ROTOKAWA RESERVOIR TRACER TEST HISTORY

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ABSTRACT

The Rotokawa Geothermal Field has been under development since 1997 with the commissioning of the Rotokawa Power Station and the 2010 commissioning of the Nga Awa Purua Power Station. Since the field has been developed five reservoir tracer tests have been conducted. In 1998 Iodine-125 was administered to the main injection line and subsequently down three separate injection wells. In 2006 napthalene sulfonates were used for the first time on the field with four isomers injected into two wells (1,5-, 1,6-, 2,6- and 2,7-NDSA; two isomers per well). In 2009 1,5-NDSA was injected into one well following re-alignment of injection in the southern part of the field. Following the Nga Awa Purua development a tracer test was conducted in 2011 using four isomers of naphthalene sulfonates (1,5-, 1,6-, 2,6- and 2,7-NDSA) in four separate injection wells. None of these tracers were detected in the field study. Autoclave testing by Mountain and Winick (2012) found these isomers were not thermally stable and samples from the 2011 test were reanalyzed for predicted breakdown products (2-NSA and 1-NSA). 2-NSA was found in a number of samples confirming suspicions around temperature instability. In 2013 Iodine-125 was injected alongside 2-NSA into the main brine injection well in the field to benchmark 2-NSA performance. This paper will discuss each reservoir tracer test, focusing on the field configuration and findings.

INTRODUCTION

The Rotokawa geothermal field is located within the Taupo Volcanic Zone (TVZ), on the North Island of New Zealand (Figure 1).

The first exploration wells in Rotokawa were drilled in the 1960's with further drilling and testing until 1997 when the field was first developed for power generation with the 24 MWe Rotokawa power station. In 2000, Mighty River Power and Tauhara North No.2 Trust formed the Rotokawa Joint Venture and the Rotokawa power station was expanded to 34 MWe in 2003. In 2010 the 138 MWe Nga Awa Purua power station was commissioned, a triple-flash plant with a dual-flow single-shaft turbine and a direct-contact condenser. As of 2015, the field generates steam from 13 production wells and disposes of waste brines and condensates to 5 deep injection wells.

The natural-state chemistry of the reservoir is summarised in Winick *et al.* (2011a) and Winick (2011b), with insight from Hedenquist *et al.* (1988). Current conceptual understanding is given in Sewell *et al.* (2015b), which details fault structures, in particular the Production Field Fault and the Central Field Fault. Geochemical response to production is given in Addison *et al.* (2015) and early response to production is detailed in Winick (2013).

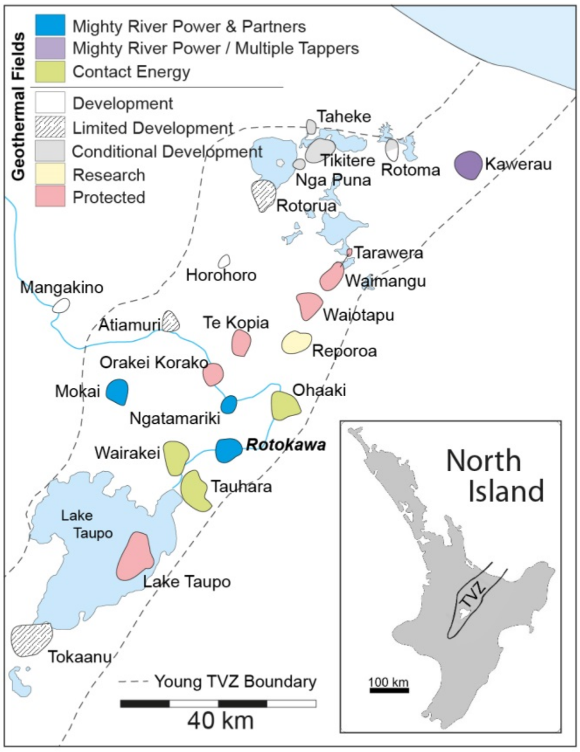

Figure 1: Location of known geothermal fields in the Taupo Volcanic Zone (TVZ) on the North Island of New Zealand as identified by Schlumberger resistivity surveys (Bibby et al., 1995). The Rotokawa field (bold) is approximately 12 km NE of Taupo, 10 km east of Wairakei geothermal field and 10 km south of the Ngatamariki geothermal field.

This paper presents the details of five reservoir tracer tests conducted on the Rotokawa geothermal field. These tests have used a range of tracers, including a radioisotope of iodine and various isomers from the naphthalene sulfonate tracer suite. Significant insights into field performance and on the tracers themselves has been obtained over these five tests, with a key learning being that naphthalene sulfonates appear to have limited suitability for the Rotokawa geothermal field due to their apparent temperature instability.

1998 RESERVOIR TRACER TEST

In 1998, GNS conducted a reservoir tracer test on the early Rotokawa development which at the time consisted of production entirely from RK5 and RK9 (Barry and Baker, 1999), supplying the 24 MWe Rotokawa power station. The field configuration in 1998 is shown in Figure 2 with flow and injection rates shown in Figure 4. The selected tracer was ^{125}I, a radioisotope of iodine with a half-life of ~59.4 days. This was dosed into the main injection line (RKIL) on June 16, 1998, just over 6 months following the start-up of the power station. A dose of 18.5GBq was used. Since the 1970's, radioisotopes of iodine had been previously been used extensively in tracer tests on the Wairakei, Ohaaki and Kawerau geothermal fields in particular.

At the time of the tracer test, Rotokawa injection was entirely to the intermediate aquifer (Sewell *et al.*, 2015b) through wells RK1, RK11 and RK12. Although RK1 was originally cased at 609mCHF and completed to 1198mCHF (spanning both the intermediate aquifer and deep reservoir) it was cemented back to 801m in 1994 limiting its injection exclusively to the intermediate aquifer. Figure 4 shows the monthly production and injection flow totals from the Rotokawa power plant for the time period over which the tracer test was conducted.

Following tracer injection, samples were collected from the same RKIL sampling point that represented the combined production flows from RK5 and RK9. Additional samples were collected from a river spring, which is one of the Waikato River seeps monitored as part of the annual thermal feature monitoring programme.

