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RESULTS OF A 13-MONTH REINJECTION TEST AT WAIRAKEI GEOTHERMAL FIELD, NEW ZEALAND

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ABSTRACT

Fluid (130°C) was reinjected, at a rate of about 570 t/h, at approximately 450 m depth, into the deep liquid zone near the centre of the Eastern Borefield, using well Wk62. The fluid caused the deep liquid level, previously at about 330 m depth, to rise in a cone of impression which decayed when reinjection ceased. The shape and extent of the cone were determined from microgravity and pressure measurements, and suggest that the fluid flowed westwards towards the Western Borefield and north-eastwards towards an area of large ground subsidence. Good line source fits to pressure transients were obtained for pressure data in nearby wells. No pressure effects larger than 0.1 bar were measured in wells more than 500 m from Wk62. A tracer test gave large, rapid returns in nearby wells. Small (though barely significant) returns in two wells in the eastern part of the Western Borefield suggesting that small amounts of fluid may have reached there. Deep liquid temperatures in wells close to Wk62 decreased by about 40°C, and mass production from the Eastern Borefield fell by 45%. There was no induced seismicity.

INTRODUCTION

Wairakei Power Scheme discharges about 5300 t/h of waste geothermal fluid directly, and indirectly, into the Waikato River. As part of a programme to improve water quality in this important waterway it is proposed to reinject a large proportion of the separated water and tests to locate suitable sites for reinjection have been underway for several years. The preferred area for reinjection has been identified as the eastern part of the field; this is furthest from the most productive part of the field and would allow waste fluid to flow, under gravity, from separation plants to reinjection wells.

In 1984 a test reinjection well (Wk301) was drilled to 1440 m depth, just inside the eastern boundary of the field. However, the well had poor permeability and proved unsatisfactory for reinjection purposes. Three separate pump tests, which injected cold water at wellhead pressures up to 35 b.g. and flows up to 668 t/h, caused some improvement in injection capacity. The injectivity increased

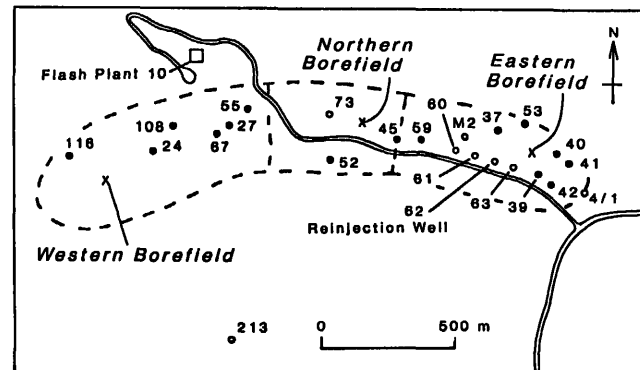


Fig. 1: Location of wells mentioned in the text. Production wells (at start of the test) are shown by solid circles; non-producing wells by open circles.

in sudden jumps, thought to be caused by hydrofracturing, and stabilised at 22 t/h/b. (Allis *et al*, 1985). The injection induced seismic activity within a radius of several kilometres of the drillhole. The activity began within a day of the pump tests starting, but always ceased immediately the pumping stopped (Sherburn, 1984). The test showed that finding good permeability in a suitable location at Wairakei was not a simple exercise.

During the 1970's and 1980's, steam zone pressures in the Eastern Borefield decreased by about 7 bars, and temperatures fell by more than 20°C (Allis and Hunt, 1986). By 1988, only seven wells (Wk37, 39, 40, 41, 42, 53 and 59) were still producing from the Eastern Borefield, and production had declined to about 40 t/h I.P. steam and several of these wells were approaching the end of their productive life. In conjunction with a programme to obtain extra production from the far western (Te Mihi) part of the reservoir, it was accepted that the Eastern Borefield could be sacrificed for reinjection; and a further test was planned.

