Proceedings World Geothermal Congress 2015
Melbourne, Australia, 19-25 April 2015

# Update on the Modeling of the Rotokawa Geothermal System: 2010 – 2014

Dario Hernandez[1], Jonathon Clearwater[1], John Burnell[2], Peter Franz[1], Lutfhie Azwar[1], Andrew Marsh[1]

[1]Geothermal Technical Resources Mighty River Power Limited, 283 Vaughan Road, Rotorua 3010, PO Box 245, New Zealand

[2]Department of Geothermal Sciences, GNS Science, 1 Fairway Drive, Avalon, PO Box 30 368, Lower Hutt 5040, New Zealand

E-mail: dario.hernandez@mightyriver.co.nz

**Keywords:** Rotokawa, modeling, simulation, TOUGH2, reservoir engineering

## 1. ABSTRACT

The Rotokawa geothermal field is located in the Taupo Volcanic Zone, New Zealand. In 1997 an initial 29 MW binary power station was commissioned on the field and in 2010 a second 132 MW triple flash plant was added. During 2011, to facilitate optimal field management, a full field numerical model using TOUGH2 was developed in collaboration between Industrial Research Limited and the Mighty River Power geoscience team.

The numerical model was based on an updated conceptual model and it was calibrated to match the thermodynamic conditions found in the natural state and the evolution during the production period, including the gravity changes. Since 2012 this model has been used in-house by Mighty River Power engineers for predicting make-up well requirements, environmental consent, testing theories about field behavior and field management.

A number of capabilities have been added to the modeling software to improve the representation of aspects of the reservoir and operations. These include permeability barriers in TOUGH2 to simulate the high degree of heterogeneity in reservoir permeability and observed pressure compartments, and functionality to enable the integration of wellbore and plant models. The Rotokawa numerical model is capable of simulating fluid take and injection requirements with automatic switching on of make-ups wells and throttling as the reservoir conditions change, making it an effective tool for reservoir management and field optimization

This paper presents the results from the collaborative effort undertaken in the last four years emphasizing the integration of field data for the coupling of the wellbore and plant models, resulting in an improvement in the matching of pressure and enthalpy evolution.

## 2. INTRODUCTION AND CONCEPTUAL MODEL

The Rotokawa geothermal field is located in the Taupo Volcanic Zone of New Zealand; 14 km northeast of Taupo (see Figure 1). To its southwest is the Wairakei-Tauhara geothermal system and to its north is the Ngatamariki geothermal field.

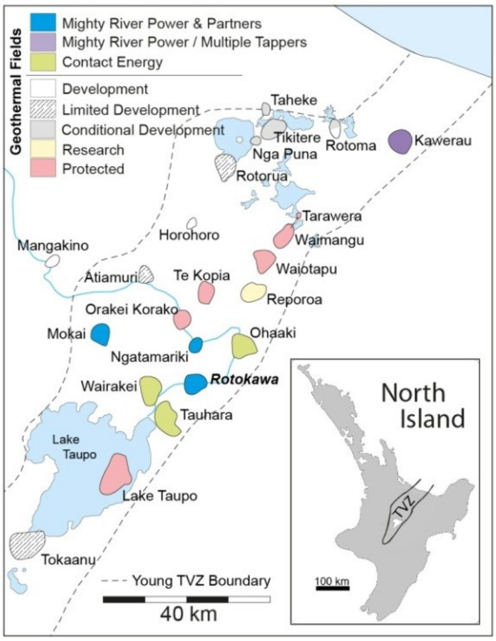


**Figure 1: Location map showing the Rotokawa geothermal field with other nearby geothermal systems. Insert shows the location of the Taupo Volcanic Zone, New Zealand.**

The first exploration wells in Rotokawa were drilled in the 1960's down to a maximum measured depth of 1200 m. These wells indicated a hot convective geothermal system and in 1984 RK4 was drilled deeper into the reservoir, encountering temperatures of 330 °C at 2500 m depth. In 1997 the 29 MW Rotokawa Power Station was commissioned and in 2010 the Nga Awa Purua (NAP)

Power Station, a 132 MW triple flash plant was added. Currently the field uses 12 production wells and 5 injectors (2 shallow and 3 deep).

