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TRACER RECOVERY AND MIXING FROM TWO GEOTHERMAL INJECTION-BACKFLOW STUDIES

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ABSTRACT

Injection-backflow tracer testing on a single well is not a commonly used procedure for geothermal reservoir evaluation, and, consequently, there is little published information on the character or interpretation of tracer recovery curves. Two field experiments were conducted to develop chemical tracer procedures for use with injection-backflow testing, one on the fracture-permeability Raft River reservoir and the other on the matrix-permeability East Mesa reservoir. Results from tests conducted with incremental increases in the injection volume at both East Mesa and Raft River suggests that, for both reservoirs, permeability remained uniform with increasing distance from the well bore. Increased mixing during quiescent periods, between injection and backflow, at Raft River suggest an area near the well bore that has a hydrologic character different from the far well bore environment. Increased flow rates for East Mesa testing resulted in a general decrease in mixing. Comparison of recovery curves from the Raft River reservoir with those from the East Mesa reservoir suggests that mixing is greatest, and therefore permeability is greatest, in the fractured reservoir. These test results indicate that injection-backflow testing with tracers can be used successfully to characterize flow in the near-well bore environment.

INTRODUCTION

Injection of fluid into the ground has the potential to cause chemical effects, such as mineral precipitation or dissolution, and physical effects, such as seismic events and reservoir cooling. It is important to understand the nature of such phenomena and be able to predict the effects of injection beforehand. Increased use of injection appears to be the best solution to the problems of maintaining reservoir pressure, disposing of spent brine and preventing surface subsidence.

The U.S. Department of Energy, Division of Geothermal and Hydropower Technologies recognizes the need for research in injection. As part of their Injection Research Program, the Idaho Operations Office of DOE, the Earth Science Laboratory of the University of Utah Research Institute and EG&G, Idaho, Inc. have designed and carried out a series of field and laboratory experiments to develop new techniques useful to industry. Specifically, we have been developing methods for simultaneously determining the nature of fluid flow paths in the subsurface and the interaction of injected fluid with the reservoir rock and fluid through use of chemical tracers and geophysical surveys. The first set of field tests was carried out at Raft River, Idaho, in late 1982, and the second set, in which Republic Geothermal Inc. participated, was carried out at East Mesa, California, in the summer of 1983.

The first phase of our research, reported here, has been concerned with developing new methods that can be used with a single well. It is the usual case in a geothermal field that each well is hydrologically isolated from other wells in the same field to a greater or lesser extent. In considering a priori the several effects of interest that could be propagated between two wells, we realize that (a) a pressure transient created at one well may be observed at a second well after a certain length of time that in practice is highly variable both among fields and among wells in the same field, (b) an actual fluid packet would take a much greater time to propagate between wells, and (c) a thermal perturbation would take an even larger time to propagate between wells and, furthermore, would be unlikely to propagate at all if a fluid packet could not be propagated (neglecting the very slow thermal conduction effects). Reservoir engineering studies to date have been most concerned with treatment of the effects in (a) above, i.e. analysis of pressure transient data. Only the most advanced models today treat the chemical and physical changes that attend the movement of individual fluid packets and little application has been made of these models to geothermal fields. However, it is clear that if we are going to understand and predict thermal breakthrough (case (c)), we must understand movement of fluid packets in the reservoir.

Our field experiments have been designed to help define movement of fluid packets around a single well. Fluid flow is set up by employing the so-called "huff-puff" technique of injecting fluid, into which suitable tracers have been introduced, and then withdrawing the fluid by backflowing. By monitoring the concentration of tracers recovered as a function of volume of fluid produced, information can be gained over and above that gained through the usual techniques of reservoir engineering measurement and analysis. These one-well tracer tests have an important advantage over two-well tracer tests in allowing us to quantify not only the dilution or mixing effects but also the chemical interaction of injected tracer and fluid with the reservoir rocks. In a two-well test if no tracer is detected at the second well from injection into the first well, one does not know whether fluid was not propagated between wells or whether the tracer was merely removed from solution by interaction in the reservoir.