Well Wk62, located in the centre of the Eastern Borefield (Fig.1) was chosen for the test. This bore was completed in September 1958 to a depth of 637 m, with 6½" slotted casing from 290 m depth to the bottom of the hole. The hole encountered Huka Formation rocks from 75 - 240 m

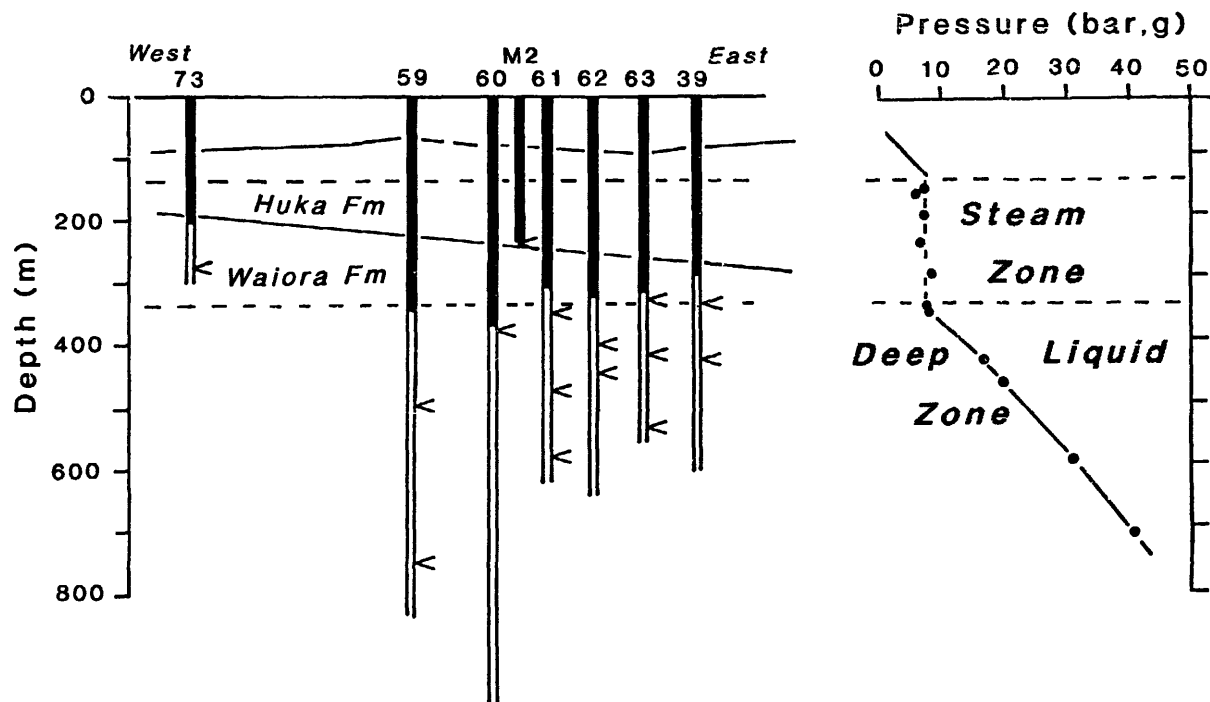


Fig. 2: Cross-section through the Eastern Borefield, showing geology (simplified), the extent of solid and slotted casing in the holes (solid, and open lines), and feed zones (<). Also shown is a plot of pressure against depth for the Eastern Borefield (before the test).

depth, and below 240 m the Waiora Formation (Fig.2) (Grindley, 1965). Tests indicate that the major feed zone occurs at about 450 m, and a subsidiary at about 400 m depth. The well was originally a high pressure well. However, pressures and temperatures dropped and it was progressively derated to a low pressure well in May 1975. Injection and tracer tests were carried out using the well in September - November 1983. A tracer test, without reinjection, showed no return of Iodine 131 tracer in nearby monitoring wells. Two further tests, with reinjection (125 and 86 kt respectively) recorded returns only in adjacent wells Wk61 and Wk63, and a small response in Wk43 (about 250 m away) (McCabe and Barry, 1983). The well failed to thermally recover from these tests, and it was shut down in November 1984.

REINJECTION TEST

Reinjection into Wk62 began on 19 April 1988 and continued, with only short breaks, until 11 May 1989. The fluid was separated water from Flash Plant 10, had a temperature of about 130°C, and was injected at a rate of about 570 t/h; at the end of the test about 5.2 Mt had been returned to the reservoir. No pumping was required; the well accepted fluid under gravity.