A schematic of the geologic setting and fluid pathways are shown in Figure 2, with the conceptual model presented in full in Wallis et al, 2013 and Winick et al, 2011.

The initial well response after production for the Rotokawa Power Station started indicated heterogeneous reservoir permeability within the field. Post NAP it became clear there were semi-isolated compartments in the reservoir with pressure drawdown ranging of 38 bar across the field. The predominant fracture direction in the reservoir is NE-SW with a major fault (called the Central Field Fault) following this direction, separating the current production and injection area.

A laterally extensive permeable mixed thermal-groundwater aquifer overlies much of the deep reservoir at Rotokawa. This aquifer is evident in measured temperature profiles, in the interval of +100 to -450mRL elevation in most of the Rotokawa wells and appears to be fed by a connection with the deep reservoir somewhere between RK4, RK3 and RK1. This connection and its relation with the Central Field Fault have very important resource management implications.

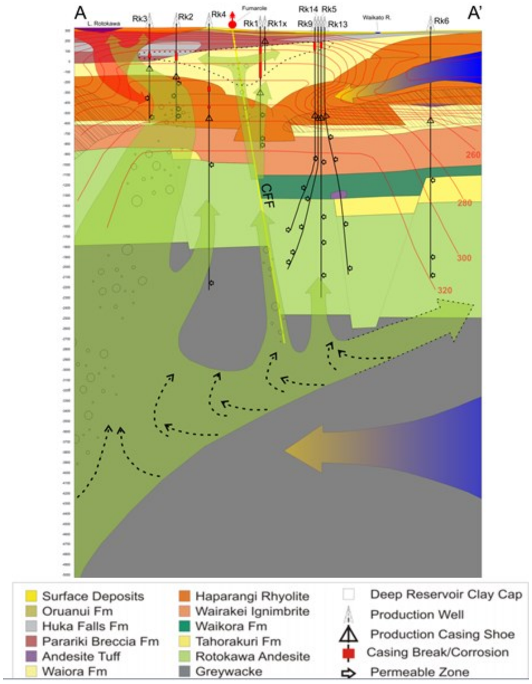


**Figure 2: N-S cross section through RK2, RK5 and RK6 with wells RK1, RK3, RK4, RK9, RK13 and RK14. Conceptual fluid flow pathways are indicated by arrows. (Winick et al 2011)**

The top of the deep reservoir goes from -500 mRL to -750mRL and was understood from natural state temperature and permeability distribution. Micro-earthquakes (MEQ) and lithology constrain the base of the reservoir. MEQ data show clusters of events above -3000m and disappear completely at -4000m. MEQ event clusters do not appear to 'sink' much below the point of injection, which may indicate that vertical permeability, at least in the southern injection area, is generally poor (Sewell and Cumming, 2011).

### 2.1. Previous numerical models

Work began on the first Rotokawa numerical model in 1992 by Kissling and White at Industrial Research Limited (IRL). This model was built for the resource consent hearing prior to initial field development. This model covered an area of 49 $km^2$ using 833 grid elements in seven vertical layers and was calibrated against natural state temperature and pressure data.

In 2003 Sinclair Knight Merz (SKM) built a model aimed to support a resource consent application and provide short and medium term forecasts. The wells included were RK-1x, 1, 2, 3, 4, 5, 6, 8, 9, 11 and 12 and the model output was compared to data from the period 1997-2001. This model had 3315 blocks and 13 vertical layers and employed 11 different rock types. The code used was AUTOUGH2, a modified version of TOUGH2 developed at the University of Auckland.

In preparation for the Nga Awa Purua development resource consent, a numerical model was developed using TETRAD (Vinsome, 1990) in 2007 and described in Bowyer and Holt, 2010. This model covered an area of 10.5 by 9 km containing 27 layers and a total of 114,210 blocks but it did not undergo a detailed history matching process.

In 2011, 18 months after the increase in production associated with Nga Awa Purua, Mighty River Power (MRP) entered into collaboration with IRL to develop a new numerical model in TOUGH2. In parallel, a process model (a simpler model with 1560 grid-blocks) was developed internally at MRP (Clearwater, 2012). The objective of the process model was to test the sensitivity of the output to variation in the parameters that could be used in the full-field model being developed primarily by John Burnell at IRL (now at GNS Science).