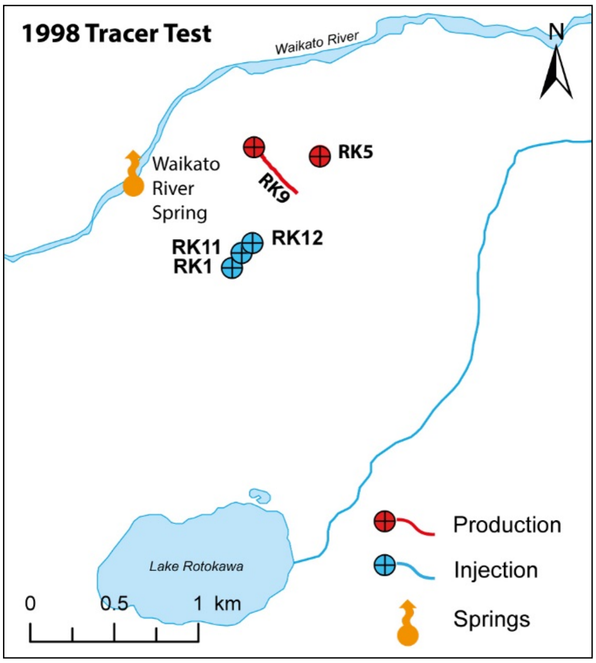

Figure 2: Field configuration for the 1998 Reservoir Tracer Test. Not all wells drilled in the field at the time are shown, only those active during the reservoir tracer test.

No tracer returns were observed over the eight month period. The two isolated positive measurements (only slightly above background at 190 and 197 days post-injection) were discounted as having resulted from post-sampling contamination or error. Normalised concentrations are shown in Figure 3. The report did present a fractional tracer return calculation on the assumption that these positive detections represented real reservoir information. From this calculation, a fractional tracer estimate of 0.4% was determined (Barry and Baker, 1999).

Overall, the 1998 tracer results indicate that the intermediate aquifer is not well connected to shallow thermal features.

If the positive detections of ^{125}I from RK5 and RK9 were real and not an artefact of contamination, then this suggests the existence of a pressure gradient between the intermediate aquifer and deep reservoir at the time that resulted in a drawdown of shallow fluids into production. Assuming the detections are accurate, quantities and rates of fluid drawdown would have been small. However, all other geochemical modelling suggests this process was not occurring at the time and that the positive detections are, as suspected, related to contamination or to a statistical counting artefact.

Samples collected from a combined flow at RKIL, rather than individual wells, made sampling and analysis cheaper due to fewer samples and no need to correct for steam fraction. However, having a composite sample does add complexity in determining the location, size and extent of connection in the event of positive returns. This complexity increases as the number of wells contributing to the composite sample increases.

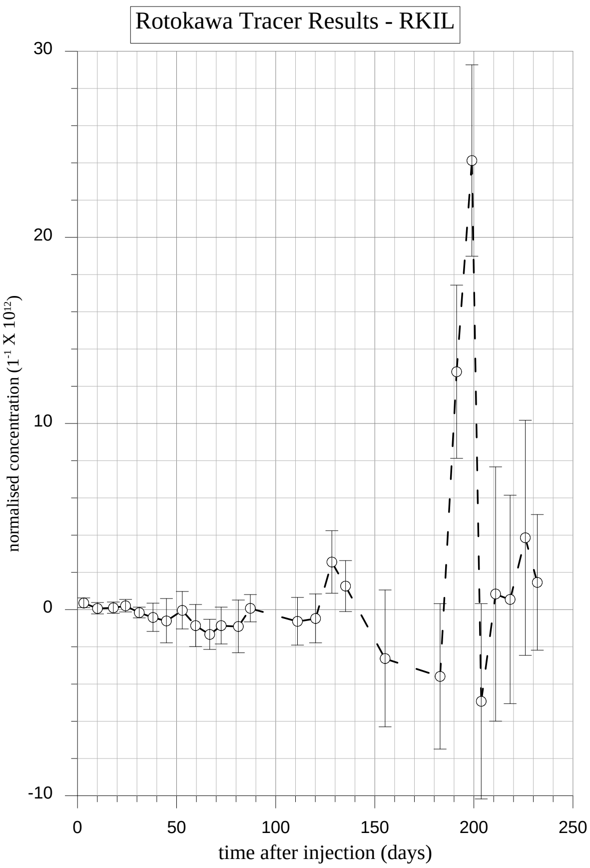

Figure 3: Rotokawa tracer results modified from Barry and Baker (1999)

