CORRELATION OF RESERVOIR MONITORING AND CONTINUOUS PRODUCTION DATA TO INTERPRET UNEXPECTED WELL BEHAVIOR IN ROTOKAWA

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ABSTRACT

Production monitoring helps to ensure reliable and sustainable mass supply from the production wells to the power stations through up to date information on changes to well behaviour. Correlated with other reservoir surveillance methods, production monitoring data were used to capture and interpret unexpected well responses in the Rotokawa field. This paper highlights the integration of various reservoir engineering methods used to monitor and evaluate well behaviours by Mighty River Power. A sample production well, RK14, was analysed based on observed production changes using (1) tracer flow testing (TFT) data, (2) pressure, temperature and spinner (PTS) analysis, (3) deliverability curves, (4) conceptual well models, and (5) wellbore modelling to understand possible subsurface changes causing the observed conditions at wellhead. The result showed an improvement in reservoir pressure support to the well as the main cause for the observed productivity increase. The changes to well behaviour were used to update the total flow capacity forecast and highlighted the need for further investigation to fully understand the reservoir's response to production.

1. INTRODUCTION

The Rotokawa Geothermal Field in the Taupo Volcanic Zone (TVZ) of New Zealand has generated geothermal power for around 15 years and has gradually expanded to support first the 34MW Rotokawa in 1997 and subsequently 140MW Nga Awa Purua (NAP) power stations commissioned in 2010. Twelve production wells and 3 deep injection wells are currently in service. Remaining wells are used for shallow injection, as pressure monitors, or as back-up capacity for production and injection (see Figure 1).

1.1 Rotokawa Production Monitoring

The main production parameters monitored in Rotokawa are wellhead pressures, well enthalpies, and flow rates.

Continuous flow metering at the power stations has been in place since 1997. This is the most accurate measure of the total field take due to its use of single-phase orifice flow meters in the brine and steam lines after the flow separator unit.

The earliest on-line production well data available are flowing wellhead pressures (WHP) from 1997. In 2006, two-phase orifice flow metering became available providing mass flow rates in addition to flowing WHP. These continuous flow data from wells were used to monitor and forecast production well decline rates while keeping the station flow meters as the primary data for total field take.

Tracer dilution techniques or tracer flow testing (TFT) to estimate production well flows and enthalpies were also used in Rotokawa. Hirtz et. al. (1993) provides more details on tracer dilution techniques. With the correct sampling port set-up, sampling techniques and laboratory analyses, TFT is currently considered the most reliable individual production well flow and well discharge enthalpy estimate in Rotokawa. In the last few years, TFT mass flow results demonstrated good correlation with the continuous wellhead production data and generally agree within 5-10% of each other (Hernandez, 2012).

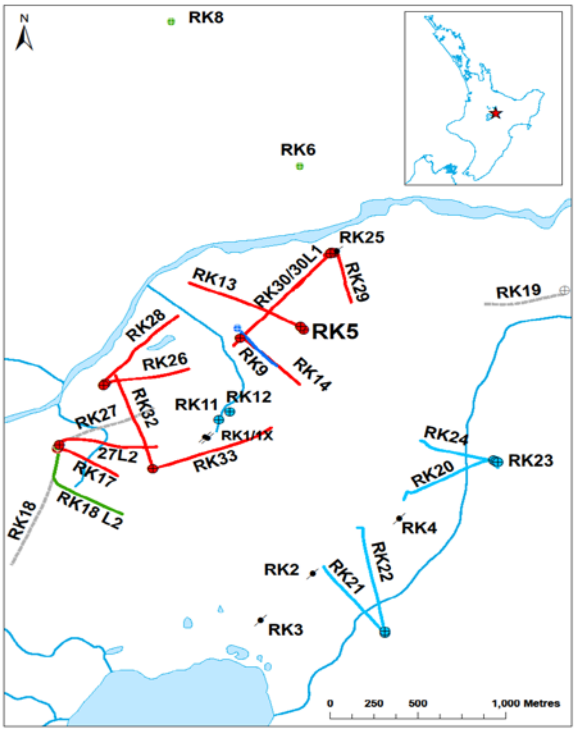

Figure 1: The Rotokawa Geothermal Field with well locations. Production wells are in red and injection wells are in blue.