This paper deals with the development of methods for the use of chemical tracers in injection-backflow testing at Raft River, Idaho, and East Mesa, California. Tracer recovery curves resulting from tests at these two sites are presented and compared. Other papers presented in these transactions deal with hydrologic evaluation of tracer recoveries from these tests (Downs and Russell), the effects of water-rock interactions on tracer behavior (Capuano), the results of laboratory experiments conducted on a physical model of a fractured reservoir (Hull and Koslow) work on development of reservoir analysis code to integrate dispersion and fracture flow (Miller), and the results of scale inhibitor experimentation conducted during injection testing (Michels).

GEOLOGIC SETTINGS

The Raft River thermal area is located in southeastern Idaho. There are two compositionally distinct thermal waters present in this system. The first is a slightly saline sodium chloride water, with dissolved solids up to 1400 ppm and measured temperatures up to 145°C. This water is found predominantly within a quartzite unit in the upper portion of the Precambrian basement. Unconformably overlying the Precambrian rocks are as much as 1600 m of Tertiary and Quaternary basin fill sediments (Blackett and Kolesar, 1983). These sediments host the second thermal water, which is also sodium chloride in character although it is more saline, with dissolved solids up to 6500 ppm, and is slightly hotter, with measured temperatures of up to 150°C.

Injection testing at Raft River was conducted on well RRGP-5, which is cased to the top of Precambrian quartzite at 1500 m. Thermal water produced from RRGP-5 is of the low-salinity type and flows predominantly from fractures in the quartzite. In the vicinity of RRGP-5 the overlying basin fill sediments are relatively impermeable and thermal water in the sediments around RRGP-5 is the low-salinity water believed to have traveled to the surface along faults in the sediments.

Well RRGE-3, which was used as the supply well for injection testing, is located approximately 2400 m from the injection well, RRGP-5. Thermal water produced from RRGE-3 is a mixture of the two thermal water types, and, therefore, is compositionally distinct from water encountered in the reservoir around injection well RRGP-5. This compositional difference can be used as a natural tracer for injection testing.

The East Mesa geothermal system is located in the Imperial Valley of southern California. The thermal reservoir occurs in a thick sequence of up to 4 km of clastic deltaic and lacustrine deposits of Tertiary and Quaternary age (Coplen, 1976). Hydrologic flow in the area is generally horizontal, with faults contributing to vertical permeability and recharge of thermal fluids (Bailey, 1977).

Two East Mesa wells were selected for injection-backflow testing, 56-19 and 56-30. These wells are located approximately 1600 m apart. Waters drawn from these wells have distinctly different compositions. Water flowing from 56-19 is 126°C, sodium chloride in character, with dissolved solids up to 5800 ppm. This solution is flowing from casing perforations extending between 800 m and 1400 m. Well 56-30 discharges a hotter, 174°C, less saline sodium chloride water, with 2700 ppm dissolved solids. This water is encountered at greater depth, 1600 to 2200 m, than 56-19 thermal water.

The supply well used for East Mesa testing, 38-30, is located only 600 m from well 56-30 and draws water of composition similar to well 56-30 from a similar depth.

TESTING

A total of eight injection-backflow tests were conducted on well RRGP-5 at the Raft River geothermal site. At East Mesa a total of four injection-backflow tests were conducted, one on well 56-30 and three on well 56-19. Several parameters can be altered during injection-backflow testing to aid in evaluation of the hydrodynamics of a geothermal reservoir. These parameters include: 1) chemical character of the tracer solution; 2) temperature of the tracer solution; 3) flow rate, during both injection and backflow; 4) quiescence time between injection and backflow; and 5) volume of tracer solution injected. During testing at Raft River and East Mesa, each of these parameters was varied. Table 1 lists a summary of the test conditions.

The chemical character of the injected solution was controlled by the composition of water from the supply well and the quantity of artificial tracers added to the water. In most cases, the supply well water was chemi-

TABLE 1. RAFT RIVER AND EAST MESA INJECTION-BACKFLOW TEST CONDITIONS

TEST	INJECTION				QUIESCENCE (hours)
	WELL	VOLUME (liters)[a]	RATE (liters/sec)	TEMP. (°C)	
RAFT RIVER					
2 Series					
2A-2	RRGP5	6.3×10^4	9.5	122	0
2C	RRGP5	1.5×10^6	9.5	122	0
2D	RRGP5	3.3×10^6	9.5	122	0
4 Series					
4A	RRGP5	1.1×10^4	9.5	122	28
4B	RRGP5	7.2×10^3	9.5	122	2
4C	RRGP5	6.1×10^3	9.5	122	12
4D	RRGP5	9.9×10^3	9.5	122	50
5 Series					
5	RRGP5	1.3×10^7	9.5	122	80
EAST MESA					
3(56-30)	56-30	7.1×10^5	19	93	12
3(56-19)	56-19	7.1×10^5	19	93	12
4(56-19)	56-19	7.5×10^5	32	93	13
6(56-19)	56-19	1.6×10^6	32	93	12

