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USES OF GEOCHEMISTRY WITH INJECTION-BACKFLOW TESTING IN GEOTHERMAL RESERVOIR STUDIES

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ABSTRACT

Injection-backflow testing provides a new technique for obtaining information on a number of reservoir properties that are not obtainable from conventional analysis of only pressure, temperature and flow-rate data. Our field experiments have demonstrated that information can be obtained on: the nature of the flow paths of injected fluids, the behavior of chemical tracers in the reservoir, the natural movement of reservoir fluids, the chemical interactions of the injected waters with the reservoir fluids and rocks, the behavior and effectiveness of scale inhibitors, and the transfer of heat between reservoir rock and fluid. We believe that injection-backflow testing will become a useful part of reservoir studies as techniques become more fully developed.

INTRODUCTION

During the past two years, the U.S. Department of Energy (DOE) has been conducting research into problems associated with the injection of spent geothermal fluids. Injection may cause degradation of permeability or channeling of injected fluids toward production wells. Yet, injection is increasingly recognized as being necessary to help maintain reservoir pressure, to increase efficiency in the mining of heat, and to obviate problems of environmental contamination.

As part of the DOE injection research program, the Idaho Operations Office of DOE, UURI, and EG&G, Idaho have been jointly developing applications of geochemistry and geophysics along with injection-backflow testing of geothermal wells as a means of determining the effects of injection. Field experiments have been carried out at Raft River, Idaho and, with the participation of Republic Geothermal, Inc., at East Mesa, California. The objectives of this paper are to describe some of the techniques we have been using, discuss their application to reservoir definition, and present examples of research results.

BACKGROUND

In order to understand how injection-backflow testing can help solve reservoir-related problems, let us develop some background by considering potential interactions of geothermal wells and discussing the present state of the art in specifying these interactions.

Consider two wells in a geothermal reservoir. The geothermal operator will be interested in how these wells interact (interfere). In general, a pressure transient can be made to propagate between the two wells by injection of fluid into one of the wells. Simultaneously, pressure can be recorded in the second well to determine the arrival of the pressure pulse. A breakthrough time (t_1 in Figure 1) will be observed which varies considerably depending on reservoir properties. The minimum time is controlled by the speed of sound in the reservoir fluid, but rarely is this minimum time observed. Usually, the pressure breakthrough is delayed due to the interaction of the fluid with the flow paths between the wells. The lower the permeability of the hydraulic connection between the wells, the longer pressure breakthrough takes.

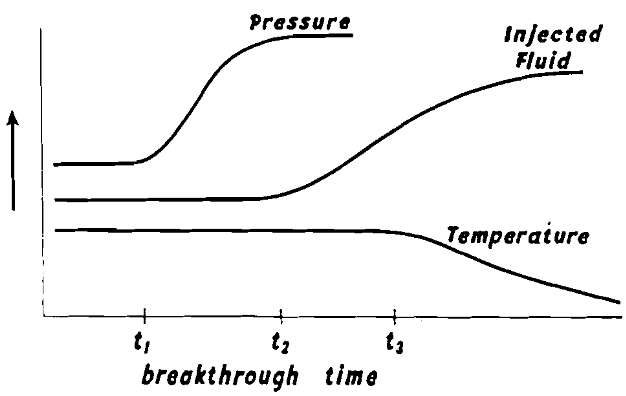

Figure 1. Potential interactions among wells.

If fluid is injected continuously into the first well, a point may be reached when breakthrough of actual injectate into the second well occurs. Such breakthrough of injected fluids can have serious consequences because the chemistry of the produced fluid may be altered, with effects on plant operating conditions. Propagation of injectate between the two wells normally takes considerably longer than propagation of a pressure pulse, and this is indicated by t_2 in Figure 1.

Propagation of a thermal pulse between the two wells will usually require the propagation of fluid between the wells. The first breakthrough of injected fluid may not cause production temperature to decrease because the injectate will be heated along its pathways. However, at some time, indicated as t_3 in Figure 1, a temperature breakthrough will become evident, with potentially disasterous effects on the production characteristics of the well.

