersive to advective flux

D_L = longitudinal dispersion coefficient.

When the ratio $D_L/vx < 0.005$, the product of the exponential and complementary error functions becomes negligible. Under such conditions, Equation 1 produces the symmetrical sigmoidal curve commonly associated with solute transport. When D_L/vx is large ($D_L/vx > 0.05$), the curve produced by Equation 1 is far from symmetrical.

Analytical solutions for radial-flow geometry have been presented by Hoopes and Harleman (1967) and Gelhar and Collins (1971). These solutions, however, are not applicable to situations where dispersive flux is significant relative to advective flux. Therefore, analytical solutions available for radial flow conditions cannot be used where injection is for a relatively short time period, and the injection plume remains near the well.

To aid in the refinement of the injection-backflow technique of well testing, two series of injection-backflow tests have been conducted. The first test sequence was carried out at the Raft River geothermal field in southern Idaho, and the second conducted during the summer of 1983 at the Republic geothermal field near East Mesa, California.

For preliminary analysis of test data collected from these two sites, simple one-dimensional analytical solutions are used to evaluate differences between tests, wells, and sites. Because many of the tests were conducted under circumstances where dispersive flux is important compared to advective flux, analytical solutions available for radial-flow geometry are not applicable. Further data analysis, using numerical simulations, will be conducted to refine the conceptual models of the two geothermal reservoirs and to estimate reservoir parameters.

EAST MESA

The East Mesa geothermal field is located in southern California, just northeast of El Centro. The reservoir is composed of interlayered sandstones and shales and is representative of a porous media reservoir. Wells 56-19 and 56-30 at the East Mesa facility were tested using the injection-backflow technique. Well 56-19 was completed as an injection well, although it has not been used extensively since the initial production tests. The well has 580 m of slotted liner and is highly productive with a productivity index of 1780 kg/hr/kPa. Spinner logs made during testing show 80 to 90 m of producing zones in the wellbore. Well 56-30 was completed as a production well and has been flowed for extended periods of time. The well has approximately 680 m of slotted liner, but only about 40 m of this length appears to produce geothermal fluids. The productivity index of Well 56-30 is 160 kg/hr/kPa, or about 10% that of Well 56-19.

These two wells were subjected to a parametric testing program designed to evaluate two injection variables, rate and volume. Tracer recovery data obtained from backflow portions of four of the East Mesa tests are shown in Figures 1 and 2. The data have been normalized, with reduced volume being the ratio of fluid recovered to fluid injected and reduced concentration being the ratio of tracer concentration measured to tracer concentration injected. In addition to measured tracer breakthrough, theoretical tracer breakthrough curves, calculated from Equation 1, are shown in the plots. These curves were fit to the early time recovery data (reduced volume <1) for each of the tests. These curves are described by the ratio of dispersive flux to advective flux (D_L/vx).

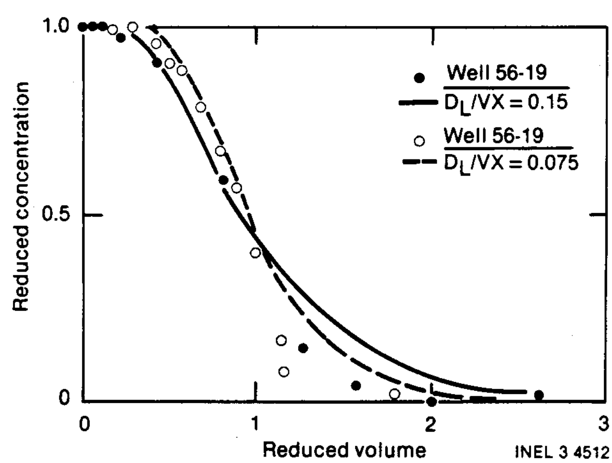

Figure 1. Tracer recovery from Test 4 (•) and Test 6 (o) on Well 56-19, East Mesa. During Test 4, 840 m^3 of tracer solution was injected and during Test 6, 1640 m^3 was injected into the well. The curves were calculated using Equation 1 and D_L/vx values indicated in the figure.

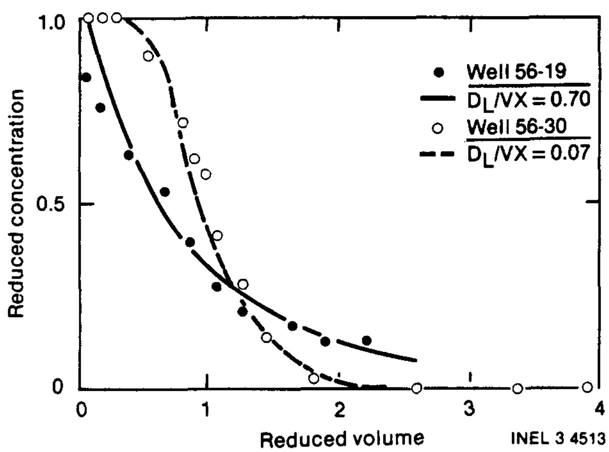

Figure 2. Tracer recovery after injecting 780 m^3 into Wells 56-19 and 56-30 at East Mesa. The curves were calculated using Equation 1 and D_L/vx values indicated in the figure.