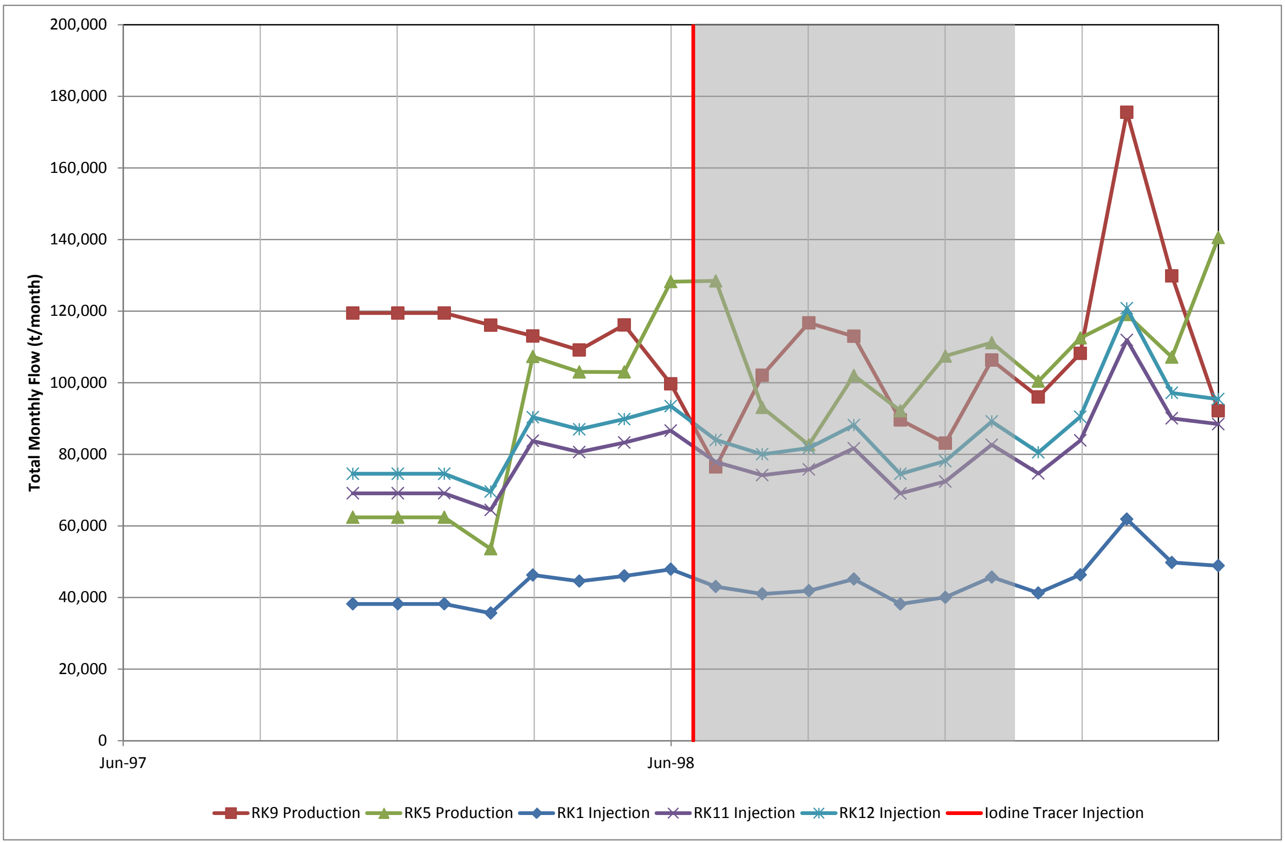

Figure 4: November 1997 to June 1999 monthly production and injection flow totals (t/month) for the Rotokawa Power Station. Tracer injection is indicated by the vertical red line and the monitoring period is indicated in grey (Winick, 2013).

2006 RESERVOIR TRACER TEST

In 2006, a reservoir tracer test was conducted to evaluate the connectivity of RK16 and RK18 injection to production from RK17 and other wells within the main Rotokawa reservoir (RK5, RK13 and RK14). The field configuration is shown in Figure 9. The Rotokawa power station had been expanded to 34MWe since the previous tracer test.

Isomers of naphthalene disulfonic acid (NDSA) were added as two separate injections into RK16 (1,5-NDSA and 1,6-NDSA) and as two separate injections into RK18 (2,6-NDSA and 2,7-NDSA) flow streams. 100kg of each tracer was used for this test. Napthalene sulfonates were used as they allowed the tracing of more than one injection well and were considered safer than radioisotopes. Due to interruptions in the RK17 production flow test, the tracer injection into RK16 and RK18 had to be performed twice, hence the use of two isomers per well to obtain a complete tracer response history from the field. Production fluids from RK5, RK13, RK14 and RK17 were monitored for the presence of NDSA for five months following the initial injection. The results of the test were detailed in Grant and Bixley (2007).

No tracer from RK16 was detected in any of the monitored wells and it was therefore believed to be poorly connected to the main reservoir. The tracer results from RK18 demonstrated large and rapid returns to RK17: 21% returns only days following injection (Figure 6 and Figure 7). Smaller returns from RK18 were also detected in RK13 (Figure 5) in the first injection test, but were notably absent following the second injection test. This response is thought to relate to a favoured structural path along the RK18-RK17-RK13 axis (Bowyer and Holt, 2010; Wallis *et al.*, 2013; Sewell *et al*, 2015b). The shut-down of RK17 production following the first tracer injection in July is thought to have allowed the injected RK18 tracer to be drawn past RK17 along this pathway to the main production area.

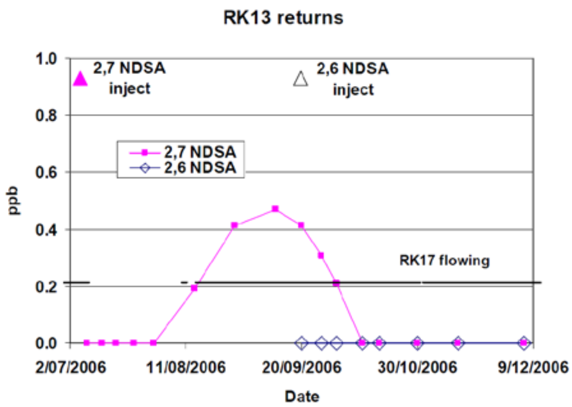

Figure 5: RK13 production well returns from RK18 injection from Grant and Bixley, 2007. Concentrations are as sampling condition. Injection dates and tracer isomers are shown in addition to when RK17 was flowing.

Grant and Bixley (2007) used the results to determine a relationship between RK17 and RK18 in terms of their flow and storage capacities (Figure 8). They determined that 20% of the pore volume swept by the tracer provided 60% of the flow between the wells, indicating a degree of non-uniform flow behaviour consistent with a SW-NE structural trend through the production area. The results of this tracer test motivated the move to deep injection off-axis relative to the main production zone. This ultimately led to the drilling of RK20 in the southern reservoir for the full Rotokawa injection load by October 2008, and further drilling for Nga Awa Purua injection afterwards.

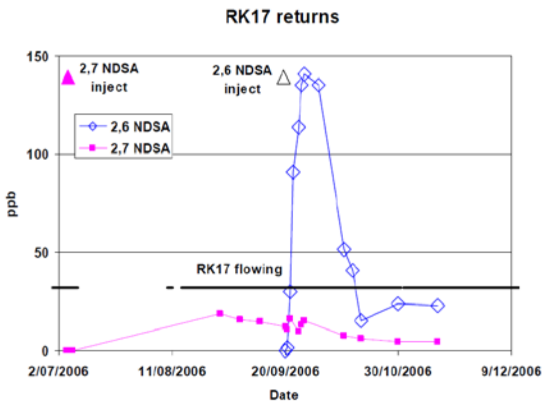

Figure 6: RK17 production well returns from RK18 injection from Grant and Bixley (2007). Concentrations are as sampling condition. Injection dates and tracer isomers are shown in addition to when RK17 was flowing.

