TRACER CALIBRATION TESTS AT WAIRAKEI GEOTHERMAL FIELD

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ABSTRACT

To investigate the potential for performing simultaneous tracer tests from multiple reinjection wells, calibration trials were done within the production area of the Wairakei geothermal field using a range of tracers. The tracers included fluorescent dyes, inert gases, organic compounds and radioactive isotopes. All tracers were injected into a non-productive well containing a natural inter-zonal flow using 6 mm capillary tubing. Tracer returns were monitored in the nearby production wells. All tracers showed similar first return times and relative to ^{125}I and the liquid tracers showed similar return patterns, but the return concentrations varied by up to ±20%. For wells producing from the liquid zone of the reservoir, tracer return patterns from the xenon gas tracer was essentially the same as for the liquid tracers, but for one well producing from both steam and liquid feed zones the returns of the gas tracers were greater than for the liquid phase tracers by four times. This difference is attributed to transfer of the gas from the liquid to vapour zones in the reservoir as the deeper liquid boils.

1. INTRODUCTION

Over the last 15 years many tracer tests have been carried out in the Wairakei field to identify fluid flows paths in the reservoir. Most of these tests have been done using the radioactive isotope tracers, ^{131}I and ^{125}I (McCabe *et al*, 1983). In general these tracer tests and other data show that there is rapid movement and recirculation of fluids within the reservoir, with hot recharge, up to 4000 t/h moving from the western part of the field toward the main production areas. Typical fluid velocities, based on tracer data, are in the order of 70-200 metres/day, although velocities up to 400 metresiday have been observed. The 1978-87 Wairakei tracer tests also showed that while large tracer returns between wells in the production area occurred within hours, to get the full picture of fluid movement in the reservoir away from the production areas, a tracer test needs to be continued for two *to* six months (McCabe, 1987).

Recently, non-radioactive tracers have been successfully used in other liquid geothermal fields to look at fluid movement and help to understand the underground processes (Adams et al, 1989). A series of new injection wells for the separated geothermal water is planned for the Wairakei field and the main objective of these experiments was to test various tracers in-situ and to evaluate the possibility of performing simultaneous tracer tests using different tracers from several injection wells.

2. TEST WELL ARRANGEMENT

The tracer injection well, WK57, is located near the centre of the main production area at Wairakei (figure 1) and was commissioned as a production well in 1962. The well was unable to sustain production after 1980 when cool fluids entered the well at its shallowest feed zone and flooded the lower parts of the well. Other nearby wells have also died as a result of cool water invasion (Bixley, 1990). By 1990 WK57 had a "natural" internal flow of about 60 t/h at 150°C, from the shallow feed at 430 m down to the deeper feed zone at 670 m.

A preliminary tracer test from WK57 in 1990 using sodium fluorescein had indicated strong returns in a nearby production well, M4, within 24 hours. Following this, further tests using ^{131}I and ^{133}Xe were done by injecting the tracer from the wellhead with a slug of cold water (about 50 m^3). These tests had given a good indication of the return pattern in some of the production wells, so that sampling in any new tests could be optimised to show the complete recovery curve.

WK57 was scheduled to be abandoned to seal off the internal flow, and it was decided to use it for a series of tracer tests before the abandonment. The location of the injection well, together with nearby producers is shown on figure 1, and a section showing the feed zone levels on figure 2.

3. TRACER INJECTION AND ANALYSIS

Experience from other tests had shown that the "best" tracer results at Wairakei (ie the largest returns) were obtained using a tracer injection well which already had an internal downflow. It appears that these internal flows efficiently flush the tracer from the wellbore into the fracture network when compared with injecting the tracer with a slug of water (usually about 50 cubic metres). To simplify tracer injection and standardise experimental conditions for the various tests, a tracer injection system using 6 mm capillary tubing and a portable high pressure water blaster pump was used for the test programme. The bottom of the tubing was located in the downflow at 550 m depth and depending on the tracer characteristics, the tracer was introduced to the tubing either upstream or downstream of the pump. The capillary tubing system allowed gas tracers to be used in a liquid well, by injecting the gas at a depth sufficient to ensure it would remain in solution and be carried down to the actual injection zone at 675 m by the natural downflow (thus avoiding the possibility of the gas returning to the surface of the "injection" well which had occurred following a wellhead tracer release in one previous test).

