REINJECTION INTO FRACTURED GEOTHERMAL RESERVOIRS

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INTRODUCTION

The movement of fluids through permeable rocks is a primary interest whether the fluid is groundwater, petroleum, geothermal steam, or radioactive or chemical contaminant. The geothermal industry is involved in the transport of fluid through fractured volcanic rocks, and the experience accumulated over the past 30 years in the production and reinjection of steam and hot water from geothermal reservoirs has implications of broad interest in other fields.

That the porosity and permeability of geothermal reservoir rocks exist mainly in the fractures has been known for many years. Measurements of the permeabilities of cores recovered from geothermal wells are extremely low (of order $10^{-17}\ m^2$), and are not characteristic of permeabilities inferred from well tests (which can be as large as $10^{-13}\ m^2$). Porosities of cores are similarly low. Thus it has been concluded that, although fluid may be stored within the rock matrix, it is mobile primarily through the fractures only (at least within the time scale of interest to geothermal developers).

In spite of this knowledge, it was originally assumed that the degree of heterogeneity represented by the fractures was such that on the scale of an entire reservoir (which might cover tens of square kilometers) the flow would be as if through a porous medium. Calculations of heat and fluid recovery were traditionally made on this basis in the 1960's and early 1970's.

The recognition of the importance of the fractures coincided with the evolution of interest in reinjection. Until 1972, the waste hot water from geothermal power developments was disposed of to surface waters or ponds. Since the water was in very large quantities (thousands of tonnes per hour) and contained toxic substances (Axtmann, [1]), surface disposal presented environmental difficulties. In addition, the loss of fluid from the reservoirs resulted in substantial drawdown of pressures, and there was concern that fluid reserves would be depleted far in advance of the recovery of the usable heat still contained in the rock. For these two reasons, reinjection was suggested as means to prolong the useful life of the resource as well as a means to avoid the release of contaminants into the environment.

In early work involved in the design of a reinjection scheme for the Ahuachapan geothermal field in El Salvador, two significant new insights into geothermal development were obtained. A tracer test, using tritium, demonstrated that flow in the reservoir was highly heterogeneous (Einarsson et al., [2]). Tracer was recovered in a producing well 400m distant from the injection well within 48 hours, while two similar wells did not receive any tracer until several months later (one well was 500m distant from the injector, and the other was 1000m). Based on these observations, Bodvarsson [3] made calculations on the "safe distance" between injectors and producers such that there would be no premature breakthrough of unheated injection water back into the production wells. Bodvarsson [3] used a model of flow in a fracture to conclude that a "safe distance" could be anywhere from 700m to 4500m, depending on the degree of fracturing in that particular direction. Thus it had been determined that; (1) fractures caused heterogeneities in flow over scales as large as one kilometer, and (2) tracer tests were very useful in determining where these heterogeneities lie.

The work described by Einarsson et al [2] and Bodvarsson [3] involved only three wells at Ahuachapan, and since large scale reinjection into geothermal reservoirs only became widespread in the early 1980's, the full significance of their observations as to the fractured nature of geothermal reservoirs did become evident until several years later. Due to the channeling of reinjected water through relatively small volumes of rock, unheated water was being returned to production wells in several different geothermal fields. The resulting loss of productivity became a serious concern to geothermal developers, who began to take pains to overcome the problem and avoid it in subsequent developments (Horne, [4]).

Since the late 1970's, a large number of tracer tests have been reported for both existing and newly developed geothermal reservoirs. Collectively, these tracer tests confirm the original observations of Einarsson et al [2], and have shown that fractures in the volcanic rocks (and some cases sedimentary ones too) can be very major conduits for flow, and are different within reservoirs as well as between one reservoir and another. It has been seen that water can flow for distances as far as one kilometer at speeds of up to 100 m/hr. This has created significant uncertainty in the process of field development, and has given birth to major research efforts in several countries. This paper summarizes the implications of the geothermal experience and the research into forecasting that has resulted from it.

The first part of the paper describes the effects of individual fractures crossing a wellbore, while the second illustrates the effects of fieldwide heterogeneity on tracer returns. The consequence of the effects of the preferential flows are discussed in the third section.