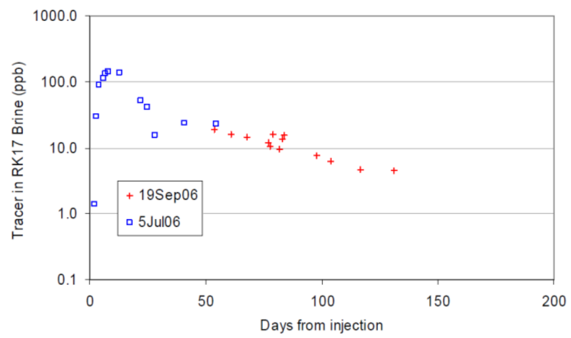

Figure 7: Concatenated RK17 production well returns from RK18 injection from Grant and Bixley (2007). Concentrations are corrected for total discharge.

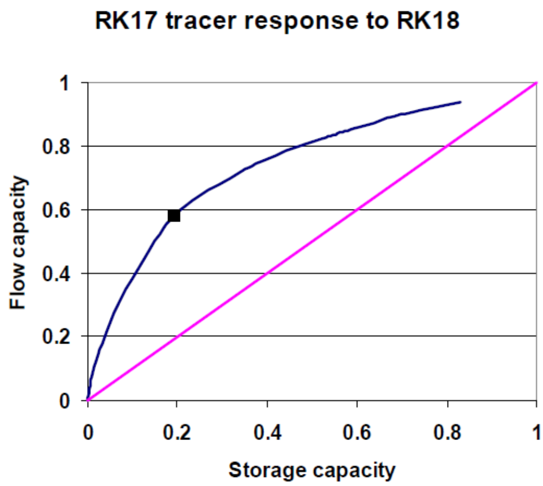

Figure 8: Moment analysis (Shook, 2005) based on concatenated RK17 dataset in Figure 7 from Grant and Bixley (2007).

Given the now-recognized thermal instabilities of NDSA tracers (covered in 2011 tracer test results), these 2006 results cannot be considered to be completely conservative. In particular, the lack of detectable tracer from RK16 in any monitored wells may be due to partial or complete breakdown of 1,5-NDSA and 1,6-NDSA at high reservoir temperatures rather than poor connectivity. Additionally, the determination of non-uniform flow behaviour or channelling based on the RK18-RK17-RK13 response may in fact be even more heterogeneous than previously considered.

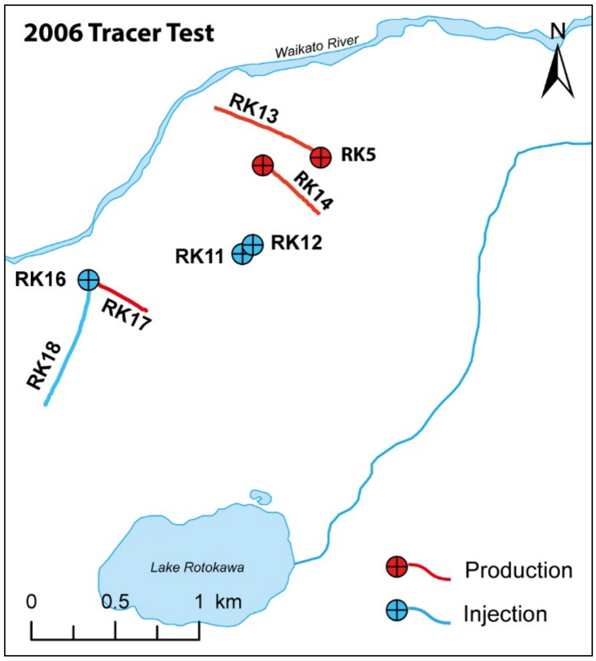

Figure 9: Field configuration for the 2006 Reservoir Tracer Test. Not all wells drilled in the field at the time are shown, only those active during the reservoir tracer test.

2009 RESERVOIR TRACER TEST

Following the establishment of the full Rotokawa injection load into RK20 and a six-month stabilisation period, a reservoir tracer test was conducted on this new steamfield configuration. On May 5, 2009, 250kg of 1,5-NDSA was injected into RK20 and tracer returns were monitored for nine months in the Rotokawa production wells (RK5, RK13 and RK14) in addition to the Parariki Stream Spring as shown in Figure 11. RKM6 was monitored for around two months using downhole tubing with no results above baseline detected. Over the monitoring period, wells RK17, RK25, RK26, RK27, RK28, RK29 and RK30 were actively being drilled and intermittently flowed in preparation for the Nga Awa Purua development, in addition to the flowing of RK18. These wells were sampled subject to their availability.

Preliminary results from nine months of monitoring indicated low-level returns and it was initially determined that the production fluids contained around 1% injectate (Grant, 2009). However this test made use of a laboratory that was analysing NDSA tracers for the first time. Cross-checking with other laboratories previously used for tracer analysis found the initial results to be erroneous due to analysis method issues. The final determination was that there was no 1,5-NDSA detected in any samples.

The interpretation of the results at the time was that deep injection fluid was not returning to the main production area, and was entirely isolated from the shallow thermal aquifer feeding the spring on Parariki stream. Due to the later identified instabilities of the naphthalene-sulfonate tracers, a lack of detectable 1,5-NDSA cannot be taken as conclusive evidence for an absence of RK20 injection return within the deep reservoir. For the shallow thermal aquifer, no significant changes have been noted in surface feature chemistry or temperatures since monitoring began in 1997 and also earlier data from 1993-1994. This validates that no returns are observed, or if there are returns they are of fluid chemistry and temperatures that are similar to original fluids feeding the shallow aquifer.