No special precautions were taken to remove oxygen from the fluorescent dye tracers before injection - about 20 litres of tracer solution were injected via *the* capillary tubing in each case.

3.1 Test Summary

Eight tests were done using the same tubing and injection well configuration.

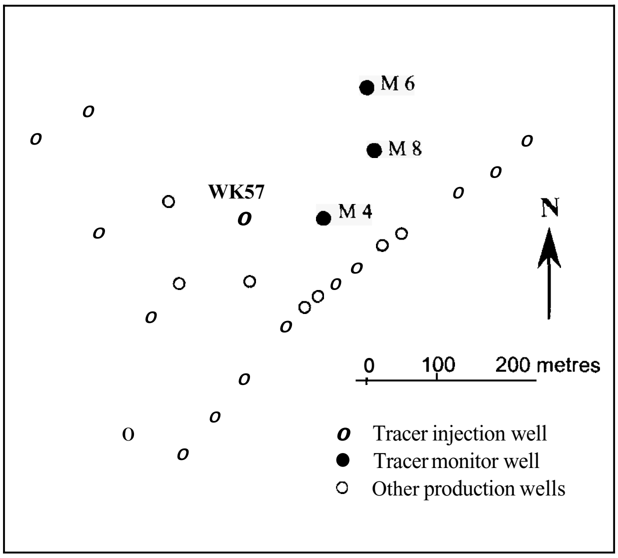

Figure 1 Plan of part of the production borefield at Wairakei showing the location of WK57, the tracer injection well together with the tracer monitor wells referred to in the paper. **All** wells shown on figure 1, except WK57 are production wells.

Table 1
Summary of tracer tests at WK57 during October-November 1992.

Date	Tracer	Quantity
19 October 1992	Rhodamine	1400 gm
10 November 1992	Sodium Fluorescein	1000 gm
10 November 1992	^{133}Xe	6.0 GBq
10 November 1992	^{125}I	2.15 GBq
10 November 1992	SF$_6$	1.116 gm
25 November 1992	Tinopal	2000 gm
25 November 1992	Sodium Benzoate	250,000 gm

The data from the tinopal test is not used in this paper because part of the measured amount of tinopal was not injected, thus it was not possible to calculate accurate normalised tracer fractions. To avoid potential problems with interference between tests, the dye tracers were injected more than three weeks apart. This allowed dye levels in the monitor wells to return almost to background values between tests.

3.2 Sampling

Separated steam and water samples were collected from a number **of** producing wells located around the injection well to determine the return patterns of tracers from the reservoir. For this paper the returns from only three of the monitor wells (**M4,** M6 and M8, see figure 1) are discussed. For the gas tracers Xe and SF$_6$, samples were collected from the steam pipelines downstream of the wellhead separators (each monitor well had an individual wellhead separator). For most of the liquid phase tracers, water samples separated at atmospheric pressure were used. For the continuous rhodamine log at **M4** the water samples were taken directly from the pressurised water line and cooled before analysis.

3.3 Analyses

The fluorescent dyes, rhodamine and fluorescein (and tinopal) were analysed using an Aminco SPF-5000 fluorimeter. This instrument can measure concentrations to less than 0.03 ppb for the dyes used in this programme. Initially there was a problem reconciling the results from the fluorescein test with the other tracers. This was resolved when correct standards, prepared under controlled pH conditions were used (Parilla, 1993)