In September of 2012 the full-field TOUGH2 model was delivered to Mighty River Power. During 2013 it was updated with production and injection data and the new wellbore and plant models were calibrated and improved for use in reservoir management. In the first quarter of 2014 an update of some conceptual model elements was incorporated into the model.

## 3. DESCRIPTION OF THE STRUCTURE OF THE FULL-FIELD NUMERICAL MODEL

The numerical model grid covers an area of 11.6 by 11.3 km with 28 by 30 grid blocks in x and y direction, respectively, and 16 vertical layers with a total of 13,440 primary grid blocks (see Figure 3)

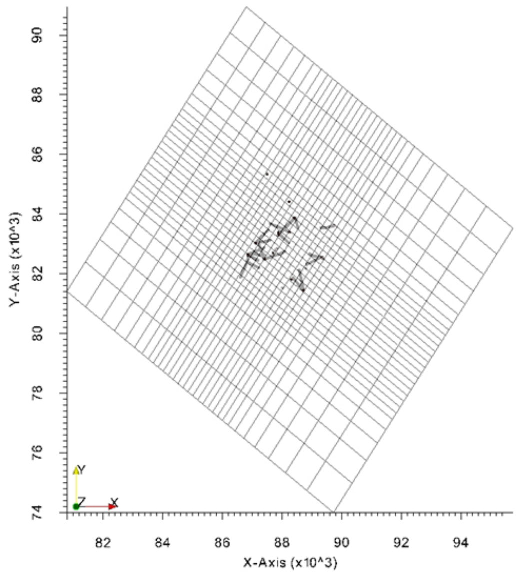


**Figure 3: Top view of the Rotokawa reservoir model showing the grid discretization in x and y direction. The coordinates correspond to NZ map coordinates without the first two digits.**

**Table 1: Center and thickness of each vertical layer in the Rotokawa reservoir model**

| Layer n | Centre (mRL) | Thickness (m) |
|---|---|---|
| **1** | 300 | 100 |
| **2** | 200 | 100 |
| **3** | 75 | 150 |
| **4** | -125 | 250 |
| **5** | -375 | 250 |
| **6** | -562.5 | 125 |
| **7** | -687.5 | 125 |
| **8** | -875 | 250 |
| **9** | -1125 | 250 |
| **10** | -1375 | 250 |
| **11** | -1625 | 250 |
| **12** | -1875 | 250 |
| **13** | -2250 | 500 |
| **14** | -2750 | 500 |
| **15** | -3500 | 1000 |
| **16** | -4050 | 100 |

The thickness of the layers is between 100 and 1000 meters (Table 1) with higher discretization in the depths where phase change is expected. MEQ and lithology indicate that the base of the permeable reservoir at Rotokawa is around -4000 mRL, and accordingly the model covers a vertical range from ground surface to -4050 mRL.

Each one of the grid elements (except the boundary elements) is dual porosity with one fracture and two matrix elements. The dual porosity structure (MINC in TOUGH2) is a key element in modeling the heat transfer between the rock and fluid. The two power plants operating on the Rotokawa field inject approximately 75% (average) of the total take from the field in different forms (i.e. brine, condensate), with temperature between 40 °C and 160 °C.

Thermal breakthrough was identified as one of the key uncertainties during the development of the field. The thermal breakthrough in the case of Rotokawa could be initiated by injection returns or cold downflow from the intermediate aquifer through the clay cap towards the production area. In this context the use of two matrix elements was required to better represent thermal effects. The importance of the MINC approach in this model was tested in a sensitivity analysis (see section 5.2.4).

While the current model is less discretized than the Holt et al (2007) model, it has advantages in the way that it uses MINC formulation to capture the thermal transient between matrix and fracture and also captures elements of the updated conceptual model.

### 3.1. Boundary conditions

The model has boundary conditions set at the top and bottom of the model, together with temperature conditions representing the Tauhara and Ngatamariki geothermal systems. At the base, a constant temperature hot plate is set with temperatures of 330 °C. Because the model grid covers the Tauhara and Ngatamariki geothermal fields, fixed temperature blocks were set to represent these systems below 0 mRL. Ngatamariki temperatures were taken from the NM6 temperature profile, with temperatures of 250 °C at -1500 mRL. The Tauhara temperatures were taken to be 200 °C up to -500 mRL. The locations of these boundary conditions are shown in Figure 4.