In the period following the NAP start-up in 2010, production monitoring has played a key role in identifying well responses to the increased take and was used to justify additional make-up well drilling to maintain field capacity.

The flow separator data and the well two-phase orifice meter measurements are gathered continuously while the TFT data are available every two months. Combining the available data sets, the wellhead two-phase orifice meter measurements are used to continuously monitor production rates in parallel with the TFT data. The power station flow separator data is used to monitor total field take and is used for snapshot comparisons between total well flows and actual station flows. Also, if the well mass flow measurement is not available, the station separator data is allocated to or distributed to the individual wells through the use of the latest well deliverability curves and individual WHP.

1.2 Rotokawa Subsurface (Reservoir) Monitoring

The main reservoir parameters monitored in Rotokawa are reservoir pressure and enthalpy. Both have direct implication on fuel supply and production sustainability of the two power stations.

Pressure monitoring wells (RK18L2, RK8, RK22) have sensors that are run on 1/8" tubes and positioned at or near the main permeable zone to gather continuous pressure data which is representative of the reservoir.

Static downhole pressure, temperature and spinner (PTS) data measured in shut-in wells provide additional information on snapshot reservoir pressure in the different areas of the reservoir. These data points gathered from all available wells are collectively used to estimate pressure drawdown and identify changes to pressure distribution as a response to production.

The continuous and snapshot pressure data sets are correlated to validate general reservoir drawdown observations and existence of localized drawdown areas.

Fluid geochemistry data are also obtained and used to track changes in reservoir enthalpy (geothermometry) and to trace the origin of potential recharge to production (i.e. injection returns, marginal fluid, hot reservoir upflow, etc.). Winick (2012) provides an example of how geochemistry is being used for reservoir monitoring.

1.3 Unexpected Well Behavior

Since 2010, monitoring has been focused on the production well responses to the significant increase in total field take following the start-up of the new NAP power station.

In March 2011, the ongoing production and reservoir monitoring activities led to the observation of a series of changes to well behaviors in a number of production wells. A burst disk failure was observed along the two-phase line between three production wells, (RK5, RK13, and RK14) and the Rotokawa power station separator. Coinciding with this event was a significant increase (60-70%) in mass flow observed in RK14 and, to a lesser extent, RK5. Up until this event, Rotokawa station's mass supply was from these three wells plus additional mass supply from a two-phase line interconnection with another production pad. After the increase in mass flow, the said three wells were able to fully supply Rotokawa station.

Investigations to better understand what happened in the wells utilized different interpretive methods to integrate the production monitoring data with the subsurface information. This paper presents the findings on RK14 as a representative well.

2. RK14

RK14 was completed on 14 September 2004 as a replacement production well for RK9 and to provide mass supply to the Rotokawa station. The well has four identified feedzones, with the upper feedzones at two-phase or saturated liquid conditions providing excess enthalpy. It has previously been noted that although the well has relatively lower permeability than nearby well RK5, it is able to sustain good production rates due to its feedzones tapping greater than 300°C fluid (Grant, 2006). This lower permeability was also indicated by the high drawdown (15-25 bars) in the RK14 area within two years of production (Grant, 2007), relatively higher than observed reservoir pressure drawdown in RK5 in the same period.

TFT data confirm the mass flow and enthalpy characteristics of the well (see Figure 2). Although the well has relatively low permeability, the sustained production suggests that a steady supply of fluid from the general reservoir is coming through to the area. Based on these observations, the well is expected to normally decline.