PRESSURE CHANGES

Deep liquid pressures were monitored during the test using capillary tubing systems in non-producing holes Wk53, 60, and 213 (Fig.3). Vapour pressures were monitored in Wk4/1, 73, and M2. Pressures and flows in production wells Wk39, 41, 59 and several wells in the Western Borefield were also measured.

Continuous pressure measurements, near the reinjection well, were made at Wk60 and later in Wk53. Soon after (several hours) reinjection began, deep liquid pressures in these holes increased rapidly; this was followed (particularly for Wk60) by a long period of near-linear increase (apart from several short period transient changes, described later) which continued to the end of reinjection. When reinjection stopped, the pressures in the holes fell rapidly, in an exponential manner, to a constant value greater than before the test: 1.3 bar for Wk53 and about 1.0 bar for Wk60. Pressures in Wk213 did not change by more than 0.1 bar. No pressure changes were recorded in the steam wells Wk4/1, 73, and M2, nor were any changes identified in wells situated in the Western Borefield.

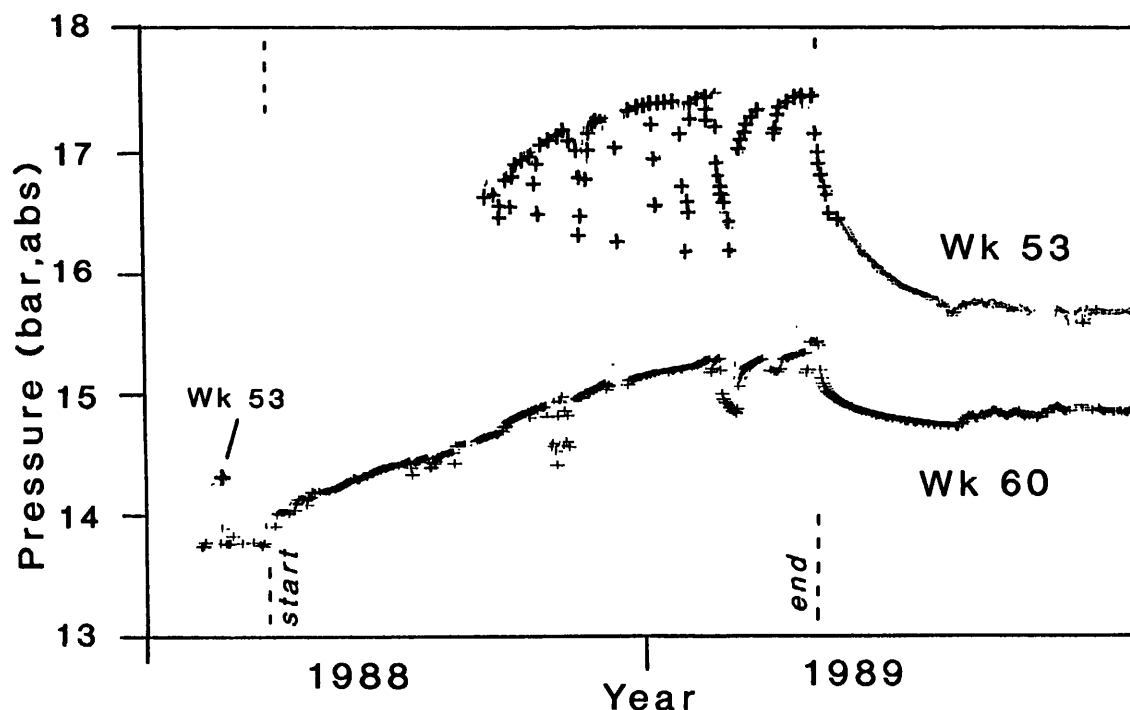


Fig. 3: Deep liquid pressures (at R.L. 0 m; approx 400 m depth) in wells Wk53 and 60 during the test.