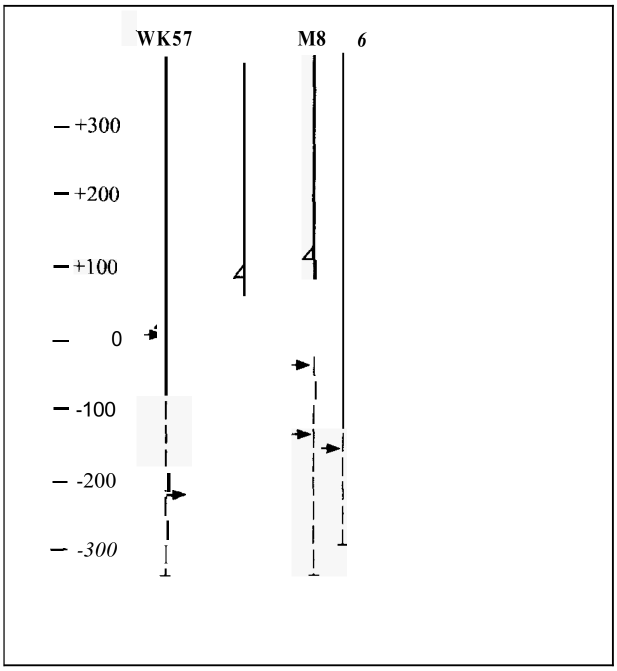

Figure 2 Schematic cross section WK57-M4-M8-M6. All wells are shown at their actual distance from WK57. Vertical and horizontal scales are the same as figure 1. Values on the vertical scale are metres relative to sea level. The tracer enters the formation at the lower feed zone in WK57, about RL -230. In this part of the production area a discontinuous vapour zone is present at elevations of -50 to -100 metres. This vapour zone is overlain by a zone of "cool" liquid at about 150°C(see Bixley, 1990).

The benzoate tracer was analysed on a Dionex 2000i/SP ion chromatograph. The eluent composition was "tailored" to enable the benzoate peaks to elute on a vacant portion of the baseline away from interference from the peaks of other species.

Sulphur hexafluoride was analysed using a Varian 3600 gas chromatograph with an electron capture detector (Glover and Kim, 1993). SF$_6$ analyses were delayed until 3 months after the sample collection, and there is a probability that there was some leakage in and out of the sample flasks. This is reflected in the variable SF$_6$ results when compared with the other tracers.

^{133}Xe was analysed by liquid scintillation counting (Barry, 1990). The non-condensable gases were extracted from condensed steam samples and the xenon separated from the naturally-occurring radioactive noble gas, radon, by gas chromatography. The xenon was then absorbed on silica and added to a standard "cocktail" for counting.

For ^{125}I analyses, 2 litre samples of water separated at atmospheric pressure were treated to remove sulphides, silica and halides other than iodide. The iodide was then precipitated and the precipitate dissolved in a "cocktail" and counted using a liquid scintillation counter.

3.4 Normalising the Data

To enable the returns of the various tracers to be compared, the field data was normalised using a method previously developed for presenting returns of radioactive tracers. The mass of tracer in 1 kg of sample, is divided by the mass of tracer injected and multiplied by 10^{12} to give reasonable working values. After the field data has been normalised, a further correction to calculate the tracer concentration in the total mass flow is required to allow comparison of gas and liquid phase data. This is a simple dryness correction to recalculate the "normalised" tracer fraction in the field sample to the fraction in the total mass flow being produced by the monitor well, assuming complete partitioning of the tracer into steam or water phases.

For example, in the rhodamine test of 19 October 1400 gm of rhodamine was injected: a maximum concentration of 5.73 ppb was measured in brine from M4 separated at atmospheric pressure (0.98 bar), 20 hours after injection. In 1 kg of sample the rhodamine content is 5.73×10^{-6} grams, therefore the normalised concentration in the separated brine (NC_{sample}) was:

$$NC_{sample} = \frac{5.73 \times 10^{-6}}{1400} \times 10^{12} = 4093 \qquad [kg^{-1}]$$

The enthalpy of the fluid produced by M4 was 970 kJ/kg, therefore the normalised
concentration in the total mass flow was:

$$\begin{aligned} NC_{totalmass} &= NC_{sample} \times (\text{Water Fraction at } 0.98\,\text{bar}) \\ &= 4093 \times \left(\frac{2676 - 970}{2258} \right) \qquad [kg^{-1}] \\ &= 3092 \end{aligned}$$

For a gas tracer collected from the steam phase at the surface, the normalised fraction in the total mass flow is calculated by making the same calculations as above, but using the the steam fraction at sampling pressure.