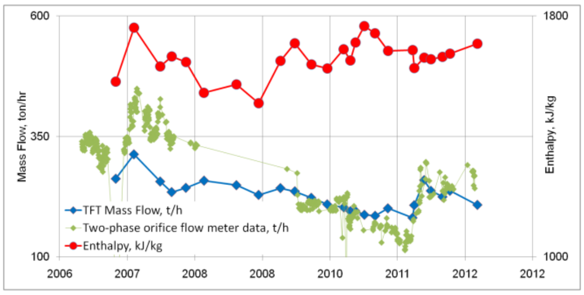

Figure 2: Continuous wellhead production data (green) and TFT mass flow (blue) and enthalpy data (red) showing RK14 behavior.

In April 2010, NAP station started up. RK14's response to the development was characterized by a rise in discharge enthalpy and a slightly accelerated production decline (see Figure 3). This was an expected response to the reservoir pressure decline caused by the increased mass take. An initial drop in reservoir pressure would lower the reservoir liquid level near RK14, increasing the enthalpy of its shallow feedzones. After which, the well was expected to stabilise as the reservoir pressure decline stabilizes.

During the burst disk event in 2011, the station monitors reported a significant increase in well productivity and a drop in station enthalpy. The well could have surged causing an increase in line pressure and bursting the disk for pressure relief.

The sudden increase in productivity of a long-term producer and a relatively stable well was unexpected and warranted a closer investigation.

2.1 RESERVOIR SURVEILLANCE

Immediate TFT surveys outside the regular Rotokawa sampling cycle were conducted to confirm the increase in mass flow rate and the drop in enthalpy observed at the station. Also, the surveys aimed to identify the main wells that were affected, with RK14 as a primary candidate.

TFT results confirmed the reported rise in productivity and sudden drop in well discharge enthalpy at the production well. Comparison between the deliverability curves from the continuous wellhead production data showed an increase in productivity (60-70%), causing a shift in the deliverability curve against the normal decline trend for the wells. After a few months of monitoring, the productivity increase was sustained while the enthalpy recovered (see Figure 3).

These observations suggest a change in flow characteristics that could be due to reservoir pressure increase, permeability change or wellbore blockage removal from the affected wells.

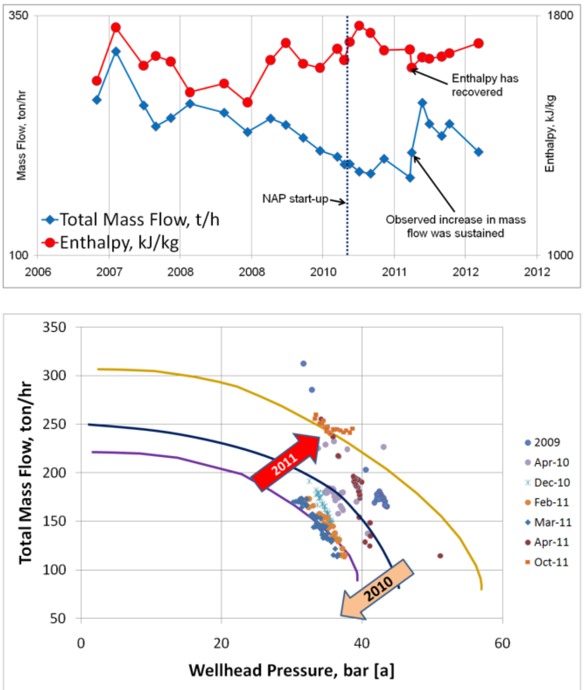

Figure 3: TFT survey confirm the rise in productivity and drop in enthalpy (top) and monthly deliverability curves (bottom) show the shift from 2010 to 2011 direction against normal pressure decline behavior.

A discharging pressure, temperature, spinner (PTS) survey was done to identify changes at the feedzones contributing to the overall productivity increase. As shown in Figure 4, the survey was not successful due to flow control issues. The wellhead was connected to the distributed control system and responded to changes in station demand causing the flow and the wellbore pressure profile to fluctuate. Ideally, the well should be on stable flow. The feedzones that contributed most to the increased productivity could not be confidently identified.