Pressure Transients

Several sets of pressure transients were recorded, associated with changes in injection flowrate. Good fits were obtained between the measured and calculated data (Fig. 4) using line source solutions. The solutions incorporated leakage, the linear trend of pressure increase, and changes in production flowrates (described later). The line source fits remained excellent, even over periods of 15 days, suggesting the reservoir behaved as a homogeneous porous medium. The solutions indicated values for permeability-thickness (kh) of about 170 d-m for transients recorded at Wk60, and about 100 d-m at Wk53. Diffusivities were in the range 0.5 - 7.5 m²/s; usually those for Wk53 being about twice those for Wk60. Assuming the deep liquid level is a free surface, porosities (ϕ) of 0.005 - 0.015 were obtained, with values at Wk53 being smaller than at Wk60. The values for kh are large, and for ϕ are small, suggesting that they reflect fracture values for these parameters.

The values for kh and ϕ at Wk53 and Wk60 were consistently different, and attempts were made to find the source of the difference by changing the models. However, introduction of permeability anisotropy, placing a local inclusion around Wk60, and inserting a linear discontinuity between Wk53 and Wk60, failed to provide satisfactory fits

to the data for both wells simultaneously. The pressure responses in Wk60 appeared to be anomalous: although much closer to the reinjection well than Wk53, the pressure changes in Wk60 during the test were always smaller. One possible explanation for the differences is that a feed zone in Wk60 allowed fluid to escape from the well to a distant part of the reservoir, as the deep liquid pressures changed.

Linear Trends

The long term pressure changes associated with the reinjection test consisted mainly of a linear increase with time. Estimates for the effective area of the Eastern Borefield reservoir can be obtained from the slopes of this linear trend and the porosity. If the above values of fracture porosity (determined from the pressure transient data) are used, the effective area is calculated to be 25-150 km², which is clearly too large. However, assuming a field-wide value for porosity of 0.4 (Pritchett *et al*, 1978), more reasonable values for area of 0.15 km² are obtained from the Wk53 data, and of 0.7 km² from the Wk60 data. In calculating these values, no allowance was made for the effects of a general rise in deep liquid level during the test and the value for porosity of 0.4 is probably too large; the area values calculated will therefore be too small.

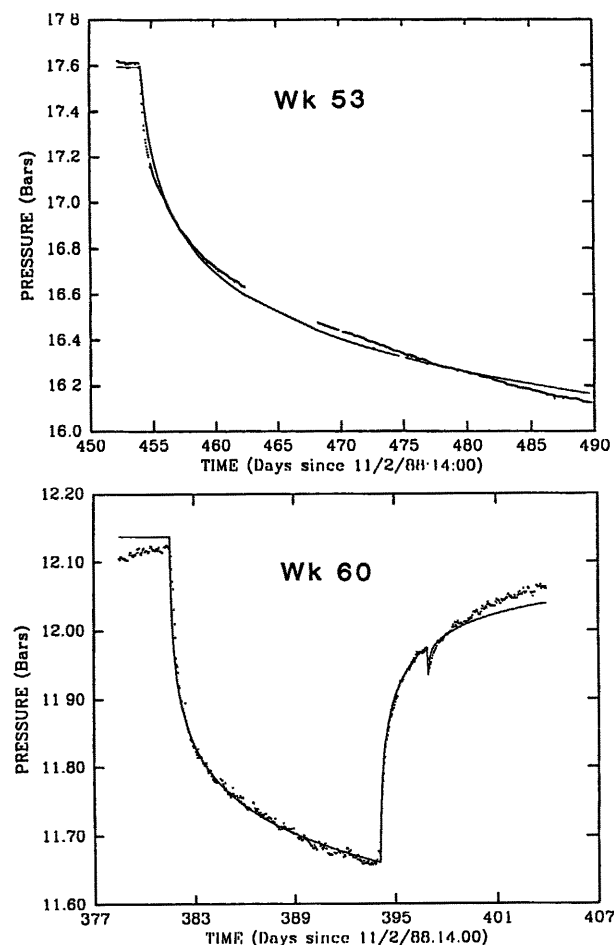


Fig. 4: Measured pressure changes (dots) and those calculated for a line source solution (solid lines).

CHANGES TO PRODUCTION WELL FLOWS

During the test, production from most wells in the Eastern Borefield decreased due to thermal degradation; by the end of the test, mass production rate was down by 45%. Wells Wk37, 40, and 53 ceased production during the test. No changes in flow rate or discharge enthalpy were observed in Wk59 (Eastern Borefield; Fig. 1), or in any production wells in the Western Borefield.