The other boundary conditions were set at the surface of the model, with an atmospheric block ($CO_2$ mass fraction of 1, pressure of 1 bar (a) and temperature of 20 °C) and the Waikato River represented by a constant pressure of 2 bar(a), temperature of 20 °C and a water saturation of 1.

For production runs, constant pressure recharge blocks were added to the locations of the natural upflows. The permeabilities of the recharge blocks were adjusted to match the measured pressure and temperature response. The total recharge flow from these blocks is less than 25 kg/s over the Rotokawa production period.

### 3.2. Sources and sinks

The hot upflow at the base of the model was split into four locations. Originally a single location at the base of the model was used, but this failed to match all the temperatures in the model. It was postulated that the four hot upflows could split from a single deeper source of hot fluid at a depth significantly below the base of the model (-4100 mRL). Rather than building a much larger deep model, it was decided to use a model down to -4100 mRL and focus on simulating the geothermal resource accessible for electricity generation.

The possibility of multiple upflow paths (rom one deeper source) was raised in the geochemistry section of the conceptual model summary (Winick et al., 2011) (see Figure 2) and supported by the temperature profiles found in RK5, RK17 and RK29. It was decided to test this concept in the reservoir model and it did provide a better match to the temperatures. This led to the current four upflow locations.

The total upflow from the four locations is 150 kg/s of 1,500 kJ/kg fluid. This amount of upflow is consistent with estimates of the total mass flow from surface heat measurements. The rates were adjusted to match measured temperatures. At each upflow location, $CO_2$ was also injected to allow boiling at the correct depth and obtain conceptually a similar chemical trend, as shown in Figure 2. The mass and $CO_2$ rates for the individual upflows are shown in Figure 4.

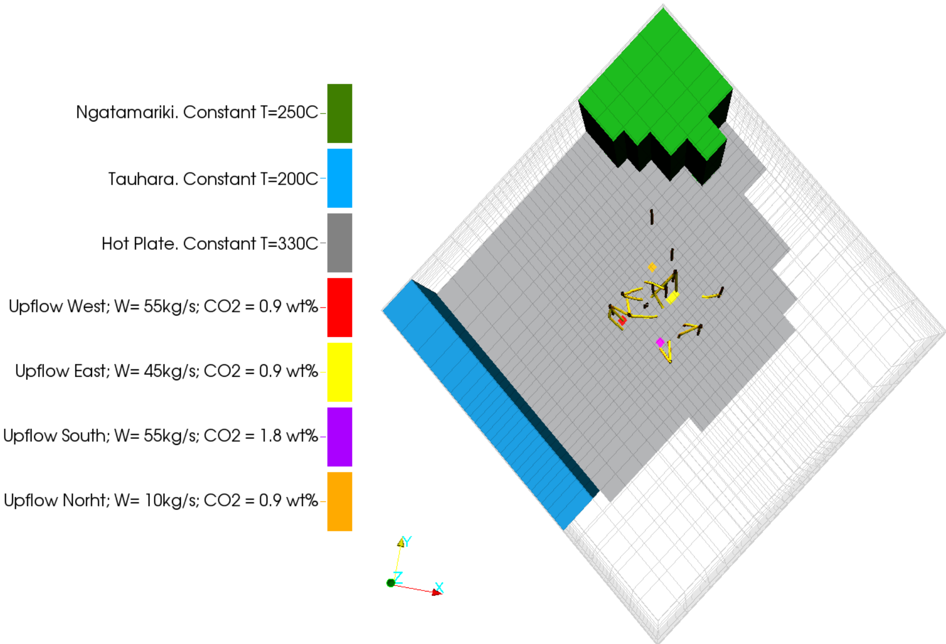


**Figure 4: Top view of the Rotokawa model and location of hot recharge and boundary condition**

Cold fluid is injected into the upper portion of the model, with 440 kg/s of 20 °C fluid injected at the surface to simulate rainfall, with an infiltration rate of 11%. The regional groundwater flow in the Intermediate Aquifer is simulated by injecting a total of 110 kg/s of 40 °C water to the east, west and south of the production field at 75 mRL.