FRACTURES BETWEEN WELLS

The pressure transients measured in a well test are transmitted through all of the connected fluid in the reservoir, whether the fluid is moving or stationary. A tracer test, on the other hand, monitors only that portion of the fluid that is actually moving between the point at which the tracer is injected and the points at which it is being recovered. Fluid that is immobile, or which is moving towards a location which is not being monitored, is invisible to the tracer test. However from the point of view of reinjection design, it is most useful to determine where the the injected fluid is going with reference to the existing production wells. That portion of the traced fluid that does not return to the production wells is of lesser significance since it holds little concern of premature thermal breakthrough. For this reason, well-to-well tracer tests have been much more common than the injection-backflow kind of tracer test used in groundwater applications to estimate regional flows.

Discussed here are some typical responses of geothermal tracer tests in fractured geothermal reservoirs, based on results from El Salvador (Aumento et al, [5], Cuellar et al, [6], Einarsson et al, [2]), Japan (Horne, [7], Inoue and Shimada, [8], Ito et al, [9] and [10]), Iceland (Gudmunsson et al, [11]), the Philippines (Dobbie and Menzies, [12], Sarit, [13], PNOC, [14]), and New Zealand, (McCabe, Barry, and Manning, [15]). Extensive tracer testing has also been carried out in the vapor-dominated geothermal system at the Geysers, California (Gulati et al, [16]) although published details are not as complete as those from other fields.

In general, the results of these tracer tests emphasize the strongly heterogeneous flow paths created by fractures - usually coincident with faults. McCabe, Barry and Manning [15] showed this particularly clearly for the set of tracer tests performed at Wairakei geothermal field in New Zealand. The tracer response characteristic of those at Wairakei (and most other geothermal fields) shows a single, sharply defined peak, suggesting only a single major flow path. Notice also the very rapid arrival time. Table 1 summarizes the responses of these various tests with respect to first tracer arrival, peak tracer arrival, peak tracer concentration, fraction of tracer recovered and horizontal and vertical separation between injection and production points. Lovekin and Horne [17] used these results to optimize the hypothetical reinjection scheme using these wells. It was found that the optimum combination of injectors and producers selected was almost the same based on any of the tracer return parameters. On the other hand, using horizontal separation alone (without including tracer test results) gave an entirely different design which failed to avoid combinations of wells in which breakthrough of injected water had been rapid. This simple observation emphasizes our appreciation of the fact that the reservoir is not areally homogeneous.

Interestingly, Lovekin and Horne [17] found that using the vertical separation between injection and production points *did* give rise to the same optimum selection of wells as did the use of the tracer test results. Table 2 shows why this was so; all of the tracer test parameters characteristic of strong and rapid tracer breakthrough (early arrival, high concentration, large fractional recovery, and early peak arrival) are well correlated with each other and with the vertical distance between wells. The correlations are negative for arrival times; this would imply that arrival time is small if the distance is large, which is counter-intuitive. However, since the correlation coefficients are not large, this means only that the first arrival and peak arrival are largely independent of vertical distance. On the other hand, there is a much stronger correlation between the fraction recovered and the vertical distance, suggesting that the fluid is generally moving downward, presumably due to negative buoyancy of the heavier, cooler water.

	1st arrival	Peak arrival	Peak concentration	Fractional recovery	Horizontal distance	Vertical distance
WK80→76	4.0	8.7	88	0.0024	142	+119
80→108	5.5	10.0	16	0.0006	229	-33
80→116	3.3	7.6	230	0.0040	499	+97
WK101→76	2.5	7.0	10	0.0005	139	+114
101→103	2.0	5.0	30	0.0009	168	+140
101→116	2.5	7.5	23	0.0005	350	+92
101→121	1.2	2.5	10,500	0.0580	489	+585
WK107→24	0.2	0.4	10,000	0.0373	209	+389
107→30	4.5	9.0	55	0.0028	238	+236
107→48	0.3	0.7	2360	0.0133	117	+617
107→55	5.5	15.7	29	0.0018	216	+290
107→67	2.2	15.3	46	0.0032	126	+248
107→68	4.0	15.0	39	0.0007	124	+214
107→70	4.0	9.5	43	0.0025	174	+182
107→81	4.8	9.5	21	0.0009	178	+270
107→83	4.5	11.0	53	0.0034	326	+167
107→108	10.0	23.0	17	0.0001	84	-7