It is possible, though unlikely, that production fluid and pressure support from the initial 15,500 t/day Rotokawa development was supplied entirely by local recharge (deep and/or marginal) and that the production drawdown did not critically stress the reservoir to the point that injection in RK20 altered the larger reservoir hydrogeology. On the basis of geochemical monitoring alone, it is difficult to determine the presence of chemical breakthrough from RK20, since Rotokawa injection and production fluids are geochemically very similar (Winick, 2013; Addison *et al*., 2015). The 1,5-NDSA was injected to test these hypotheses, but the test was ultimately not conclusive due to probable tracer breakdown.

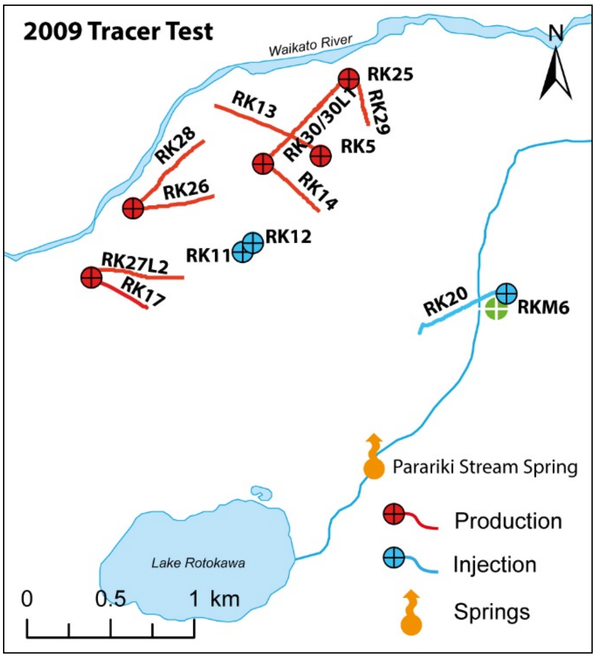

Figure 10: Field configuration for the 2009 Reservoir Tracer Test. Not all wells drilled in the field at the time are shown, only those active during the reservoir tracer test.

2011 RESERVOIR TRACER TEST

In April 2011, after nearly one year of Nga Awa Purua operations, a reservoir tracer test was performed on the Rotokawa field in an effort to better understand the reservoir hydrogeology and fluid movements in response to the combined Nga Awa Purua and Rotokawa production and injection activities.

As Nga Awa Purua has a direct-contact condenser, the condensate is aerated and therefore is injected separately from the pH-modified brine from Nga Awa Purua. Condensate from Nga Awa Purua was injected into RK23 at approximately 300 t/hr. Brine from Nga Awa Purua (~1100 t/hr) was originally injected entirely into RK21 at start-up and was shifted to RK24 gradually between December 2010 and February 2011 until RK24 was accepting all the brine. Rotokawa fluids were injected predominantly into RK20 (~550 t/hr) with injection of a slip stream into RK11 (100 t/hr). Production in the field was from all available production wells. During the test RK32 and RK33 were drilled and were sampled after they were producing to the power station. The field configuration is shown in Figure 11.

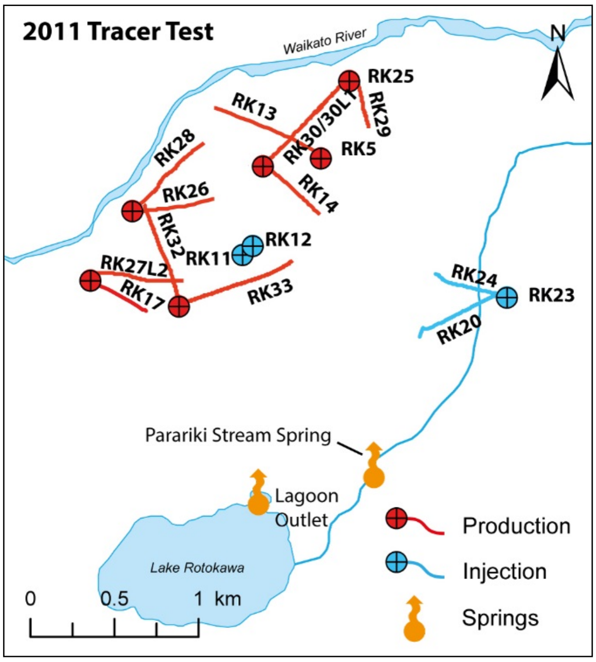

Figure 11: Field configuration for the 2011 Reservoir Tracer Test. Not all wells drilled in the field at the time are shown, only those active during the reservoir tracer test.

Four NDSA isomers at 300kg each were injected as an instantaneous, concentrated slug into four separate injection wells (RK20, RK23, RK24 and RK11). The selection of the tracers was based on their successful application at a number of other geothermal reservoirs around the world including Ohaaki, Negros (Philippines), Awibengkok (Indonesia) and Dixie Valley (USA) (Rose *et al.*, 2000) and the quantities based both experience of staff and from reservoir volume calculations. Reservoir tracer tests were also being conducted on two other MRP operated fields, Mokai and Kawerau, using the same NDSA isomers. Furthermore, many of the tracer compounds had been tested to temperatures as high as 330˚C in the presence of distilled water and were found to be stable.

For a year following tracer injection, production wells and selected thermal features (Lagoon Outlet and Parariki Stream Spring) were monitored for the presence and concentration of injected tracer. After extensive analysis of the samples, none of the original tracer isomers were detected, similar to the 2009 reservoir tracer test that also failed to detect any measurable tracer. These findings were surprising given that other geochemical indicators suggested some degree of chemical breakthrough from injection (increasing chloride and silica with declining NCG's) as shown in Winick (2013) and Addison *et al.* (2015). However, with temperatures of 337˚C in natural state (measured in RK22) in the injection area (Hernandez *et al.*, 2015), Rotokawa is one of the hottest geothermal reservoirs currently in commercial operation. Considering these factors, concerns arose as to the stability of injected NDSA isomers under Rotokawa reservoir conditions.

A study was commissioned to investigate tracer stability at Rotokawa reservoir temperature, pressure and chemistry conditions. The results from this study are detailed in Mountain and Winick (2012), confirming that at higher reservoir temperatures, the tracer compounds either break down completely or into more refectory compounds (2NSA) that had not previously been recognised or analysed as part of the 2006, 2009, or 2011 reservoir tracer tests as shown in Figure 13.