Conventional reservoir engineering studies have dealt mainly with propagation of pressure effects in a reservoir, although computer codes are under development to account also for heat, mass and solute transport (Narasimhan and Witherspoon, 1977; Lake et al., 1981). A complete numerical model for simulating fluid flow, heat transfer, and chemical changes in a geothermal reservoir is a very large undertaking that has not yet been achieved.

Present-day techniques can be used in many reservoirs to forecast with significant reliability the probability, magnitude and timing of pressure interference among wells. However, forecasting of fluid breakthrough in geologically complex geothermal reservoirs is not possible with any reliability, and forecasting of thermal breakthrough is even further removed. Research and development of techniques for reliably specifying the three basic interferences among wells must include both field experiments and interpretive modeling.

DESCRIPTION OF THE INJECTION-BACKFLOW TECHNIQUE

The injection-backflow technique has been used to a limited degree in the petroleum and mining industries and in ground water hydrology, where it is sometimes known as "huff-puff" or "push-pull" testing (Drever and McKee, 1979; Pickens et al., 1981). Until now it has not been applied to geothermal problems. The technique consists of: (1) characterizing pre-injection, native fluid and rock chemical and physical properties at the injection site, (2) injecting a fluid having known chemical and physical properties, perhaps labeled with tracers, at a measured rate for a measured time, (3) allowing the injected fluid to remain in the formation for a quiescent period ranging from minutes to hours, days or months, (4) producing fluid from the well at a controlled, measured rate of backflow for a measured time, (5) characterizing the chemical and physical properties of samples of the produced fluid taken at specified intervals, and (6) interpreting the data in terms of chemical and physical properties and processes in the reservoir.

Several parameters in the field experiment can be controlled. Among these are: injection rate and duration; quiescent period; production rate and duration; tracer composition; continuous or slug injection of tracer; and, in some cases, chemistry and temperature of injected waters. Increasing the injection rate increases subsurface pressure and may cause new zones of uptake to open. By increasing the total volume of water injected, a larger volume of reservoir around the injection well can be interrogated. During injection, one phenomenon taking place in the reservoir is dispersion of the injectate, which is caused by physical mixing of the injected water with the native reservoir fluid during advective transport of the injectate and by molecular diffusion. The rate and extent of this dispersion are functions of the nature of the fluid pathways. By measuring dispersion, one would expect to obtain useful information on the fluid flow paths.

Once injection is completed, the injectate may be left in the reservoir for any desirable quiescent period, during which time a number of phenomena may occur. Among these is chemical interaction between the injectate and the reservoir fluids and rocks. The extent of such interaction will depend, among other things, on the kinetics of the reactions, the area of contact and the duration of the quiescent period. Some reactions such as adsorption/desorption and ion exchange may be relatively fast, but others such as mineral precipitation or dissolution may require long periods even at elevated temperatures. By characterizing the chemistry of the injected and recovered fluids, one would expect to obtain useful information on chemical processes in the reservoir. An additional phenomena that may become manifest through the quiescent period is movement of the injectate due to natural fluid circulation in the reservoir.

Backflow of fluid, after a quiescent period, is done to recover and examine the injectate. Production of a volume equal to two to six or more times the injected volume appears to be necessary in order to recover most of the injectate.

It is important to note that during the injection-backflow test, pressure, flow rate and temperature of fluids can be measured in the injection well, the supply well and in surrounding monitor wells. These data allow reservoir engineering analyses to be done in conjunction with the further analyses made possible by the huff-puff technique.

APPLICATIONS TO RESERVOIR ANALYSIS

In our field experiments to date, we have been able to demonstrate that injection-backflow testing can obtain information on:

1. The nature of the subsurface flow of injected fluids, i.e. porous media flow vs. channeled flow due to fractures;
2. The presence of natural circulation of reservoir fluids;
3. The behavior of various chemical tracers in the reservoir;
4. The chemical interactions of the injected waters with the reservoir fluids and rocks;
5. The behavior and effectiveness of scale inhibitors in the reservoir; and
6. The transfer of thermal energy between reservoir rocks and injected fluid.

Conventional reservoir testing provides some information on (1) above, but essentially no information on the other items. These items, except (6), will be discussed separately below and illustrated with results from field tests at Raft

River, ID and East Mesa, CA. Before discussing the results, however, we will present a summary description of the field tests.