[a] Less volume remaining in the cased portion of the wellbore.

cally distinct from the reservoir water in the vicinity of the injection well. This compositional difference provided a suite of natural tracers such as Na, K, Ca, SiO_2, Cl, SO_4 and HCO_3. Artificial tracers added to the injected solution, both continuously and as slugs, were used to give the injected solution a distinct chemical composition for each test, thereby allowing prediction of contamination by solution unrecovered from previous tests. In addition, artificial tracer slugs were added at various times during injection to aid in understanding the effects of mixing on solution traveling different distances into the formation. Artificial tracers included Cl, Br, I, SCN (thiocyanate), B, Mg, K, Li and the organic dyes, disodium fluorescein and rhodamine-B. The composition of the injected solution and the use of artificial tracers are discussed in more detail by Capuano (1983).

TRACER RECOVERY

The variation in composition of the recovered solution reflects the amount of mixing that has taken place in the reservoir. To produce a mixing curve for each tracer, the fraction of tracer recovered in individual water samples was calculated using the mixing relationship, $X = (C_b - C_r)/(C_i - C_r)$, where "X" is the fraction of injectate in the backflow sample, and "C" is the concentration of tracer in the backflow sample, (b), reservoir water (r), and injection water (i).

The injection concentration, C_i, was taken as the average concentration in the injected solution. The concentration of the element in the reservoir water, C_r, was taken from analysis of water collected from the injection well prior to injection testing. Before testing began each of the injection wells was backflowed for up to 24 hours, while the water chemistry was monitored, to ensure that the reservoir would produce water with a relatively uniform composition. If less than 100% of the injected solution was recovered during backflow of any given test, natural and artificial tracers remained in the reservoir. These tracers were a source of contamination during subsequent injection tests. For all tests, with the exception of the Raft River 4 Series tests (see Table 1), the amount of solution injected was much greater than the amount of contamination from previous tests. Contamination, therefore, was assumed to have little effect on the character of tracer recovery from these tests. The Raft River 4 Series tests, however, had relatively small injection volumes ranging from 6000 to 11000 liters. Contamination of the reservoir by previous tests, therefore was relatively important. To account for this contamination, a corrected reservoir concentration equivalent to the concentration of that element in the last backflow sample, was used to calculate mixing.

Besides mixing, other processes can affect tracer concentrations in the recovered solution. These include tracer gains or losses as a result of adsorption or desorption, ion exchange, mineral dissolution or precipitation, and in the case of the organic dyes, disodium flourescein and rhodamine-B, thermal instability. Because these processes can have a substantial effect on tracer recovery, it is important to account for the resulting gains or losses in preparation of mixing curves. One means of doing this is to use a "conservative" tracer, one which is relatively unaffected by these processes. Ultimately the extent of these various effects on other tracers may then be estimated by comparing the recovery curves of conservative and nonconservative tracers.

An ideal conservative tracer is one which is unreactive with the geologic formations present in the study area, is not present in the rocks in a form that is readily released into the tracer solution, and whose concentration in the tracer solution can be well documented. For testing at Raft River the natural tracer Cl appears to best fit these criteria. Its solubility in natural waters is well above the maximum concentration of 3000 ppm injected during testing. Because Cl is not greatly affected by adsorption, desorption and ion exchange, minor gains and losses resulting from these processes would be relatively small compared to the high Cl concentrations in the injectate. In addition, Cl-bearing minerals were not identifed in the reservoir rocks in the vicinity of RRGP-5 (Blackett and Kolesar, 1983) and therefore Cl gains resulting from mineral dissolution were not of concern.

A generalized mixing curve for each Raft River test was, then, derived from a visual estimation of a best fit Cl curve. This is done under the assumption that the fraction of conservative tracer in the recovered solution is proportional to the fraction of injectate in the recovered solution. Generalized mixing curves for the 2 Series tests and Test 5 are presented in Figure 1 and will be discussed below. The 4 Series curves are not presented because of space limitations. For further discussion of the 4 Series test results see Downs and Russell (1983).