Two experimental factors should be considered: the water:rock (~2:1) ratio in the apparatus was more water-dominated than actual reservoir conditions; and the fluid residence times in the experiment were significantly less than actual residence times in the reservoir (hours to days in the experiment vs. weeks to months in the reservoir). Tracer breakdown would therefore be expected to be more strongly expressed within the reservoir. .

The work of Mountain and Winick (2012) suggests that 2-NSA, and possibly 1-NSA would have been sourced as breakdown products from either, or both, RK20 and RK24 (600kg of originally injected tracer in total). A program of sample reanalysis was subsequently conducted which confirmed the presence of 2-NSA in several wells but found no 1-NSA (Figure 12).

Arrival to production as only 2-NSA indicates that the injection fluid was significantly re-heated along the flow path toward production. The tracer first-arrivals of around three months is of the same order of magnitude as that observed for geochemical responses in the steamfield following the move of Nga Awa Purua brine from RK21 to RK24.

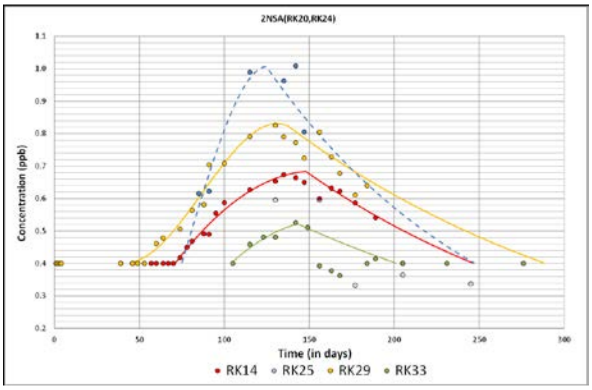

Figure 12: 2-NSA returns to the four main wells that showed a response as per Table 1.

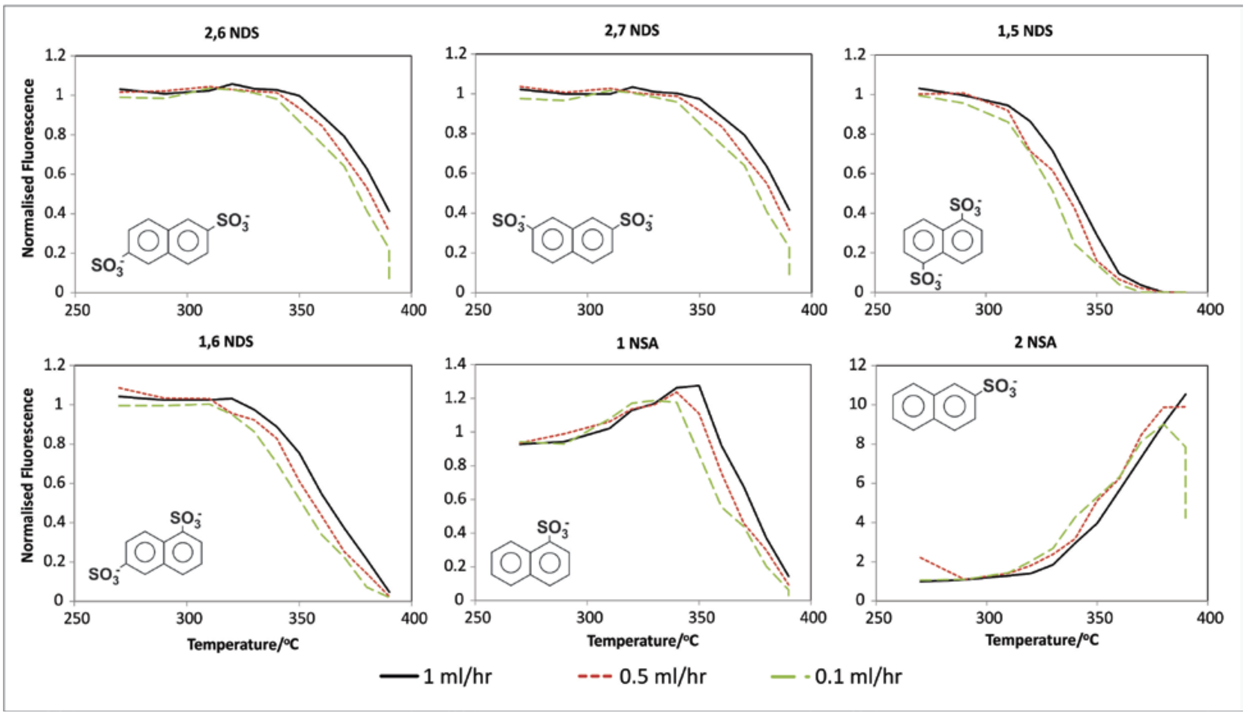

Figure 13: Normalised fluorescence of six naphthalene sulfonic acids versus temperature at three different flow rates after Mountain and Winick (2012). Black, red, and green lines represent different flow rates and therefore water:rock residence times.

Table 1: Calculated reservoir parameters based on detected 2-NSA responses.

Well	Tracer Mass Recovered (kg)	Tracer Recovery (%)	**Fraction of Injection in Production (Xi)**	**First Arrival (Days)**	Peak Arrival (Days)	Mean Residence Time (Days)	Distance from Injection (m)	Average Velocity (m/Day)
RK14	0.54	0.09%	**0.62%**	**71**	135	154	862	5.6
RK25	0.21	0.03%	**0.76%**	**75**	123	151	1463	9.7
RK29	2.12	0.35%	**0.95%**	**45**	130	155	1127	7.3
RK33	0.18	0.03%	**0.29%**	**104**	142	152	872	5.8

Given the now-recognised differences between 2-NSA returns and ^{125}I tracer results, discussed in the next section, these results can be considered absolute minima such that returns are likely much higher, with longer peak arrivals and mean residence times.