TEMPERATURE CHANGES

Temperature changes in the Eastern Borefield were measured in two non-producing holes; by the end of the test, the temperature at 450 m depth (deep liquid zone) had fallen from 202°C to 160°C in Wk61 and from 192°C to 155°C in Wk63. Temperatures in production wells in the Western Borefield remained unchanged throughout the test.

MICROGRAVITY MEASUREMENTS

Gravity measurements at approximately 100 benchmarks were made in January 1988 (before), and repeated in May - June 1989 (after the test). Standard observation and reduction techniques, previously employed at Wairakei were used (Hunt, 1984). The gravity values obtained had mean standard errors of 10 and 6 microgal (0.10, 0.06 $\mu\text{N}/\text{kg}$) for the 1988 and 1989 surveys respectively. Differences in the value of gravity at each benchmark, between the surveys, corrected for the effects of elevation changes (hereafter called gravity changes) were then calculated taking the vertical gravity gradient as +302 microgal/m of subsidence. Elevation changes (ground subsidence) at the benchmarks used were determined by linear interpolation of graphs of elevation against time. The gravity gradient was determined from measurements over vertical intervals of 2.5 - 3.5 m at three places in the borefield, and has a standard error of 5 microgal/m. Gravity changes at eight benchmarks located well outside the field had a mean of -1 (± 17) microgal, indicating that there was no change in gravity at the reference benchmark and that the significance level of the gravity changes was less than 20 microgal.

Previous gravity measurements have shown that since the early 1970's gravity changes in the Northern and Eastern borefields have steadily increased, caused mainly by the deep liquid level in the reservoir rising (i.e. steam zone becoming thinner) as a result of inflows of cold water (Allis and Hunt, 1986). During the period 1983-1988, gravity changes at benchmarks in the Northern and Eastern borefields increased by up to 120 microgal (Hunt, 1988) and extrapolation of the linear trends in these areas suggests that during the period of the test the gravity changes there would be expected to be up to 30 microgal (Fig.5).

Gravity Changes

Gravity changes associated with the test (Fig.5) were obtained by taking a contour map of the measured changes between the 1988 and 1989 surveys and subtracting the contours of expected changes. In performing this subtraction it has been assumed that the reinjection had no effect on the inflows which caused the changes between 1983 and 1988. It has also been assumed that the gravitational effects of changes in the level of the shallow, cold groundwater system which overlies the reservoir were negligible (≤ 10 microgal, i.e. ≤ 1 m of level change); this is a reasonable assumption for the borefield area because data from several shallow monitor holes indicates there were no changes in level greater than 1.5 m.

The contours of gravity change associated with the test are roughly crescent-shaped (Fig.5) centred near the reinjection well, with one arm extending westwards towards the northern borefield and the other arm extending north-eastwards towards the area of greatest ground subsidence.

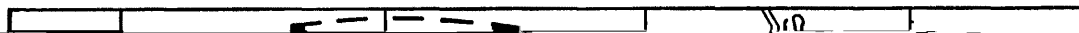
The maximum gravity change is more than +80 microgal (approximately 4 times the significance level), and the changes can be discerned up to 1 km from the well.

Interpretation

The most likely cause of the gravity changes associated with the test is that the reinjected fluid flowed out of the well, at about 450 m depth, and displaced the deep liquid level upwards in a roughly cone-shaped form. To determine the size and extent of the displacement a cone-shaped geophysical model was set up. The base of the model was taken as being at the depth of the bottom of the steam zone (330 m). It was also assumed that, for the lower part of the steam zone near the reinjection well: the displaced liquid completely saturated the steam zone; the temperature at the start of the test was about 180°C (Allis and Hunt, 1986); liquid saturation was about 0.7 (Hunt, 1988); and the porosity of the rocks was about 0.4 (Pritchett *et al*, 1978). These assumptions lead to an increase in density associated with the influx of reinjected fluid of about 112 kg/m³. The gravity effects of the model, taking this value for density change, were calculated (Talwani and Ewing, 1960) and compared with the measured gravity changes. The shape of the model was adjusted and its effects recalculated until the calculated and measured values were in good agreement. The final model so obtained is shown in Fig.6.