Preliminary mixing curves for East Mesa injection-backflow tests are presented in Figure 2. Calculation of generalized mixing curves for East Mesa testing is not as straightforward because the presence of evaporite minerals in the reservoir rocks may not allow Cl to act conservatively. These and other problems will be evaluated further upon completion of additional analyses.

WELL-BORE RECOVERY

The effects of water-rock reactions and mixing are minimal in solution confined to the cased portion of the well bore. Therefore, the tracer content of the final solution injected into the well bore should equal the tracer content of the initial solution removed from the well bore. This comparison provides a unique opportunity to evaluate errors in data collection. For example, errors in chemical analyses or in measurement of flow rates, mixing in the well bore and accidental flow during quiescent periods are all potential problems that can be evaluated.

Comparison of the mass of the conservative tracer Cl, and for Raft River, Na and K, injected into and recovered from the cased portion of the well bore (hereafter called "well-bore recovery") shows less than 7% error for all Raft River and East Mesa injection-backflow tests, excepting Raft River Tests 4A, 4D and 5. Considering analytic precision, which ranges from 3 to 5%, and the probable 5% or greater error on flow rate determinations, these comparisons are surprisingly close.

Poor well-bore recoveries for Raft River Tests 4A, 4D and 5 are believed to be the result of backflow that occurred accidentally during the quiescent period. Solution lost from the well bore during quiescence is replaced with mixed water from the reservoir, thereby accounting for these poor comparisons. The exact volume of solution backflowed during the quiescent period for each of these tests is unknown.

RESULTS

Three test series were run on Raft River well RRGP-5. For the 2 Series tests all variables were held constant except injection volume, which was increased from 6.3×10^5 liters during Test 2A-2, to 1.5×10^6 liters during Test 2C, and to 3.3×10^6 liters during Test 2D. The shapes of the recovery curves from these three tests are very similar, indicating an almost exponential increase in mixing with increased backflow. These results suggest that the portion of the reservoir involved in testing is responding uniformly to the different injection volumes. Normalization of the recovery curves with respect to injection volume (Figure 3) shows that they not only have similar shapes but also overlap. The good agreement between the normalized recovery curves suggests that mixing varied in proportion to the volume of solution injected, and that the rate of mixing of the injected and reservoir waters was independent of the distance traveled by the solution. It is therefore concluded that the portion of the reservoir tested has uniform permeability. These generalizations, of course, only apply to the portion of the reservoir around RRGP-5 penetrated by the maximum volume of water involved in testing.

The addition of tracer slugs at various times during an injection test can also be useful in evaluating the character of a reservoir. Two five-minute tracer slugs were added to the injectate during Test 2D: an I slug was added at the start of injection and a B slug was added after one third of the injection was completed. Recovery curves for I and B, normalized with respect to the volume of solution injected after each respective slug, are shown in Figure 4. Despite the different injection schedules, there is excellent agreement between the normalized volumes of recovery needed for return of both tracer slugs. Furthermore, the slopes of these normalized recovery curves are very similar. The similarity of the response of these tracer slugs to mixing, independent of the distance traveled in the reservoir, further supports the conclusion that the portion of the reservoir tested has uniform permeability.

Raft River Test 5, which involved an injection volume of 1.3×10^7 liters (four times greater than that of Test 2D) can be compared with results of the 2 Series tests. In addition to injection volume, Test 5 also differed from the 2 Series tests by one other parameter, namely, the presence of a quiescent period between injection and backflow. Test 5 involved 80 hours of quiescence, whereas the 2 Series tests involved no quiescence. There are two distinct parts of the Test 5 recovery curve. The first is the curve for the initial 1.7×10^5 liters of backflow, which differs markedly from the 2 Series recovery curves. The second is the remaining backflow, beyond 1.7×10^5 liters, which in contrast, produces a recovery curve similar in trend to those of the 2 Series (Figure 1). These similarities are also apparent on Figure 4, which shows the normalized recovery curves. The Test 5 results, therefore, further support the conclusion of a uniform permeability reservoir. The Test 5 normalized recovery curve is however, slightly offset from the curves for Tests 2D and 2C. This suggests a trend of slightly increased mixing rate with increased injection volumes used for Test 5.