Field Tests at Raft River, Idaho

The Raft River area has been described in numerous publications (e.g. Dolenc et al., 1981). Injection-backflow testing was conducted on well RRGP-5. This well has been hydrofractured, and the near-well flow regime is believed to be dominated by one major fracture. Thermal water produced from RRGP-5 is of the sodium chloride type with 1400 ppm TDS and a temperature of 145°C. Its source is fractures in Precambrian basement. Well RRGE-3, which was used as the supply well, is located approximately 2400 m from RRGP-5. Water produced from RRGE-3 is higher in salinity (4700 ppm TDS), and, therefore, compositionally distinct from water encountered in the reservoir around RRGP-5. This compositional difference was used to provide natural tracers.

Table 1 summarizes the test program conducted at Raft River. During the first test (2A-1), tracers were injected for sufficient time to fill the wellbore but not enter the formation. Approximately 96% of the injected tracers were recovered, indicating excellent operational control. Two series of parametric tests were then conducted in conjunction with the evaluation of various tracers. First, the effect of increasing volumes of injected fluid was studied (tests 2A-2, 2C and 2D). Flow was held at 150 gpm and backflow was initiated as rapidly as possible after the completion of injection. The second series of tests (4A, 4B, 4C, and 4D) investigated the effect of delay between injection and backflow. The final test (5) was a long-term injection test to determine if tracer breakthrough could be obtained at well RRGP-1, nearby. No breakthrough was achieved.

TABLE 1

Summary of Raft River Tests

(flow rate = 150 gpm)

No.	Injection Time (hrs.)	Quiescent Time (hrs.)	Backflow Time (hrs.)
2A-1	1	0	1
2A-2	2	0	10.4
2C	46.5	0	110
2D	96.5	0	231
4A	0.3	27.5	8
4B	0.3	2.2	10.5
4C	0.3	12	8.5
4D	0.3	50	48.5
5	376	80	120

Field Tests at East Mesa, California

At East Mesa the reservoir occurs in a sequence up to 4 km thick of clastic deltaic and lacustrine deposits of Tertiary and Quaternary age (Coplen, 1976). Hydrologic flow in the area is generally intergranular, with faults contributing to vertical permeability and recharge.

Two East Mesa wells, 56-19 and 56-30, approximately 1600 m apart, were selected for injection-backflow testing. Waters from these wells have distinctly different compositions. Water flowing from 56-19 is 126°C, sodium chloride in character, with total dissolved solids up to 5800 ppm. Well 56-30 discharges a hotter (174°C), less saline (2200 ppm) sodium chloride water. The supply well, 38-30 is located only 600 m from well 56-30 and draws water of composition similar to well 56-30.

Table 2 summarizes the test program at East Mesa. Injection-backflow testing was initiated in each well after a series of flow tests (not shown on Table 2) designed to yield standard reservoir engineering data. Two tests (3 and 4) were run on 56-30 using essentially the same flow rate and injection time, but a large variation in quiescent period (12 hrs. vs. ∿6 months). Four tests (3, 4, 6 and 8) were run on 56-19, with the final test being a ∿6-month quiescent period also. Results of these tests are discussed below.

TABLE 2

Summary of East Mesa Tests

No.	Injection (hrs)	Injection (gpm)	Quiescent Time	Backflow (hrs)	Backflow (gpm)
Well 56-30					
3	11.5	300	12 hrs.	67	300
4	12	300	∿6 mos.	43	300
				51	450
				46	370
Well 56-19					
3	12.5	300	11 hrs.	53.3	300
4	7.4	500	13 hrs.	25	500
				20	400
6	14.5	500	12 hrs.	39	500
				9	450
8	7.3	500	∿6 mos.	140	400