Results from Tests 4 and 6 conducted on Well 56-19 are shown in Figure 1. Both tests were conducted at equal injection and backflow rates, but twice the volume of water was injected during Test 6. The calculated dispersion-advection ratio for the longer test is half the ratio for the shorter test. With a greater volume of fluid injected, the distance the front moved into the formation increased. This increased x in the D_L/vx ratio and, therefore, decreased the value of the overall ratio.

Results from Test 3 on Wells 56-19 and 56-30 are shown in Figure 2. Test 3 on both wells was at the same rate and of equal injected volume. The dispersive to advective flux ratio is very different for the two wells, with the ratio for Well 56-19 being about 10 times the ratio for Well 56-30. This suggests that the two wells have greatly different dispersive characteristics, or that the injected front travels significantly farther from the wellbore of Well 56-30. Because of the correlation between the productivity indices and the D_L/vx ratios, the change in ratios is probably related to a reservoir property. The most likely candidate is the length of the producing zone. Spinner surveys show twice the length of producing zones in Well 56-19 as in Well 56-30.

Tracer recovery curves from East Mesa wells follow behavior that corresponds to conventional theory for porous media. Analysis and interpretation of the data will be refined using radial-flow geometry and a numerical simulation code.

RAFT RIVER

The Raft River geothermal well field is located in southern Idaho and has been studied since the mid-1970s. Extensive data have been collected that show that the reservoir is fracture dominated and not amenable to conventional reservoir analysis (Dolenc et al., 1981; Russell, 1982).

The test well selected at Raft River was RRGP-5, a 1432-m deep production well. This well has been subjected to a series of tests including an experimental hydrofracture for well stimulation purposes. Logging operations conducted after the hydraulic fracturing indicated that a nearly vertical fracture had been generated, approximately 1.5 cm wide and 43 m long.

The results of the postfracturing pumping tests suggest the presence of a massive fracture with reservoir characteristics analogous to a constant-head recharge boundary. Although five producing zones have been identified in this well, spinner surveys indicate that there is one primary producing zone, associated with the major fracture. The tests conducted at Raft River were designed to evaluate the effects of variable volume and quiescence on tracer recovery curves (Downs et al., 1982). All tests were conducted at a constant rate of 34 m^3/hr.

Test 2A2 was a 4-hour injection test in which 137 m^3 of tracer solution was injected into the reservoir. Backflow immediately followed injection, with no quiescent period between. Test 2C was similar in format but required 48.5 hours to inject 1650 m^3 of tracer solution. Reduced tracer concentration curves versus time are shown in Figure 3. The recovery curve from Test 2C is much more spread out over time, indicating that greater mixing took place as the injection front moved farther from the wellbore. This follows classic dispersion theory with the length of the mixing zone increasing with distance traveled. Figure 4 shows tracer recovery curves during backflow in terms of reduced volume. This figure demonstrates that, in terms of injection volumes recovered, the tracer response was identical for the two tests.

Despite the 10-fold difference in injected volume, and presumably a significant difference in the distance traveled by the front, the recovery curves for the two tests are very similar. For the two curves to be the same, the ratio of dispersive to advective flux must be the same. Since the advective flux term increases as the distance traveled increases, the dispersive flux term must also increase. In the fracture-dominated

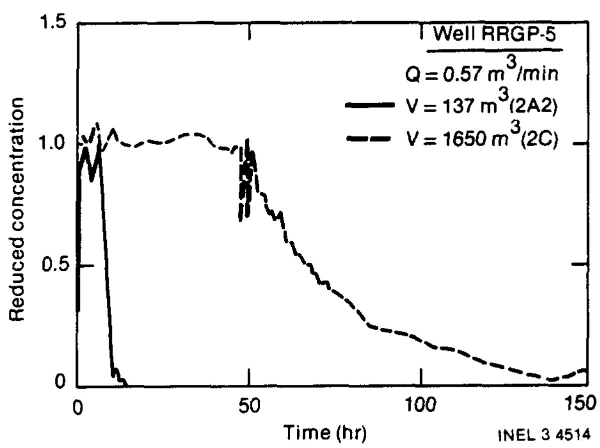

Figure 3. Tracer concentration during injection and backflow phases of Tests 2A2 and 2C at Raft River geothermal field. Test 2A2 was a 4-hour injection test and 2C a 48.5-hour injection test.