## 4. SIMULATION CODE AND TOUGH2 ADDED CAPABILITIES

The numerical model was developed in TOUGH2 using EOS2 as the equation of state in order to account for the effect of CO2 on reservoir thermodynamics and to enable comparison with the distribution of CO2 concentrations throughout the reservoir (see green arrows in Figure 2). The version of TOUGH2 used in the Rotokawa model incorporates some added capabilities discussed below.

### 4.1. EOS2 control

Parameters can be set to give a finer control over phase changing in EOS2. These parameters include default saturations and saturation pressures after phase transitions and a threshold saturation to test for two-phase conditions, resulting in improvements to TOUGH2 run-times.

### 4.2. Permeability barriers

The compartments concept identified in the conceptual model is applied to the numerical model through the use of “permeability barriers”. These barriers are implemented as low permeability connections between two rock types.

The major advantage of this construct is that low permeability barriers between sections of the reservoir can be introduced without requiring intermediate sections of low permeability elements. This avoids increasing the number of grid elements, simplifies the model and reduces the run time. Three main compartments are implemented in this way.A fourth southern compartment (current injection area) is implemented through the Central Field Fault, which has a reduced permeability in the NW-SE direction to reduce the pressure connection to the southern area. The locations of the compartments in the model are illustrated in Figure 5 and the effects on pressure are shown in Figure 6. The barrier permeability was adjusted as part of the calibration process to match the measured pressure response to production.

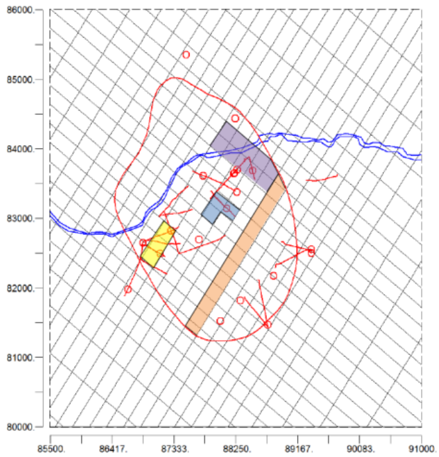


Figure 5: Compartments used in the model, yellow, blue and magenta areas are regions with lower permeability connection to the "main reservoir". The orange area represents the central fault which has lower permeability in the NW-SE direction.

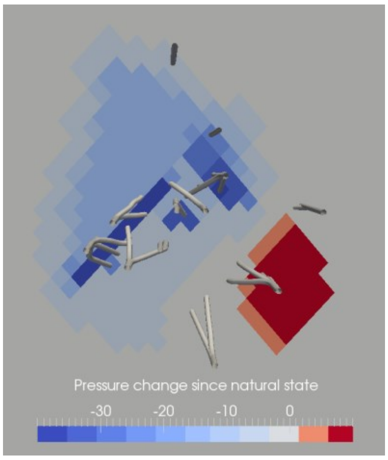


Figure 6: Simulation of pressure change in the period 1997-2014 at -1500 mRL. The areas with the largest pressure drawdown are confined to inside the production compartments.

### 4.3. Time dependent permeability

This extension was added to TOUGH2 to represent the stimulation of permeability near injection wells. Permeability placed around the southern injectors was increased in May 2010 to 100md in the NW-SE direction to account for the initial increase in injectivity index observed on these wells after injection started.

### 4.4. Wellbore model calibration and coupling to reservoir model

Alongside the reservoir model, wellbore models were used to define characteristics of the production wells. Where possible, the wellbore models were calibrated using recent flowing and static PTS surveys with TFT surveys for the output curve of flow rate and enthalpy vs. wellhead pressure. For the Rotokawa model, the calibration process of a wellbore model was accomplished as follows:

- For each well, a detailed wellbore model was developed using GeoWell (developed by Mauro Parini, PhD, 2013 for MRP) as shown in Figure 7 and Figure 8.