4. RESULTS

4.1 Well M4

M4 is the closest production well to the tracer injection well, WK57, and showed the most rapid returns with the highest tracer concentrations. It is located 120 metres east from the injection well and has two major liquid feed zones at 440 and 830 m depth (figure 2).

All the liquid tracers showed very similar return patterns (fig 3). First returns were detected 11 hours after injection with peak values of about 3500 kg $^{-1}$ after 18-22 hours, followed by gradually declining concentrations. The xenon gas had the same pattern and concentration, except that three analyses at the peak return time had values of 4100-4700 kg $^{-1}$. The SF_6 gas showed the same return time and peak value as the liquid tracers, but after 48 hours the tail of the SF_6 curve had declined below the liquid tracer concentrations.

The normalised concentrations for rhodamine in all monitor wells appear to be offset from the other liquid data by a factor of about 0.7. The exact reason for this has not been ascertained, but as the difference is an offset rather than a different trend line it is likely to result from the normalisation calculation, rather than decay of the tracer. The original amount of rhodamine used to calculate the normalised concentration may not have been exact as the rhodamine was provided as a made up solution by the local supplier and was not independently analysed at the time of the tests.

While all the tracers showed a similar return pattern, at the time of peak returns, there is some variation in values for the different tracers, ranging from 2500 kg $^{-1}$ for benzoic acid to 4700 kg $^{-1}$ for xenon. The other tracers showed good agreement with maximum return values of 3100 to 3600 (±7%).

M4 has two feed zones, and at the time of these tests its output cycled over a 50 minute period as the contribution from each zone changed. The varying contribution from each zone was confirmed in the continuous (5 minute measurements) rhodamine log which at the time of peak tracer returns showed a cycle between 3450 and 3850 kg $^{-1}$ (±5%) over the same period as the production cycle. This cycle would account for some of the variation in the analyses from the different tracers from spot samples. All of the tracer produced from M6 is likely to come from the deep feed point at 830 metres, as the upper feed zone at 440 metres is 200 metres above the injection point in WK57 (fig 2).

Table 2

Well data for tracer test. All depths are metres. The major feed zone in M4 is at 830 metres depth. The cooler shallow zone in this well produced intermittently during the tracer tests (see text).

Well	WK57	M4	M6	M8
Elevation	442	425	421	416
Prodn Csg	430	345	454	309
Feed Zone	430	440	575	460
Feed Temp °C	150	200	219	Vapour
Feed Zone	670	830	--	550
Feed Temp °C	?	221		221
Dist from WK57	--	120	260	210
TD	675	832	632	641

4.2 Well M6

M6 is also a liquid-fed well, located 260 m NE from WK57. The major feed zone in M6 is at 575 metres, about 100 metres above the injection level in WK57 (fig 2). Tracer returns were first seen after 14 hours, with the peak return at 27 hours (fig 4). Peak return concentration is 700-1000 kg $^{-1}$, about one quarter of the peak value in M4. Good data is only available for ^{125}I, fluorescein and benzoic acid. The rhodamine sampling started after 140 hours when the tail of the tracer return had already declined to 1/10 of the peak values, and the concentrations were nearly at the limit of detection. No gas tracer sampling was done on M6.

The ^{125}I, fluorescein and benzoic acid return times and overall pattern show good agreement, although the peak values for benzoic acid are 1.5 times higher than for the other tracers, whereas at M4 the benzoic was lower than ^{125}I by 0.7 times.

4.3 Well M8

M8 is 210 m NE from the injection well, in between the other two monitor wells (fig 1). It was chosen as it has a discharge enthalpy of about 1100 kJ/kg, compared with 950-970 kJ/kg found in most of the liquid-fed wells nearby. The "excess" enthalpy in M8 is a result of this well having separate liquid and steam (or two-phase) feed points (fig 2) and it was thought that the liquid and gas tracer returns at the surface might be different from those obtained from solely liquid-fed wells. Any consistent differences could assist with assessment of underground processes in a boiling reservoir and with interpreting tracer return patterns in or near a boiling zone. A previous gas tracer test in 1991 using ^{133}Xe had indicated large differences between gas and liquid return concentration for tracers injected into WK57.