The centre of the model is located about 150 m south of the reinjection well, but this discrepancy is probably due to errors associated with contouring the data, and subtracting the expected gravity changes. The main uncertainties in the modelling are with the values adopted for porosity and saturation of the lower part of the steam zone. If the porosity was greater than 0.4, or the saturation was less than 0.7, the height of the model would be smaller, and the converse holds. The most likely error is that the value for porosity is too great, so that the height of displacement of the deep liquid level is under-estimated. The lateral extent and shape of the model would not be significantly influenced by differences in these values, however, the outer limits of the model must be treated with caution because the gravity effects here are small and it is known that the steam zone itself does not extend, in places, as far as the model suggests.

The model suggests that fluid spread out from the reinjection well in two main directions: westwards towards the Western Borefield, and north-eastwards towards an area of large ground subsidence (Allis and Hunt, 1986). A cross-section drawn through the model suggests the displacement of the liquid level was similar in shape to a cone of impression. The height of the displacement was at least 50 m.



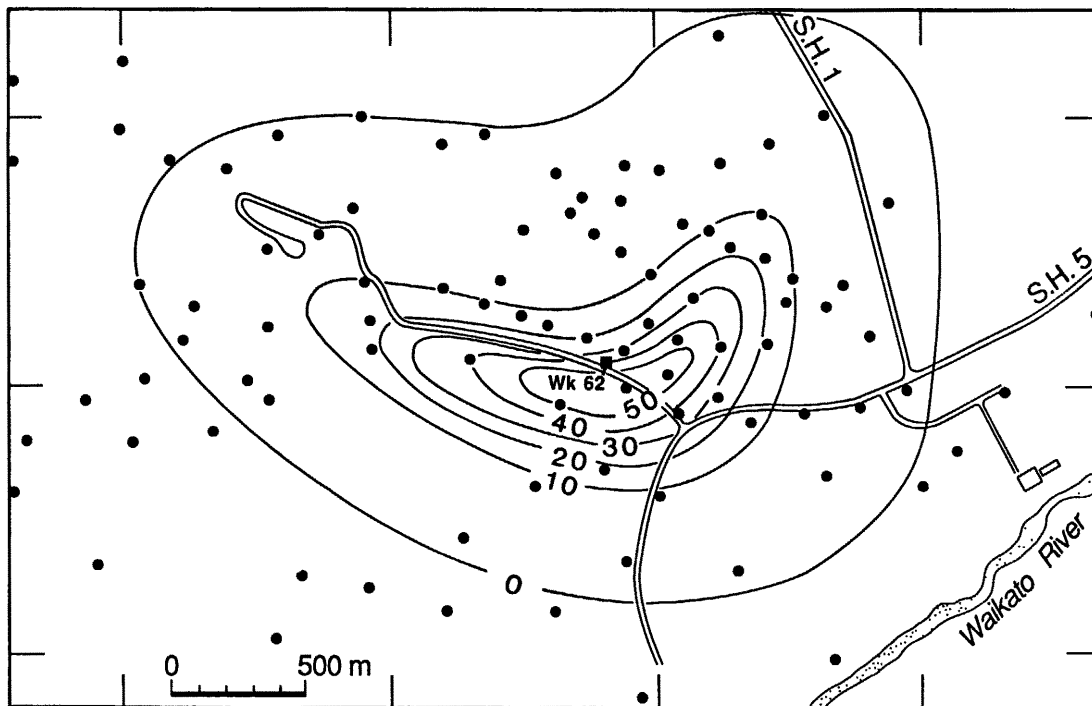


Fig. 6: Shape of the cone of impression about three weeks after the end of reinjection, determined from the gravity data. Contours are the change in height of the deep liquid level (contour interval 10 m). Note the extensions towards the north-east and west.

The volume of the model is approximately $44 \times 10^6 \text{ m}^3$, corresponding to a mass of about 4.9 Mt; this value is close to that of 5.2 Mt actually reinjected, which suggests that little ($\sim 6\%$) of the fluid reinjected was removed by production wells during the test. The value of 4.9 Mt is not influenced by errors in the values adopted for porosity and saturation, but it must be treated with caution because of the errors inherent in determining the volume of the model and in matching the gravity effects of the model to the measured gravity changes.