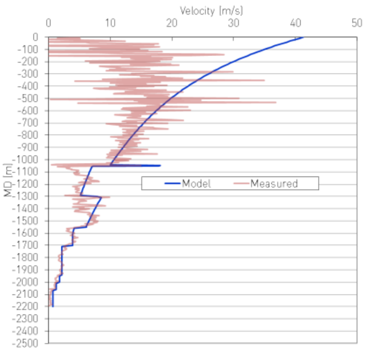


Figure 7: Modeled fluid velocity from flowing PTS survey

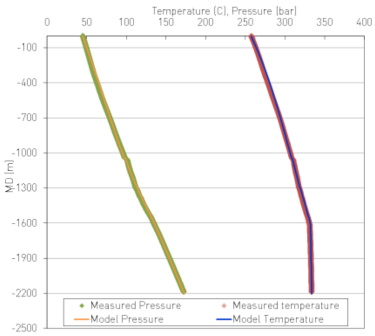


Figure 8: Modeled pressure and temperature matching of flowing PTS survey

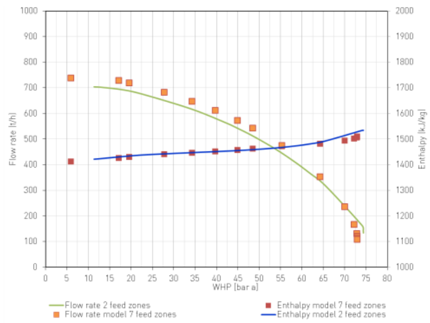


Figure 9: Output curve of wellbore model and simplified output curve

- Using this wellbore model as a template, a simplified version with two feed zones is developed to match the output curve, maintaining the total productivity index (PI) and combining the feed zones into the most representative ones (higher contribution feed zones). (See Figure 9).

In the cases where a recent flowing PTS survey was not available, the calibration procedure was as follows:

- Reservoir pressure and enthalpies were taken from the reservoir model.
- The wellbore PI's were adjusted to match measured flow rates and enthalpies using historical pressures and enthalpies at feeds from the reservoir model. Overall, the wellbore models provide a good match to flow rate and enthalpy data.
- As an additional test of all the calibrated wellbore models and the historical reservoir model match, historical flow rates were calculated at a prescribed wellhead pressure for which data is available. Historical pressures and enthalpies at each feed were taken from the reservoir model and used to calculate flow rates and enthalpies from the wellbore model at this prescribed wellhead pressure and compared to measured data from the well at that wellhead pressure.

The calibrated wellbore models were used to generate tables of flow rates from each feed zone for a range of reservoir conditions, by running each wellbore model under 625 different reservoir conditions of pressure and enthalpy.

#### 4.4.1. Transition between history match and forecast scenario

The well bore models were adjusted to smooth the transition between the historical production and a forecast scenario. For production runs flow rates from each feed are prescribed, whereas for the forecast flow rate is calculated from the model.

In the Rotokawa model two feed zones may have very different enthalpies, i.e. shallow two phase enthalpy with deep compressed liquid. If the relative contribution of each feed zone to the total production of the well changes between historical and forecast scenarios, it produces a discontinuity in the enthalpy and in the downhole pressure that leads to a mismatch in the forecast.

Figure 10 shows the transition from historical to forecast production in the 2012 version, which resulted in an increase of nearly 5 bar in the downhole pressure. This has been fixed in subsequent versions, obtaining a smoother transition (green line in Figure 10).

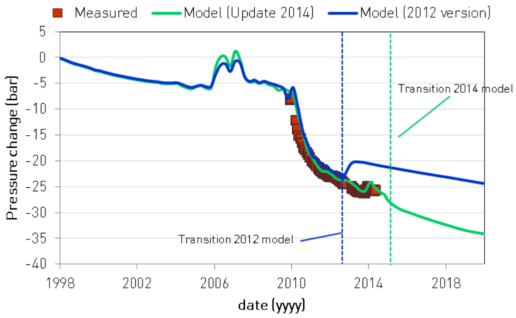


**Figure 10: Downhole pressure change in a monitoring well in the production area. Note that the 2012 model (blue line) shows a sharp change between scenarios of up to 5 bar and the 2014 model corrects it by reviewing the feed zone contribution at the time of transition to forecast.**

### 4.5. Power plant models and coupling with wellbore models

Power generation from the Rotokawa field comes from two power plants: Rotokawa, a flash binary plant and Nga Awa Purua, a triple flash plant. A simplified power plant model has been developed and coupled with TOUGH2 with enough flexibility to simulate different generation technologies and accurately reflect the total fluid take required from the steam field and the changing rate of injection into the reservoir over time.