For the liquid tracers first returns at M8 were seen after 15 hours, with peak values of 300-450 kg $^{-1}$ at about 48 hours (fig 4). Thus the first returns take longer and the peak values were about 1/10 those detected in M4, although M8 is closer to the injection well than M4. The xenon tracer indicated much larger returns than the liquid tracers, consistent with the 1991 xenon results. The peak xenon value was more than four times the peak value for ^{125}I. The SF_6 results are quite variable when compared with the other tracers. The higher SF_6 values lie between those for liquid tracers and xenon, while the remainder are similar to the liquid tracer values. As at M4, after 48 hours the SF_6 tail also declines quickly below the liquid tracer values.

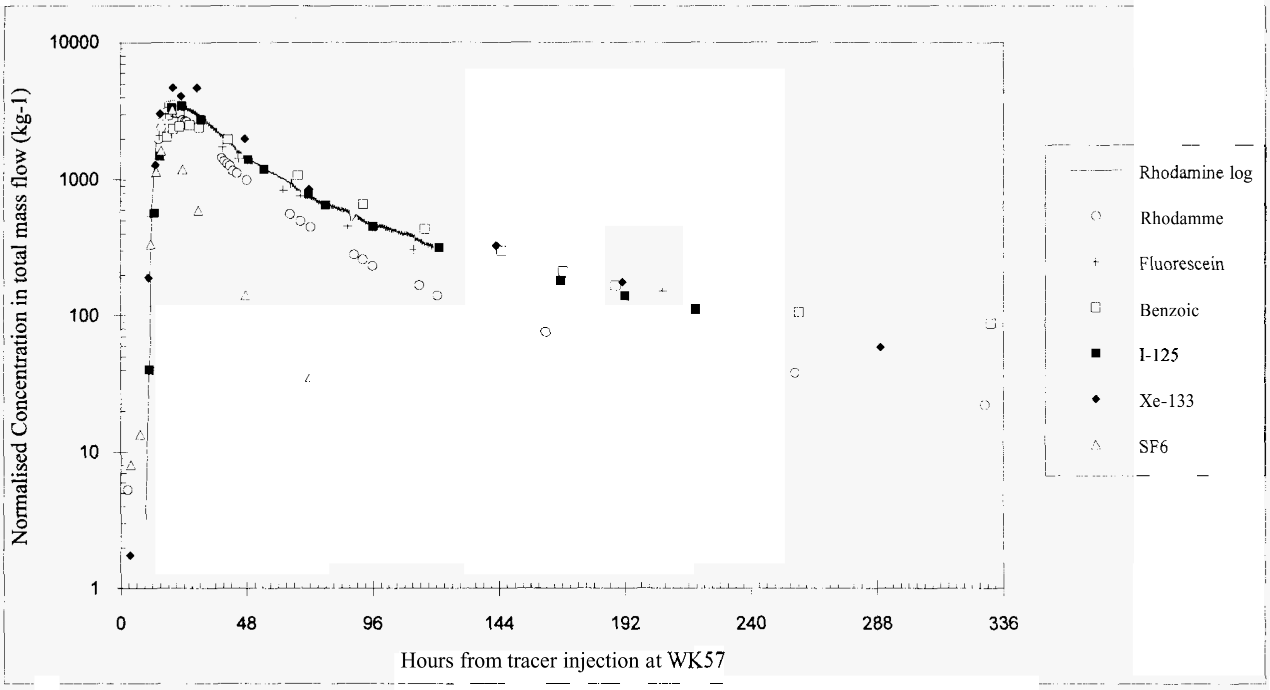

Figure 3: Tracer returns at **M4** from WK57.