Nature of Subsurface Flow

In many instances, data from conventional well tests can apparently be interpreted by using analysis developed for porous media even though it is known or suspected that the fluid actually flows in fractures. This is not entirely surprising because such testing usually interrogates a large volume of the reservoir, which may contain enough hydraulically connected fractures to behave as a porous media. Only during the first seconds or minutes of such tests are data normally collected that pertain to the near vicinity of the well, and these short-time data are often disturbed by spurious effects in the system as the test gets underway. In our research program, we have hypothesized that collection of chemical data in huff-puff tests could help determine the mode of fluid flow in the reservoir, i.e. could distinguish uniform, porous media flow on one end of the spectrum from severely channeled, single-fracture flow on the other end of the spectrum, and perhaps distinguish cases between. The dispersion of injectate during injection and subsequent backflow should be different for porous media flow than for fracture flow. Our approach in determining dispersion has been to isolate changes in chemical concentrations of natural and introduced tracers due to the mixing process from changes due to chemical interaction in the reservoir. This can be done with careful chemical characterization of both injected and recovered fluids. When conservation of a natural or introduced chemical tracer can be demonstrated, then the variation in its concentration as a function of volume of solution recovered during backflow provides dispersion data (Capuano et al., 1983). Basically, we determine the fraction of injectate in the backflow solution as a function of the amount of fluid recovered. Figures 2 and 3 show results for composites of selected injection-backflow tests at Raft River and East Mesa, respectively. In the Raft River tests, about 3 injection volumes of fluid must be recovered before the fraction of injectate is less than about 0.1, whereas at East Mesa, recovery of about 1.5 injection volumes is sufficient to achieve the same level. Thus, dispersion is considerably greater at Raft River than it is at East Mesa.

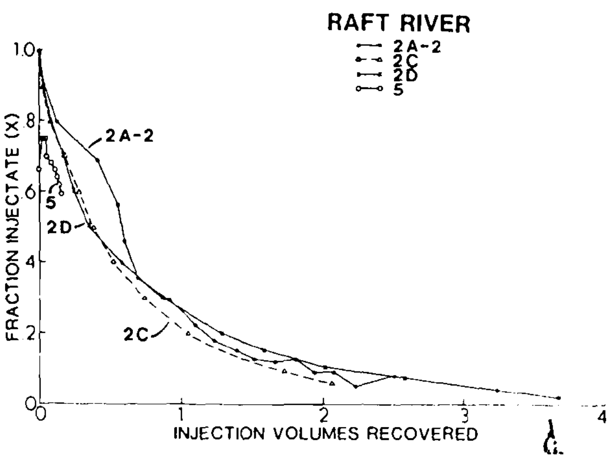

Figure 2. Raft River dispersion curves.

Russell et al. (1983) have presented a hydrologic interpretation of these data. The Raft River dispersion curves are consistent with analysis using theory for fracture networks or layered porous media. Russell et al. (1983) expect to be able to refine their analyses considerably when modeling codes now under development at EG&G, Idaho became fully operational. By contrast, East Mesa dispersion curves follow behavior that corresponds to conventional theory for porous media. Because these results are in accordance with accepted reservoir models for Raft River and East Mesa, we believe that they strongly support our hypothesis that dispersion data obtained from injection-backflow testing can help define the nature of subsurface fluid flow.

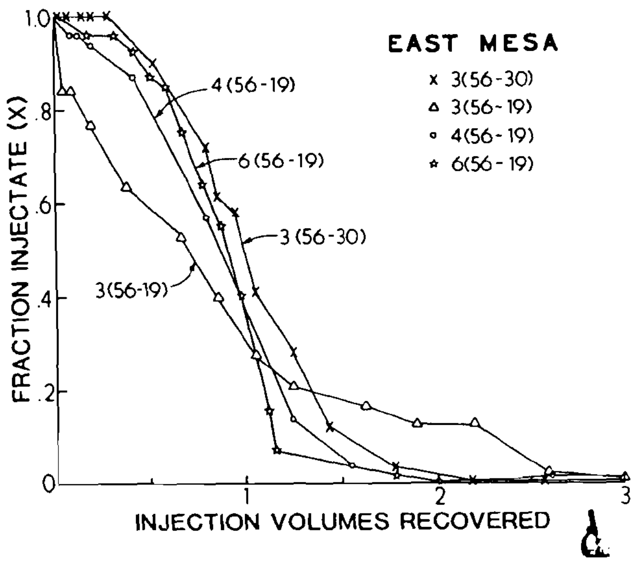

Figure 3. East Mesa dispersion curves.