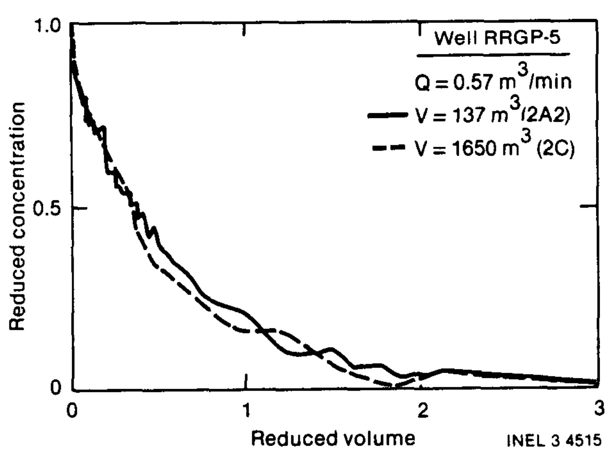

Figure 4. Normalized tracer recovery curves from backflow portions of Tests 2A2 and 2C.

system at Raft River, therefore, the dispersion coefficient must increase as the distance traveled increases. This increase in dispersion coefficient proportional to distance is consistent with theory for layered porous media or fracture networks where fracture apertures are log normally distributed (Neretnieks, 1983). The process causing this effect is the different velocities between layers or fractures. In the injection-backflow test mode, however, these velocity differences should cancel.

Taylor dispersion theory for parallel plates (Horne and Rodriguez, 1983) was applied to the test data in an effort to relate the tracer recovery curves to fracture aperture. Attempts to find a D_L/vx ratio for Equation 1 that fits the data from Tests 2A2 and 2C are shown in Figure 5. None of the curves has quite the right shape to fit the Raft River data, indicating that a single, relatively clean fracture is not a good model. Another model, which may fit the data better, is a dual porosity model. Tracer diffuses, or flows under a low gradient, into a fracture network off the major fracture. Tracer concentration drops off rapidly upon withdrawal because some of the tracer mass has been lost to this secondary fracture network. This "lost" tracer is then recovered slowly, producing a long, drawnout tail to the recovery curve. Attempts to fit the Raft River data to this latter conceptual model will be made in the near future using the FRACSL code (Miller, 1983).

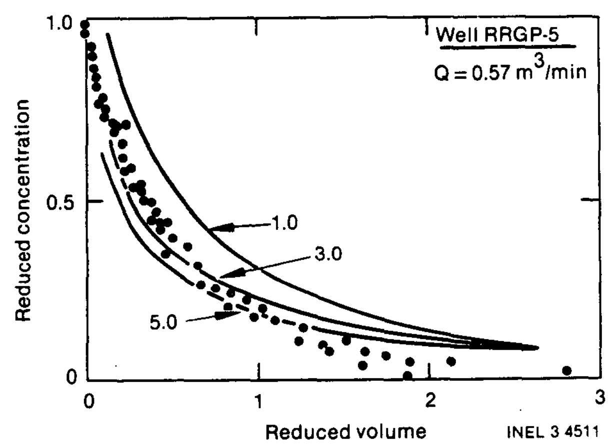

Figure 5. Comparison of normalized tracer recovery from Tests 2A2 and 2C with curves calculated using Equation 1 and D_L/vx ratios indicated for the three curves.

APPLICATIONS TO THERMAL BREAKTHROUGH

For tests conducted at Raft River and East Mesa, a cooler fluid was injected into a warmer reservoir. The temperature of the backflow was higher than injected due to mixing with reservoir fluid and exchange with reservoir rocks. Tracer recovery curves provide a measure of the ratio of the injected and native reservoir fluids from which an expected temperature response can be calculated. The difference between the expected and actual temperature response gives an estimate of the enthalpy added to the injected fluid. Downhole temperature measurements during backflow are necessary because thermal exchange in the wellbore will complicate data interpretation. Data collected at Raft River and East Mesa are being studied to evaluate this application of injection-backflow testing.

CONCLUSIONS

The East Mesa and Raft River reservoirs represent two very different configurations, and tracer recovery curves from the two sites reflect these differences. The East Mesa data can be adequately addressed using existing porous media theory while the Raft River data appear significantly more complex. Data collected at Raft River imply that flow is dominated by a major fracture with some form of dual porosity comprised of secondary fractures or a porous matrix.

The injection-backflow tests have provided data that have assisted in refining the conceptual model for Raft River and have apparently confirmed the East Mesa reservoir configuration. The numerical simulations planned for this next year will aid in refining the interpretation of the test data and improve our understanding at the Raft River and East Mesa reservoirs.

ACKNOWLEDGMENT

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