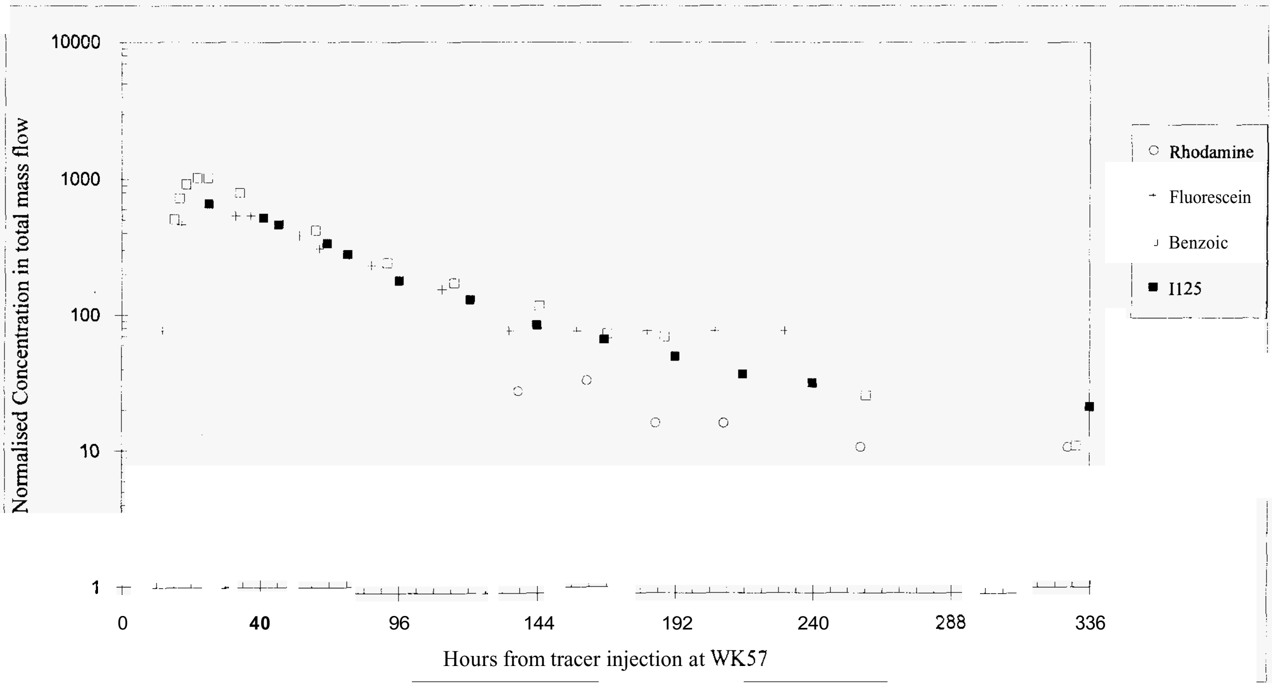

Figure 4: Tracer returns at M6 from WK57.

5. DISCUSSION

5.1 Comparison of Tracers

For most of the tracer tests that have been completed at Wairakei, radioactive isotopes, usually ^{131}I and ^{125}I, have been used due to their high sensitivity and their natural decay which avoids contaminating the reservoir by raising the background tracer concentrations after repeated tests. It seems that these tracers are not absorbed by the formation as in one test almost 100% of the ^{125}I was recovered over a six month period. On table 3, the peak returns of the various tracers are compared with the ^{125}I return values. Some of the discrepancy between different tracers will be due to uncertainties in the absolute amount of tracer injected, and in the tracer concentrations measured in the field samples. During these tests the tracer concentration from **M4** was also varying over a 50 minute period due to cycling flows from the wells. These factors can be expected to make the margin of error in the normalised concentrations up to at least 10%.

Although fluorescent dyes degrade in geothermal conditions, for the subsurface temperatures found in this case (about 220°C), degradation does not appear to be significant within the two-week duration of the tests. For the small amounts of tracer injected for most of the tests, return concentrations had reached the limit of detection after 2-3 weeks. ^{125}I samples taken 70 days after injection showed that detectable amounts of tracer were still present (6-10 kg $^{-1}$).