The similarity of the latter portion of the Test 5 recovery curve with those of the 2 Series suggests that the initial portion of the Test 5 recovery curve should also be similar to the 2 Series curves if injection volume was the only parameter varied. The apparent truncation of the initial portion of the Test 5 recovery curve is therefore believed to be a product of increased mixing due to hydrologic effects during the 80 hour quiescent period.

At East Mesa, four injection-backflow tests were conducted. The first two, 3(56-30) and 3(56-19), were identical tests conducted on different wells in order to compare recovery curves from tests conducted on different portions of the reservoir. The recovery curves resulting from these two tests (Figure 2) show that less mixing has taken place in the reservoir surrounding 56-30 than in the reservoir surrounding 56-19. Preliminary calculation of the percentage of injectate recovered shows that, with a similar volume of backflow, 95% of the injectate was recovered from Test 3(56-30), whereas only 85% of the injectate was recovered from Test 3(56-19). This further supports the premise of less mixing during Test 3(56-30).

The remaining two East Mesa tests were both conducted on well 56-19. Test 4(56-19) was similar to Test 3(56-19) with the exception that the flow rate was nearly doubled for Test 4(56-19) (from 19 liters/sec (300 gal/min) to 32 liters/sec (500 gal/min)). Comparison of the recovery curves from these two tests shows that doubling the flow rate resulted in slightly less mixing.

Test 6(56-19) was run under the same test conditions as Test 4(56-19) (with the faster flow rate), with the exception of injection volume, which was doubled. Comparison of the recovery curves from Test 4(56-19) and Test 6(56-19) indicates that mixing varies in proportion to the volume of solution injected. This is further supported by the similarity in the recovery curves when normalized with respect to injection volumes for Tests 6(56-19) and 4(56-19) (Figure 5). The relationship between injection volume and mixing is similar to that noted for the Raft River tests, and suggested that the volume of reservoir tested has uniform permeability.

Comparison of the recovery curves from testing in the Raft River reservoir, in which fracture flow dominates, and the East Mesa reservoir, in which dispersive flow dominates, is difficult because of the preliminary nature of the East Mesa test results and the wide variation in parameters used. A general comparison of the normalized East Mesa recovery curves for Tests 3(56-19) and 3(56-30) with those of the Raft River 2 Series tests (Figures 3 and 5), suggests lesser mixing in the matrix-controlled East Mesa reservoir and therefore suggests lower permeability.

East Mesa Tests 3(56-19) and 3(56-30) were conducted with a flow rate of 19 liters/ sec, double that used for Raft River tests (9.5 liters/ sec.). As shown from East Mesa testing, an increase in flow rate resulted in a decrease in mixing in the porous reservoir. The effect of flow rate in the fractured reservoir was not tested. A portion of the decreased mixing noted in the East Mesa reservoir as compared to Raft River could be the result of the faster flow rate. On the other hand, East Mesa Tests 3(56-19) and 3(56-30) involved a 12-hour quiescent period, whereas the Raft River 2 Series tests involved no quiescence. In the Raft River reservoir it was found that increased quiescence could result in increased mixing. It is believed that a detailed evaluation of East Mesa tracer recoveries including that of tracer slugs, will allow a better comparison of these reservoirs.

CONCLUSIONS

Injection-backflow tracer tests have been used successfully in both fracture- and matrix-dominated geothermal reservoirs. Testing in the fractured reservoir at Raft River indicated that the portion of the reservoir tested has a relatively uniform permeability. This reservoir of uniform permeability, however, can be divided into a portion near the well bore in which hydrologic effects during quiescence resulted in increased mixing between the injectate and reservoir solution. At greater distances from the well bore increased quiescence had very little effect on mixing.

The maxtrix-controlled East Mesa reservoir also appears to have regions of near uniform permeability around the two wells tested. Results from tests on wells penetrating different portions of the reservoir, however, suggest that different areas of the reservoir have different permeabilities. In addition, it was found that, in the porous East Mesa reservoir, an increase in flow rate resulted in a decrease in mixing.

Comparison of the test results from the matrix-dominated reservoir at East Mesa with those of the fracture-dominated reservoir at Raft River suggests that at East Mesa the rate of mixing and therefore permeability is lower than at Raft River.