Relation to Changes in Deep Liquid Pressure

Theoretical pressure changes (deep liquid), calculated from the upward displacement of the liquid level given by the gravity model, were determined assuming reinjected water at 130°C displaced steam at 180°C (i.e. $\Delta\rho = 900 \text{ kg/m}^3$). The theoretical pressure changes are 1.8 bar at Wk53, and 2.6 bar at Wk60; the measured pressure changes, between the times of the gravity measurements are 2.8 bar and 1.1 bar respectively (Fig. 3). However, the measured changes include the effects of the long term rise in deep liquid level which had not been included in the gravity model (because the gravity effects of this had already been estimated and subtracted). The gravity effect of the long term rise was

estimated to be about 30 microgal (Fig. 5), corresponding to a rise of about 10 m in deep liquid level (Allis and Hunt, 1986), which would cause a pressure increase of about 0.9 bar. The measured pressure changes, taking the long term rise into account, are therefore about 1.3 bar for Wk53 and 0.3 bar for Wk60 (Fig.3). There is, therefore, reasonable agreement at Wk53 between the theoretical pressure changes (calculated from the gravity model) and the measured pressure changes, but poor agreement at Wk60. However, as noted above, the pressure changes measured at Wk60 appeared to be anomalous, and must be treated with caution.

The lack of any observable pressure responses in wells in the Western Borefield and the very small change in Wk213 are consistent with the results of the gravity data; these wells lie close to the edge, or outside, the cone of impression.

With hindsight, it would have been useful to have measured gravity changes, near Wk62, on a regular basis, during and after the test, to monitor the rise and fall of the cone of impression.

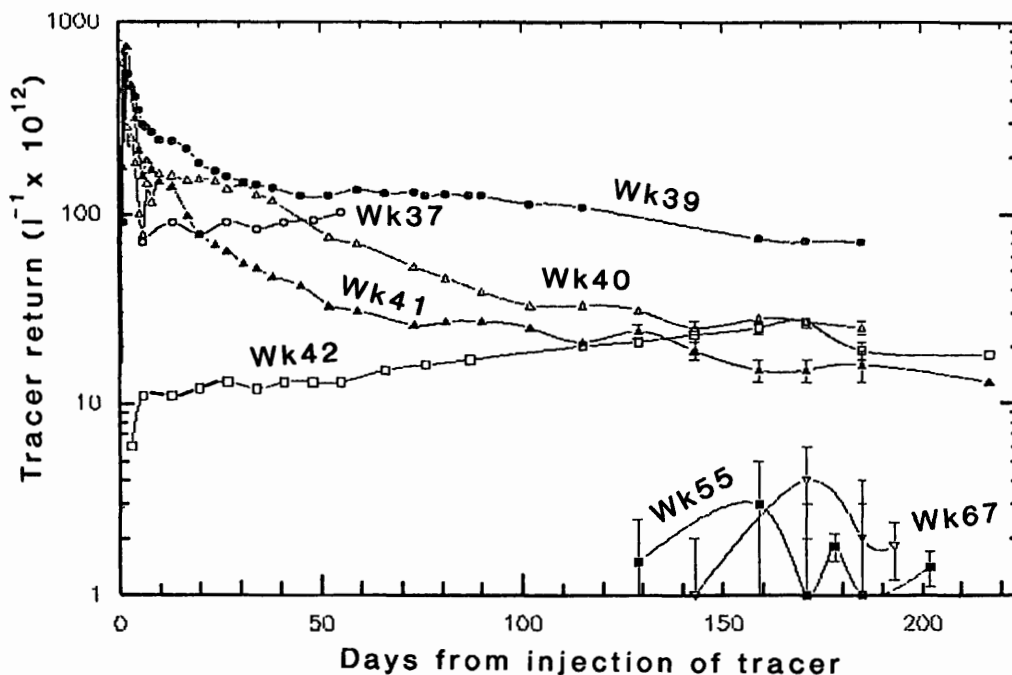


Fig. 7: Plots of tracer returns in wells. Note that the returns in the Western Borefield are barely significant: errors bars are shown for the 68% confidence level.