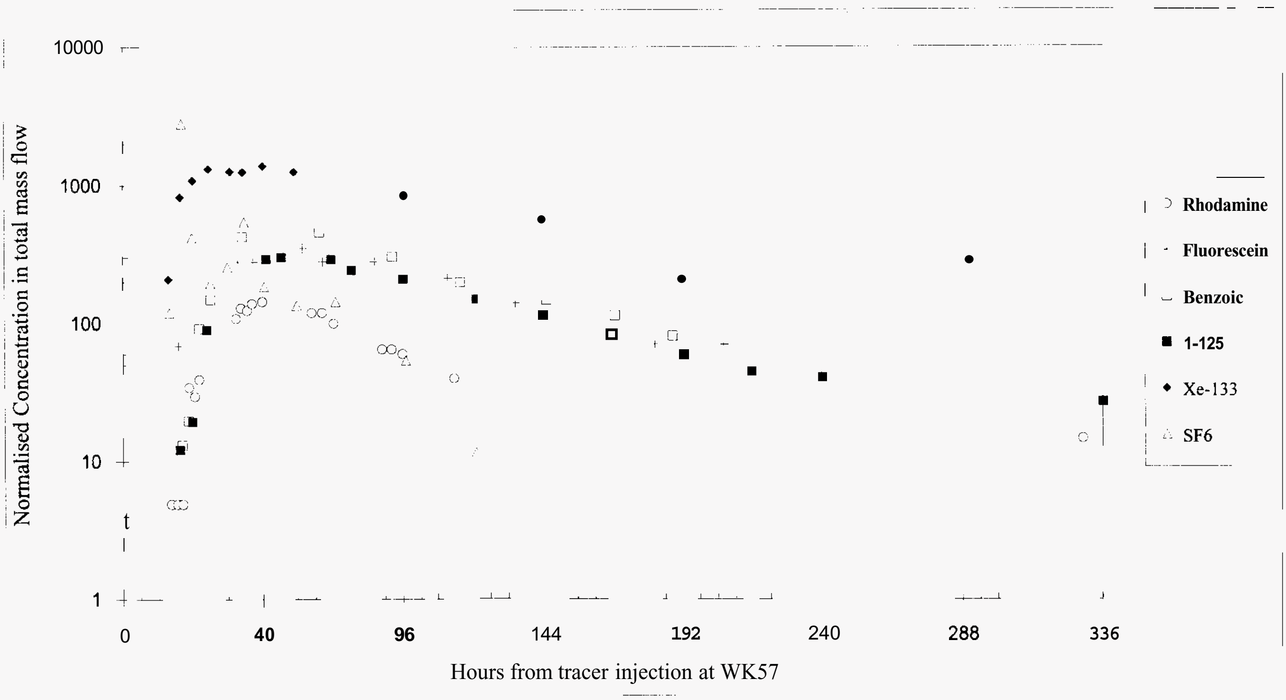

Figure 5: Tracer returns at M8 from WK57.

Table 3

Comparison of tracer returns for the three monitor wells, relative to ^{125}I

Tracer	M4	M6	M8
^{125}I	1.0	1.0	1.0
Benzoic acid	0.7	1.5	1.5
Rhodamine	0.9		0.5
Fluorescein	1.0	0.8	1.2
Xenon	1.4		4.3
SF_6	0.9		

5.2 Gas Solubility

Where the gas tracers remain in solution then solubility is not a concern and the gas tracer follows the liquid movement and gives the same results as for liquid tracers. However where there is some gas separation or boiling along the tracer pathway, the gas solubility becomes important. As far as we are aware there is no experimental data available for the solubilities of SF_6 and xenon at the temperature and pressure conditions found in this trial (Glover and Kim, 1993). At 30°C the solubility of xenon is more than 10 times that of SF_6. While the solubilities will change with temperature, their relative values are unlikely to change dramatically. It is not clear that this difference in solubilities is the reason why the tail of the SF_6 returns measured in both M4 and M8 declines more rapidly than for the other tracers.

6. CONCLUSION

Comparisons of the various tracers used in these tests indicate that while velocities for the different tracers are usually very similar, the normalised return concentrations can vary by 20%, so that comparing yield calculation data from different tracers needs to be treated with caution.

Gas tracers may be used to follow the movement of the liquid phase, while the gas remains in solution. Where there is boiling of a liquid containing a gas tracer it is possible to use gas tracers to follow movement of the evolved gas and vapour components. Further investigations are needed to determine solubilities of suitable gas tracers, together with field trials to compare liquid and gas tracer performance in more detail.

The data from these tests indicate that in the Wairakei production area environment (220-230°C) the fluorescent dyes did not degrade significantly in two weeks.

7. ACKNOWLEDGMENTS

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