A shut downhole pressure survey was done to verify any changes to the reservoir pressure. The well has been known to produce from a local reservoir area whose pressure drawdown response is much larger than the general reservoir. The result (see Figure 4) showed the well pressure to be almost identical to the well pressure in 2006 suggesting zero net drawdown over five years including the period of increased take to supply the NAP station.

Continuous deep reservoir pressure monitoring has demonstrated an overall pressure decline associated with the NAP start-up. Distinct pressure signals during RK14 shut-ins in conjunction with the Rotokawa station shutdowns and RK14's observed response to the NAP start-up shows that the well is still connected to the main reservoir and should have a reservoir pressure declining with the rest of the field. RK14's declining deliverability curves (Figure 3) prior to the unexpected change were also consistent with an overall declining reservoir pressure which impacted performance as previously described.

Therefore, from 2006, the reservoir pressure near RK14 should have declined, reaching low pressures before increasing back to the latest 2011 pressure data. It is likely that the 2011 pressure masked the lower RK14 reservoir pressure state and is currently showing the effective pressure after the change. The investigation focused on how much pressure change is required to match RK14's productivity increase.

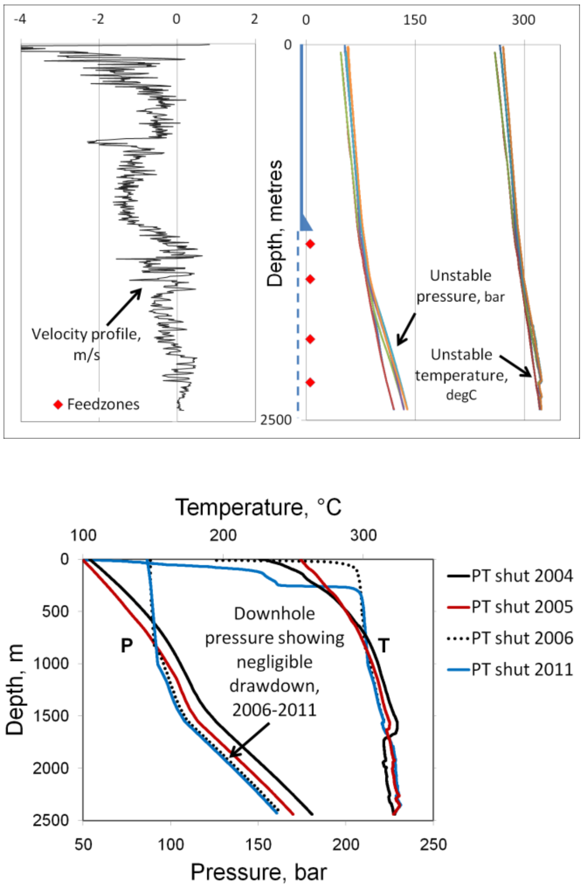

Figure 4: Unstable discharging PTS survey (top); shut downhole pressure (bottom) show similar deep pressures between the 2006 pre-NAP and the 2011 survey, a period of 5 years.

A wellbore simulator currently being developed for MRP was used to evaluate if the change in well behaviour could be fully explained by a change in reservoir pressure in the RK14 area. The simulator uses the Duns and Ros pressure-drop correlation (Hasan & Kabir, 2002).

Using the 2011 reservoir pressure, a wellbore model match to the corresponding 2011 total mass flow and enthalpy was estimated. The feedzone productivity indices (PI) of the wellbore model match was kept constant while the reservoir pressure was varied to match the production mass flow and enthalpy immediately prior to the change. The PI correction for mobility was not implemented since the discharge enthalpy data from 2011 (Figure 3) is relatively stable and suggests no major changes to feedzone enthalpies i.e. feedzones evolving from liquid to steam and vice versa. The reservoir pressure changes used for the match were based on actual measurements in nearby wells. The resulting output curves of the wellbore models are shown in Figure 5.