Table 1: Summary of Wairakei tracer results

Notice in Table 2 that the horizontal separation is uncorrelated with any other parameter - the tracer return results are completely independent of areal separation of the wells. This result is even more significant than the correlation table shows, since the table only includes wells for which tracer actually broke through in measurable quantities. Thus there are several other monitored

	First arrival	Peak arrival	Peak concentration	Fraction recovered	Horizontal distance	Vertical distance
1st arrival	1.0000	0.8533	-0.5272	-0.5156	-0.2336	-0.6546
Peak arrival		1.0000	-0.5753	-0.5573	-0.3448	-0.5746
Peak conc			1.0000	0.9760	0.3624	0.6686
Fraction recov				1.0000	0.4519	0.7117
Horiz dist					1.0000	0.1397
Vert dist						1.0000

Table 2: Correlation matrix for Wairakei tracer results

wells within similar distances for which there was no tracer recovered. Thus the tracer returns are even less dependent on separation than is evident in the table.

Even though the tracer returns are independent of distance, they are not independent of location. A map of the Wairakei field test shows that there was a distinct correlation between the fault locations and the strong returns. The seemingly paradoxical behavior along the Kaiapo fault in which the largest return (indicated by the solid arrow line) is over the largest distance is explained by the fact that well 121 is the deepest. McCabe et al [15] explain the high recoveries in wells 24 and 48 (both of which are deep) as a flow down the Wairakei fault and back up the Waiora fault, postulating that the faults intersect at depth.

Another aspect of the fracture flow was evident in a series of tracer tests conducted in the Tongonan geothermal field in the Philippines. In June 1981, I^{131} injected into well 4R1 was recovered at wells 404, 401, 108. A total of 16.29% of the injected tracer was recovered (compared to a maximum of only 6% in any of the Wairakei tests described above) with 11.45% being recovered in well 404 alone. 2.84% was recovered in well 401, and about 2% in well 108 (PNOC, [19]). The arrival times indicate a minimum tracer speed of 57 m/hr for well 404, 30 m/hr for well 401 and 22/m/hr for well 108. The tracer responses at Tongonan differed from those at Wairakei in that each return was characterized by two or more peaks, whereas all but one of the Wairakei returns showed only one peak.

Tracer tests at another well at Tongonan, well 2R2, emphasize this two path effect. Unlike the Wairakei tests, in which the tracer was injected at a single point, the Tongonan tests were performed by releasing the tracer downhole using a wireline sampling bottle. In March 1981, I^{131} was released in well 2R2 at the depth of its upper feed zone (400m). In June 1981, a second test was conducted in which tracer was released into the lower feed zone at 1300m depth. In the March test (upper feed zone), positive returns were measured at well 213 with a peak arrival at 19 hours and a recovery of 0.34%. In the June test (lower feed zone), much more of the tracer was recovered (1.68%) at well 213, but the first concentration peak did not arrive until 4.4 days. These results emphasize the individual behavior of single fractures intersecting the wellbore, and demonstrate that the flow paths are not necessarily connected out in the reservoir (although the surface locations of wells 2R2 and 213 are only about 200m apart). The injection rate into well 2R2 was constant at 200 tonnes/hr (Sarit, [18]).

There are other examples of results similar to those described in these two geothermal fields. Many of these are available in the open literature, although many are still confined to proprietary company files and reports. The selection of these two examples is not intended to be comprehensive, but simply to point out some of the salient aspects of the problem.

IMPLICATIONS OF FRACTURE FLOW

Based on the observations described in the previous section, we are able to formulate a conceptual model of the way in which injected fluid (and perhaps naturally occuring fluid, too) flows through fractured geothermal reservoirs. The fractures clearly provide the major conduits for flow, both at the scale of a single wellbore as well as that of the entire reservoir. Fluids move along planar fault zones, and are frequently constrained to flow in straight paths from one side of the reservoir to the other. Thus we can postulate that the tracer responses should be characteristic of linear flow in a planar fracture.