Natural Movement of Reservoir Fluids

At East Mesa, tracer-labeled injectate was allowed to remain in the reservoir for a period of about 6 months in wells 56-30 and 56-19 (see Tables 1 and 2). Upon backflow of 56-19, none of the injected tracer was detected in the returned fluid even though the well was flowed at approximately 450 gpm for 6 days. Backflow of 56-30 did succeed in recovering previously injected tracer for both 12 hour and ~6 month quiescent intervals, as shown in Figure 4. After a 12-hour quiescent period, all of the injectate was recovered in about 22 hours of backflow. The initial plateau on the curve is due to emptying of the well bore. However, after the ~6 month quiescent interval, nearly 30 hours of backflow (3 injection volumes) were required before the first detectable return of tracer. The much different shape of the recovery curve after ~6 months of quiescence indicates that the tracer slug had moved from the point of injection and had become considerably dispersed.

Although interpretation of these data is not complete, we believe that these results are a clear indication of natural fluid movement in the reservoir. Moreover, the complete lack of tracer return from 56-19 indicates a different, perhaps faster, flow regime for this portion of the reservoir. These results are highly significant because they indicate fairly rapid sweeping of injected solutions away from the wells. The value of such data, if available on an areal basis, in helping to determine regional hydrologic flow and/or recharge is evident.

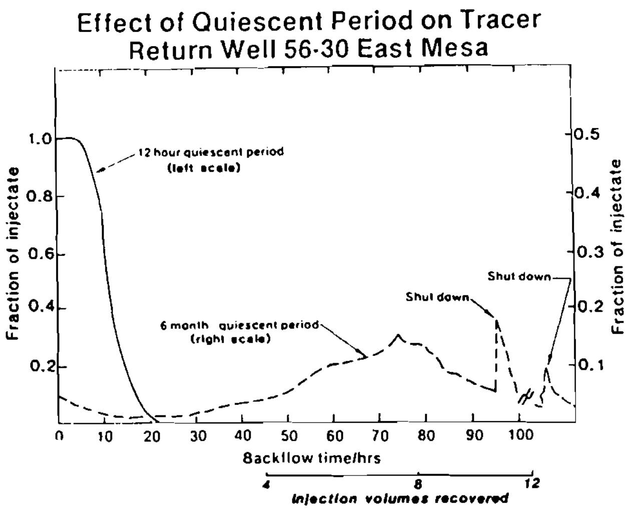

Figure 4. Effect of quiescent interval on tracer returns for Well 56-30, East Mesa.

Behavior of Chemical Tracers

Besides mixing, several 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 fluorescein and rhodamine-B, thermal instability. Because of the higher reactivity of waters and rocks at high temperatures in geothermal systems, tracers used successfully in ground water injection can be affected substantially by these processes. Reduction of tracer concentration in response to water-rock reactions can greatly alter a breakthrough curve and confound interpretation based on that curve. Also, in a two-well tracer breakthrough test, when no tracer is detected in the recovery well, one does not know whether fluid was not propagated between the wells or the tracer was simply removed. Injection-backflow testing allows us to use the earth as a full-scale laboratory to determine the behavior of various tracers in the reservoir.

One means of studying tracer behavior is to use a conservative tracer, one which is relatively unaffected by chemical processes in the reservoir. The extent of various effects on other tracers may be estimated by comparing the recovery curves of conservative and nonconservative tracers.

At Raft River, nine artificial tracers were investigated: sodium iodide, sodium bromide, sodium thiocyanate, magnesium chloride, lithium chloride, potassium chloride, boron (as borax), disodium fluorescein and rhodamine-B. The reactivity of the anion tracers, I, Br and SCN, and the dye tracers, disodium fluorescein and rhodamine-B were tested through comparison with the percent recovery of the conservative tracer Cl. For each of the tests listed in Table 2, Cl recovery indicated that 100% recovery of these tracers would be expected. Of the anion tracers, Br appears to be the least reactive. Iodide, the most commonly used groundwater tracer, was lost due to reactivity upon its first usage (test 2A-2), whereas later tests indicate complete recovery and even additional recovery of I from the earlier loss (test 4C). SCN, with 87% recovery, is slightly reactive. The 91% to 100% recovery of the organic dyes, disodium fluorescein and rhodamine-B suggest that they are thermally stable up to the test temperature, 122°C. Their adsorbing properties are untested because of an earlier dye injection that went unmonitored which could have filled all adsorbing sites.