2013 RESERVOIR TRACER TEST

Following the recognised thermal instability of the naphthalene sulfonate tracers at Rotokawa the 2013 reservoir tracer test made use of ^{125}I, a known thermally-stable and conservative tracer. The results of this testing are detailed in Winick *et al.*, (2015). Some key aspects are summarized below.

Besides managing health and safety concerns for ^{125}I, the main practical downside of the radioisotope use in a geothermal reservoir tracer test is that only one well can be fingerprinted at a time. To enable more options in the future, 2-NSA was injected and tested alongside ^{125}I to determine its thermal stability within the reservoir (the apparent most stable of all the sulfonates). ^{125}I was used as ^{131}I half-life of 8-days was too short for expected return times based on previous tests, with us expecting the test to need to last 250-300 days for a complete return profile. Only RK24 was injected into as the main Nga Awa Purua brine injector. Due to half-life decay, ^{125}I levels within the reservoir after one-two years are practically zero. The upside of this is there isn't a need to correct for an elevated baseline from previous tests as is often the case with naphthalene sulfonate tracers.

The field configuration for the 2013 test was as per the 2011 test (Figure 14), however injection for Nga Awa Purua brine was split between RK24 and RK23, with RK23 being connected to Nga Awa Purua brine immediately prior to the reservoir tracer test. RK20 was used for injection of Rotokawa injectate alongside RK11. RK12 was used for injection of Nga Awa Purua condensate.

Tracer purity testing was performed on the 2-NSA which indicated a purity of 90%, with only minor tracer impurities of 2,6-NDSA (0.5%) and 2,7-NDSA (0.05%). The remaining 9.45% of the tracer mass is likely to be inert, un-sulfonated naphthalene which does not affect the test other than by reducing the overall mass of the active injected compound.

Solubility tests were performed on the 2-NSA. Whilst testing identified limited solubility of the tracer, it was found that upon injection to the brine that the 2-NSA would completely dissolve due to the elevated temperature. As anticipated, the low solubility of the 2-NSA did present both mixing and pumping challenges on the day of injection. Considering estimated losses of ~50kg during mixing, an effective dose of 405kg of pure 2-NSA was administered to RK24 as slug injection on the 12th of July, 2013. Just over one week later 16.1 GBq of ^{125}I was injected on the 20th of July, 2013.

Samples were collected and all samples were analysed for ^{125}I (in addition to sodium) using established methods given in McCabe *et al.* (1998).

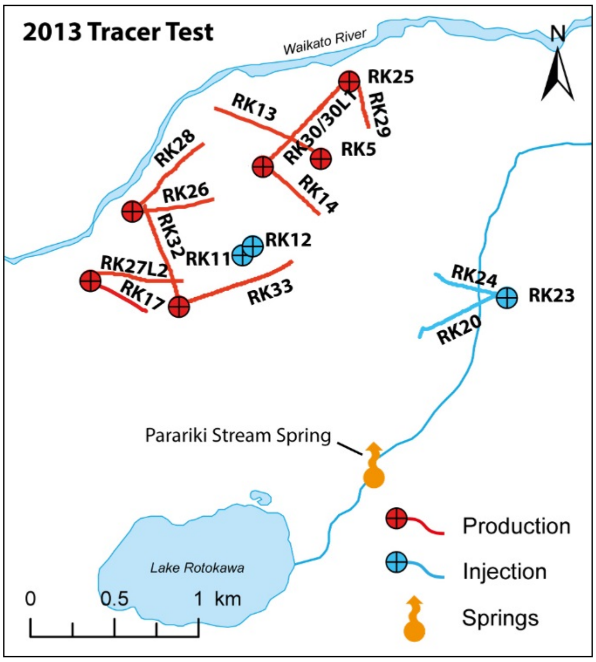

Figure 14: Field configuration for the 2013 Reservoir Tracer Test. Not all wells drilled in the field at the time are shown, only those active during the reservoir tracer test.

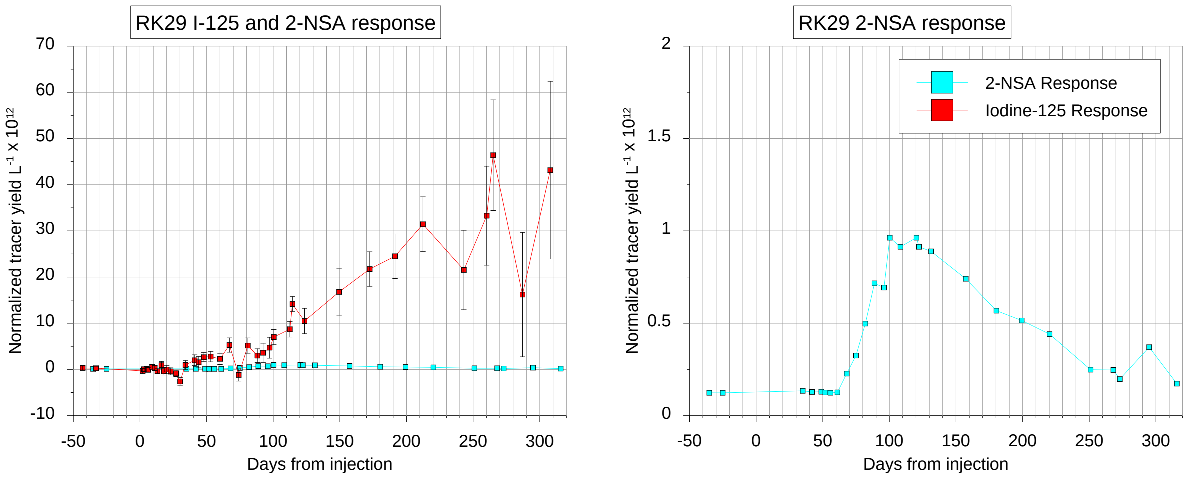

Figure 15: RK29 tracer responses for ^{125}I and 2-NSA, both normalised to the same scale and corrected for sampling condition and station shuts. The graph on the right shows the curve profile for 2-NSA in greater detail.