TRACER TEST

A tracer test was begun on 22 July 1988 by inserting 18.5 GBq (500 mCi) slug of Iodine 125 into the reinjected fluid. A sample collection technique similar to that described by McCabe *et al* (1983) was used; the size of the sample taken was 2 l, though later samples were 16 - 22 l. Wells in the Eastern Borefield were initially sampled daily, and then, along with wells in other parts of the field, with reducing frequency; in all, 22 wells were sampled over a period of 230 days. In total, about 9% of the tracer was recovered from discharging wells during this time.

Returns in the Eastern Borefield

There were large and rapid (<3 days) initial returns of the tracer in wells Wk37, 39, 40, and 41, situated east of the reinjection well, but only a small initial return in Wk42, also located in this area (Fig.7). The largest return velocity, calculated from first arrival times, was about 30 m/h. Nil returns were measured in well Wk59 situated west of Wk62. No data could be obtained from wells Wk53, 60, 61, and 63; however, the 1983 tests showed rapid responses occurred in Wk61 and Wk63 to tracer injection in Wk62.

The rapid returns in Wk37, 39, 40, and 41, are consistent with results of the gravity data, but it would appear that the nil return in Wk59 is inconsistent. However, in all previous tracer tests in the Wairakei Field, there have been no returns to Wk59.

The tracer return curves for Wk39, 40, and 41 (Fig. 7) are complex, but similar, and resemble those from previous tests in other parts of the field. After an initial sharp peak, there is a period of roughly exponential decay with a half-value time of about 30 days, which changes to a near constant return, then a reversion to a near exponential decay with a half-value time of about 130 days. This could be due to the presence of two or more flow paths with different aperture and pore structures.

Returns in the Northern Borefield

There were no returns in two wells monitored (Wk52, 45), but this is not surprising because they have shallow steam feeds.

Returns in the Western Borefield

There were no returns in wells Wk24, 27, 108, and 116. Very small, though barely significant (≤ 3 parts in 10^{12} l), returns were measured in wells Wk55 and Wk67 about 4 months after the tracer was inserted (Fig.7); these wells are located at the eastern end of the Western Borefield (i.e. closest to Wk62). If these returns are real, it is the first time tracer movement between the Eastern and Western Borefields has been detected. The smallness of the returns could be the result of rapid dilution; most production comes from this part of the Wairakei Field and the lack of gravity changes since the early 1970's (Hunt, 1988) indicates significant recharge is occurring here.

Interpretation

The tracer returns indicated that the bulk of reinjected fluid flowed north and east of the reinjection well. Fluid may also have flowed west of Wk62, with small amounts reaching the eastern edges of the Western Borefield; this is consistent with the gravity measurements.

INDUCED SEISMICITY

Microseismic monitoring was carried out using a network of 5 seismographs. During the test an average of only four earthquakes per month were located within the field; this level of seismic activity was similar to that observed in the four months prior to, and the three months following, the test. During the test there were no local earthquakes larger than those recorded prior to the test, and there was no clustering of micro-earthquakes near the reinjection well.

The lack of any long term change in local seismicity suggests there was no induced seismic activity. This lack of activity is probably due to the relatively low (< 5 bar) pressure build up during the test, and is in marked contrast to the induced activity associated with the injection testing in 1984 at Wk301 (Sherburn, 1984; Allis *et al*, 1985) when a large pressure build up occurred.

CONCLUSIONS

1. The reinjected fluid flowed rapidly to most production wells in the Eastern Borefield and caused large decreases in deep liquid temperatures and mass production.
2. The reinjected fluid caused the deep liquid level to rise in a cone of impression the height of which decayed with time when reinjection stopped. The shape and extent of the cone suggests the fluid flowed in two main directions; westwards towards the Western Borefield where most production comes from, and north-eastwards, towards an area of large ground subsidence.
3. No changes in temperature, deep liquid pressure, or mass production were observed in the Western Borefield. However, microgravity and tracer measurements indicate small amounts of reinjected fluid may have reached the eastern part of the Western Borefield towards the end of the test.

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