There are several different models available to describe the linear flow of a dissolved substance in a fracture. Horne and Rodriguez [18] demonstrated that Taylor Dispersion was likely to be the dominant dispersive mechanism in the fracture itself, and derived an extension of Taylor's dispersion coefficient (Taylor, [19]) to include the linear planar flow configuration. This model was then used to model the tracer return profiles from the Wairakei tests by Fossum and Horne [20]. Although the profiles could be matched, matching was possible only by considering two separate paths with their corresponding responses superimposed upon each other. This was an unsatisfying result since it did not correspond to the basic concept. The inclusion of a second path was required in order to match the characteristic long "tail" in the return profile (see Figure 1, for example). One of the possible explanations for this delay in arrival of the trailing edge of the tracer spike is diffusion (Neretnieks, [21]). Jensen and Horne [22] used the "matrix diffusion" model of Neretnieks et al [18] to provide a response with a longer tail than the pure convection-dispersion model, and were able to match most of the Wairakei returns with only a single path. Figure 1 and 2 compare the matches of Fossum and Horne [20] and Jensen and Horne [22] to one of the Wairakei tests.

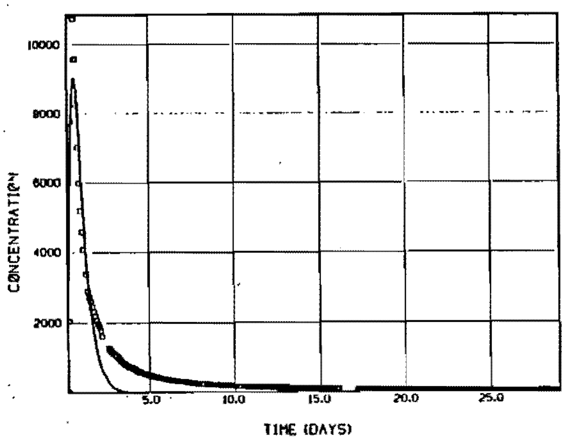

Figure 1. Single path match of convection-dispersion model to WK24 tracer response, from Fossum and Horne [20].

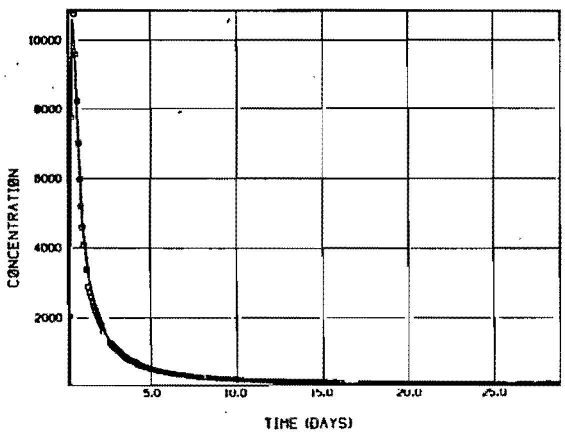

Figure 2. Single path match of matrix-diffusion model to WK24 tracer response, from Jensen and Horne [22].

Thus the high speed transport of geothermal water containing tracers appears to follow the same model as that of Neretnieks et al [23] which was derived for transport of radionuleides through fractured rocks at very much slower rates. This demonstrates that one of the principle mechanisms governing the transport of the tracer is physical loss of the tracer out of the fracture flow stream. The precise mechanism of this loss term is still unclear. It could be due to adsorption, chemical reaction, diffusion into the rock matrix around the fracture, diffusion into stationary fluid in other fractures, degradation of the tracer or ion exchange. All of these mechanisms are capable of giving rise to similar terms in the differential equations governing the model. Using a laboratory core with a fracture created along its axis, Johns [24] found that more tracer was retained in the core than flowed through. Research to pinpoint the site and mechanism of the holdup is ongoing.

SUMMARY

Geothermal reservoirs are by their very nature highly permeable formations of rock. In reservoirs of commercial interest, fluids are produced in very large quantities, and must flow at very high rates. It is not surprising therefore that almost all commercial reservoirs have major flow conduits within them. Based on drilling experience and on the results of tracer tests such as those described here, it is clear that faults and fractures provide the most permeable paths through the reservoir. That these paths provide short circuit routes for injected fluids to pass quickly through the reservoir is of great commercial significance.

Many of the tracer returns have been easily correlated with faults previously recognized from geological mapping and from drilling records. There are counter examples however in which the faults have been inferred from the tracer tests themselves. Remembering the example of the two kinds of response in well 2R2 in Tongonan, it is evident that the forecasting of injected water breakthrough would require the knowledge of the position of all major faults in three dimensions throughout the reservoir. Since this is usually only partially realizable, there seems no alternative but to carry out a series of tracer tests to determine these connections.

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