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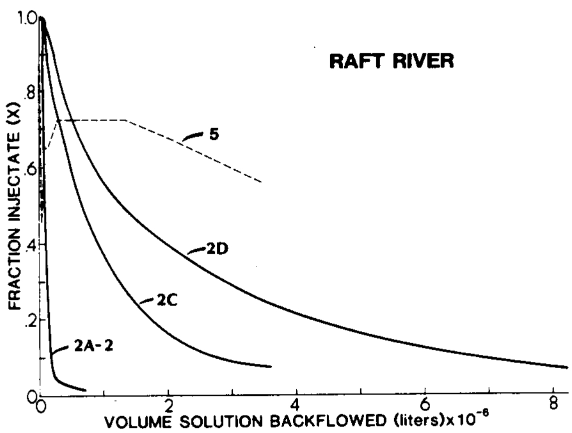

Figure 1. Recovery curves, Raft River tests.

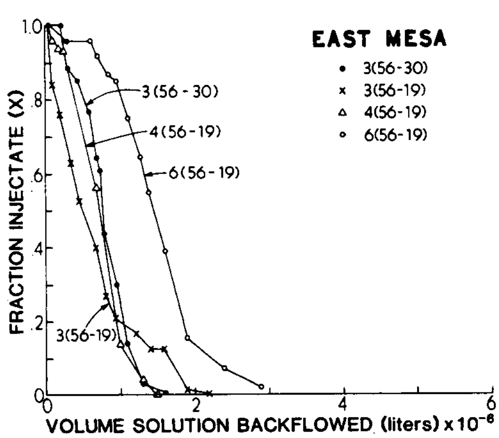

Figure 2. Preliminary recovery curves, East Mesa tests.

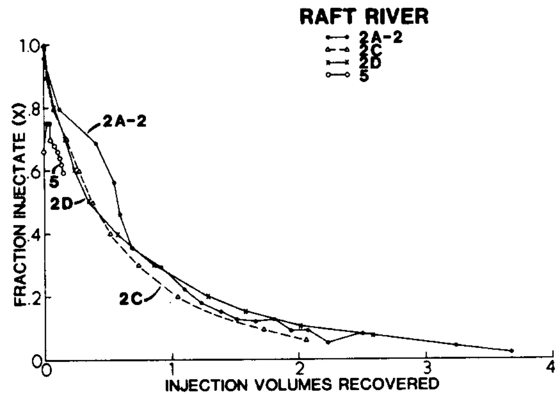

Figure 3. Recovery curves normalized with respect to injection volume, Raft River tests.

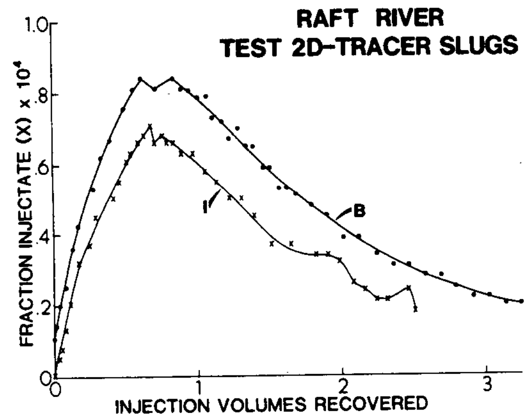

Figure 4. Tracer slug recovery curves normalized with respect to injection volumes, Raft River Test 2D.

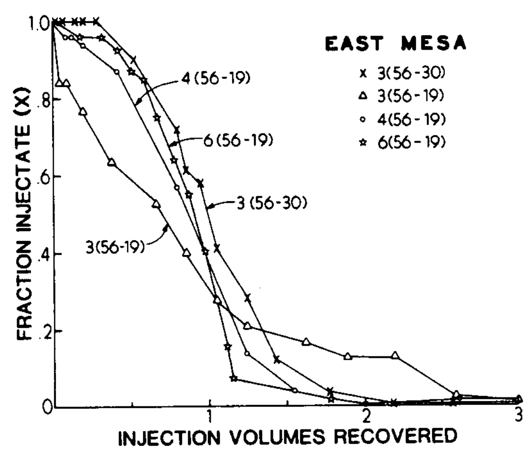

Figure 5. Recovery curves normalized with respect to injection volume, East Mesa tests.