Chemical Interactions in the Reservoir

Although scientists have spent years on geochemical research, it is clear that a great deal more needs to be done before reliable predictions of the chemical behavior of a geothermal reservoir can be made. At the present rate of progress, it will be at least another decade before some problems are well in hand. One great virtue of the injection-backflow technique is that it provides samples of water that has been placed in the reservoir and has interacted with reservoir rocks and fluids under natural conditions. Field experiments of the type we have been conducting thus offer a means of obtaining important data on chemical interactions in the reservoir. Such information is useful in specifying potential mineralogic changes which can alter formation permeability, obtaining information on the kinetics of reactions, and helping to calibrate computer codes.

Chemical analyses are not available at the time of this writing for samples taken at East Mesa after the ~6-month quiescent period. During the Raft River tests, quiescent intervals were too short to allow much chemical interaction between injected fluid and reservoir rocks. Nevertheless, Figure 5 shows results of some elements that underwent change during the Raft River 2C test. The curves shown are cumulative losses or gains as a function of the volume of recovered solution. There was a notable gain in calcium and smaller gains in bicarbonate and strontium. Magnesium, silica and, to a minor extent, fluorine were lost. The amount of calcium gained is nearly the molar equivalent of the amount of magnesium lost, indicating that an exchange reaction may have taken place. As there was essentially no quiescent period between injection and backflow in test 2C, this exchange occurred almost immediately. This apparent mineralogic control on the maximum concentration of magnesium has significant implications for understanding the chemical controls on the magnesium correction to the commonly used cation geothermometer. Because of this, we chose to test two other cations, lithium and potassium, during the injection-backflow testing at East Mesa.

Testing of Scale Inhibitors

Michels (1983) points out the utility of the injection-backflow technique in determining the behavior and effectiveness of scale inhibitors. Data obtained during huff-puff testing of well 56-30 at East Mesa are interpreted by him to indicate significant degradation of the effectiveness of a calcite scale inhibitor beginning as soon as 14 hours after injection. The same results indicate complete exhaustion of the inhibitor 30 hours after injection. Michels' (1983) analysis of the data further indicates that failure of the inhibitor would not lead to quick degradation of porosity. Testing of scale inhibitors is clearly one important application of the techniques we are developing.

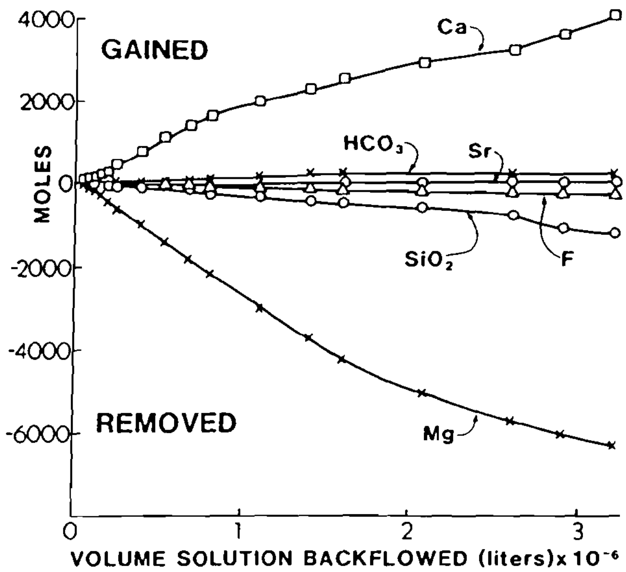

Figure 5. Gains and Losses during Test 2C, Raft River.

CONCLUSIONS

The use of geochemistry with the injection-backflow technique has a great deal of unexplored potential for contribution to understanding of reservoir properties and processes. This paper gives only a few examples of that potential. Field experiments of the type reported here not only provide information that is unobtainable in other ways, and is valuable in its own right for reservoir evaluation, but also provide data sets for evaluation and calibration of computer-based models. We believe that injection-backflow testing will become a recognized part of reservoir studies as techniques become more fully developed.

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