The wellbore model result shows a reservoir pressure change of 25 bars required to match the pre and post-change output curves while keeping the feedzone PIs constant. This is a significant, but not an impossible, pressure change. RK9, which was replaced by RK14, believed to be in the same local area as RK14 was observed to have a pressure recovery of 21 bars after about a five-day shut-in period in 2001.

The pressure change could have come from a recharge or pressure support that accelerated the area's pressure recovery, increasing the pressure back to pre-NAP levels and supporting the sustained productivity increase. This recharge can be from a combination of sources

The burst disk event in March 2011 happened after about a year of NAP operation and after moving about 60% of total deep injection from RK21 to RK24. This injection well is located closer to RK14 and RK5 and is in the same area as two other in-service injection wells, RK20 and RK23. Prior to the observed RK14 production increase, the whole production area was producing mass flow and re-injecting majority of it in the RK20/RK23/RK24 area (see Figure 1).

The simplified conceptual model for the RK14 area is shown in Figure 6 where the gray shades represent areas of lower permeability.

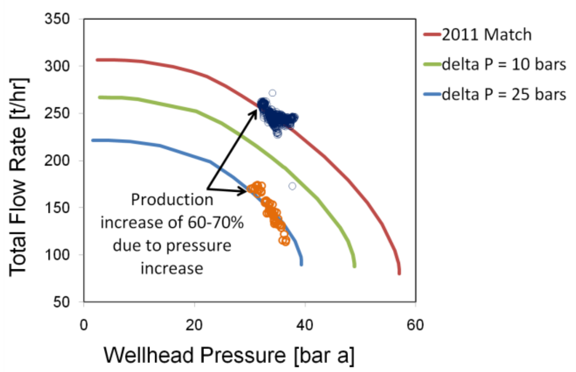

Figure 5: Wellbore simulation varying the reservoir pressure to match the observed increase in production data.

The pressure differential between the RK14 local high drawdown and the surrounding higher pressure areas could have reached a critical level, improving the connection and providing pressure recharge to the local area.

In addition to the concept of a developed connection to a stronger pressure source, there is the concept of the pressure-dependent natural recharge with significant effect to RK14 area but insignificant impact to the general reservoir volume, hence limiting the effect to RK14.

It should be noted that the 25 bar pressure change that produced a model match in Figure 5 did not produce a very strong pressure signal to the deep pressure monitor well RK18L2. The lower permeability in the RK14 area has the potential to attenuate the pressure change from affecting other areas. Also, the pressure signal could have been dampened by the general production area.

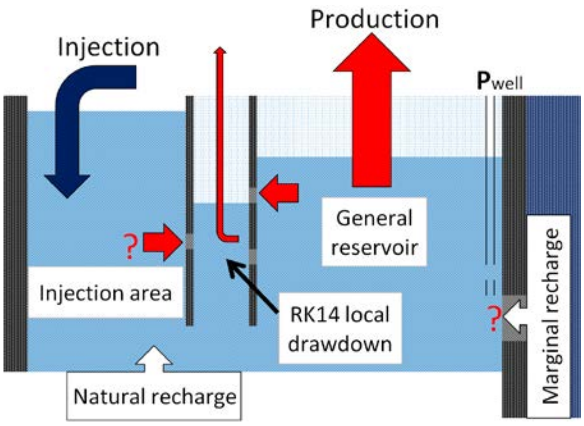

Figure 6: RK14 reservoir area simplified conceptual model.

A scenario of wellbore blockage removal was also simulated by using the 2011 wellbore model match (1) reducing the wellbore diameter and (2) deactivating the deeper feedzones to represent flow area reduction and feedzone blockage, respectively. The 2011 match feedzone characteristics and the reservoir pressure are held constant. The results are shown in Figure 7.