The results presented in Winick *et al.* (2015) have been updated with more recent, complete test data and are presented herein. Following nearly a year of monitoring, the quantity of tracer remaining in the reservoir was limited and error was large due to half-life decay, thereby limiting the duration of the test. Results indicated a significant difference between the ^{125}I response and that of 2-NSA, as shown in Figure 15 for RK29 and Figure 16 for RK14. ^{125}I returns to most wells did not provide a definitive peak, or any indications as to the shape and size of the tail of the return profile.

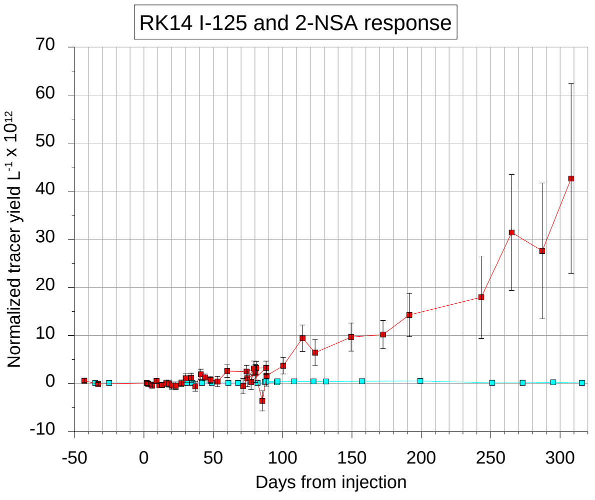

Figure 16: RK14 tracer responses for ^{125}I and 2-NSA, as per Figure 15.

^{125}I concentrations from each well were corrected for production mass flows, with a predicted curve fitted for each well. As both RK29 and RK14 were yet to conclusively see their respective peak and there were no indications as to the shape of the tail, these were created as symmetrical peaks with peaks predicted around the 300 day mark. Therefore the results from these wells can be considered as minima. The calculated recoveries for wells with returns are shown in Table 2, alongside average mass flows for the wells, a calculated fraction of injection as a function of production fluids and the first arrival of the main response.

Minimum recovery of 7.12% of the injected ^{125}I has been calculated for RK29, with total tracer recovery around 12%. Conversely only 0.11% of the injected 2-NSA was recovered in RK29. This discrepancy in response indicates a thermal breakdown process strongly affects 2-NSA in the reservoir. In addition there were signs of a very slight delay of the 2-NSA relative to the ^{125}I, indicating a potential column effect within the reservoir.

Figure 17 shows the 2-NSA tracer response in production wells from the 2013 tracer test, in addition to RK5. A normalized value of $1x10^{12}$ equates to a response of ~0.4 ppb tracer concentration. The presence of small, early peak detection prior to the larger main tracer peak returns, particularly for RK25 and RK30, may suggest some complex reservoir hydrogeology with potential injection fluid segregation along sets of permeable pathways of dramatically varying connectivity to production. Both the 2-NSA and the ^{125}I showed this response, however the calculated returns in this small peak across all wells was <0.1% of the ^{125}I injected tracer, therefore it was considered inconsequential.

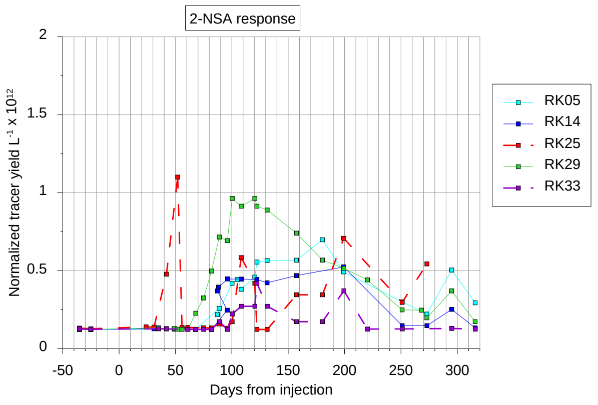

Figure 17: 2-NSA tracer response for wells that showed a response in 2011 test and also including RK5. The apparent time-shift in injection for RK14 relates to time corrections accounting for station outages.

Table 2: Results summary for ^{125}I from Addison (2015) for the 2013 Reservoir Tracer Test

Well	^{125}I Tracer Recovered (%)	Average TMF (t/hr)	Fraction of RK24 in Production (%)	First Arrival of main Response (days)
RK29	7.12	675	9.0	60-70
RK14	2.81	300	8.0	80
RK5	1.01	150	5.7	80-90
RK30	0.42	145	2.5	170
RK25	0.41	80	4.3	140
RK33	0.20	120	1.4	100

The returns found in the test are consistent with observations in microseismic activity (Sewell *et al.*, 2015a), pressure data (Hernandez *et al.*, 2015) and chloride responses (Addison *et al.*, 2015). The test confirmed that there was no connection of RK24 within one year to the western wells RK17 and RK27L2, which have seen a dramatic increase in chloride. This has been attributed to significant reservoir boiling associated with pressure drawdown in this part of the field, though the influx of a possible high-chloride fluid upflow in the south may also contribute. This is discussed in greater detail in a companion paper in these conference proceedings (Addison *et al.*, 2015).

Based upon the peak and mean residence times indicated from this test, generally 300 days or longer, average velocities are nearer 2.5 – 5 m/day based on the 2013 results compared to 5 – 10 m/day as calculated from the 2011 results for RK29. Temperature measurements, both measured and through geothermometry indicate that this appears to provide the fluid with sufficient time to heat up prior to being produced.

FUTURE ROTOKAWA TRACER TESTS

Tracer tests form an important part of sustainable reservoir management on the Rotokawa geothermal field. Geothermal fields, once developed, generally become more complex with time as more wells are drilled and the field responds to production. With both new production wells and new injection wells coming online with time, there is a need to know where the fluid pathways are within the reservoir and the extent of these pathways.

At this stage future reservoir tracer tests at Rotokawa will look to make use of ^{125}I and work will be undertaken to increase the possible length of any reservoir tracer test, likely through injection of a higher quantity of tracer, larger sample sizes and longer count times. ^{125}I results match observations in production chemistry, compared to naphthalene sulfonates. We encourage further work in research around temperature-stable reservoir tracers that can be used in geothermal fields that exhibit high temperatures such as Rotokawa.

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