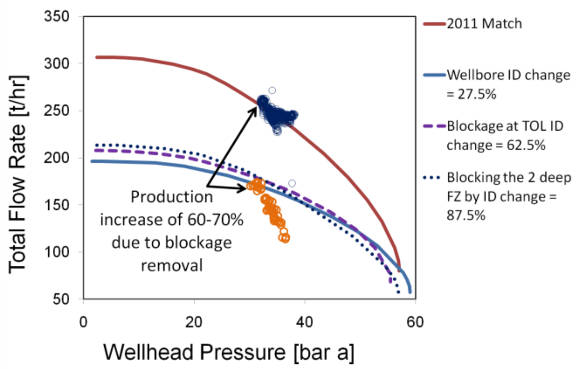

Figure 7: Wellbore simulation varying the casing ID and deactivating feedzones to match the observed production data.

The model behaviour for the total wellbore internal diameter (ID) change is expected to be similar to a well being recompleted to a different casing diameter or a well with uniform wellbore scaling (Grant and Bixley, 2012). It can also be similar to the size scale down of a production size well to a slimhole well (Hadgu, et. al., 1994). The closest match is achieved by an ID change of 27.5% for the entire wellbore. It is highly unlikely that a 2-inch layer of scale covering 2480m of wellbore was naturally dislodged.

Another blockage scenario assumes a restriction near the top of the liner (TOL) blocking all the feedzones. The restriction has to reduce the flow diameter by at least 62.5% to match the data. A similar scenario, this time placing the restriction above the two bottom feedzones, has to reduce the flow diameter by 87.5% to match the mass flow data. However, this deep blockage results to a rise in discharge enthalpy as the shallow two-phase feedzones contribute more to the total flow.

These localised blockages are more common in geothermal wells that have scale deposition issues and usually appear above the feedzone, restricting the flow until it completely blocks the wellbore. RK14 has a low scaling potential therefore the blockage removal scenario is not supported. Furthermore, none of the current Rotokawa production wells have demonstrated any indication of downhole silica or calcite scaling during production (Winick, 2012).

There is a well-established link between transient elevated reservoir pressures and the re-opening of previously sealed fracture permeability in a hydrothermal system (Sibson, 1996; Rowland & Simmons, 2012). The impact of pressure on reopening or creating new fracture permeability at Rotokawa has not yet been modeled. However, it is likely that the RK14 productivity increase is a combination of complex processes – where permeability has been either enhanced in the near wellbore environment (i.e., a change in PI) or the connection to the wider reservoir has been improved (i.e., increased pressure support). A discharging PTS and a pressure transient test should be done to verify feedzone permeability changes and connection to the wider reservoir.

3. CONCLUSION

Production monitoring served as an immediate indicator of unexpected changes to well behaviour and informed the succeeding reservoir surveillance activities to confirm and understand the relevant reservoir processes. This paper, through RK14, highlighted how the different interpretive methods provided additional information to develop concepts and explain the production changes. It identified reservoir pressure change as the most likely cause of the increase in mass flow with an unconfirmed possibility of other complex processes, such as pressure-driven fault/fracture reactivation, assisting the increase. It also demonstrated the use of wellbore simulation in Rotokawa to evaluate well behaviours as previously reported (Acuña, 2003; Alvarez & Cinco, 2011). The wellbore simulation exercise highlighted the non-unique solutions that are available. It showed the importance of conceptual development and cross-discipline collaboration to narrow down the possible explanations that provide consistent answers to integrated data sets and observations.

The paper also identified possible stimulation and permeability enhancement due mainly to pressure gradients that develop in a reservoir responding to significant pressure distribution changes. This will potentially provide insight into the stability of existing permeability structures in a reservoir and the likelihood of permeability enhancement after a critical pressure gradient is breached. Geochemical analyses are also underway to characterize the fluid source sustaining the production increase in the area.

ACKNOWLEDGEMENTS

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