The current model allows the total mass flow required to be defined in two ways:

- Mass flow target: A constant total take is required from the production wells (and make up wells), typical of a binary plant.
- Steam flow target: A constant steam take is required meaning the mass rate required is calculated from the enthalpy of the production fluid, typical of a flash plant.

A simple plant model is set up for each target. The total take has a linear correlation with enthalpy so that multiple enthalpy ranges can be specified with a different equation in each one to describe the plant requirement. Figure 11 is an example of the station model using a range of enthalpies to define the total fluid take required.

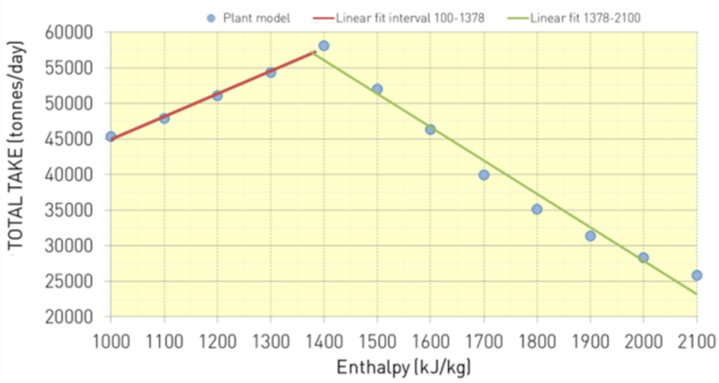


**Figure 11: Field enthalpy versus total take requirement**

A separation pressure in the flash plant is also defined to allow the calculation of injection flow rates. Once the total take and the enthalpy of the production wells is known for a model time step, the calculation of the injection flow rates is straightforward. In Nga Awa Purua a pressure of 3.5 bar(a) produces the same steam and brine flow rates as three flash units combined in series at 23.2, 9.2 and 2.5 bar(a) respectively.

For injection side, the flow rates are calculated in two different ways depending on the plant type:

- Total fraction: Specify the fraction of total take reinjected as brine and condensate (combined). In a binary plant this fraction is typically 1, but in some situations a different number might be more suitable, e.g. simulation of injection outside the field or simulation when brine needs to be dumped.
- Separated components: Brine and condensate are split. In a flash plant condensate is calculated as a fraction of the steam flow rate and brine flow rate is equal to the total take minus the steam.

4.5.1. Coupling of plant model with wellbore model

The coupling of reservoir, wellbore and plant models is a key element in the integration of the reservoir model as a tool for reservoir management. Pressure and enthalpy changes in the reservoir affect the performance of the production wells and the capacity over time that result in a change of the plant performance (output per unit of fluid take) and in the injection flow rate. The injection flow rate returns to the production area closing the loop as shown in Figure 12.

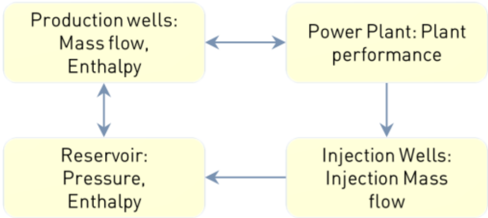


**Figure 12: Simplified diagram showing the relationship between reservoir, wellbore and plant models**

After every TOUGH2 time step, the coupling of the reservoir properties with wellbore and plant models follow the following procedure:

1. In the first iteration, the pressure and enthalpy of each generation block are used to calculate the maximum flow rate achievable in each well. A two dimensional closest neighbor algorithm is used to find the flow rate from each feed zone from the tables previously generated by wellbore models as described in section 4.4.
2. The mass flow requirement from the plant is calculated as a function of the enthalpy that the wells can provide. See Figure 11.
3. If the current existing wells can provide more than the plant requirement, then the generation from each well (and each feed zone) is throttled by a common percentage. Otherwise a new production well is activated, becoming an active production well and the calculation loop continues back in step 1.

Once the total production and enthalpy is obtained, the calculation of injection flow rates is performed using the power plant model. The flow rate in each injection well is distributed proportionally to the capacity specified in the GENER section of the input file. Injection make up wells are also activated automatically with a similar procedure as described for production wells. Figure 13 is an example of how if the enthalpy from the production wells decline, the total take increases at a rate given by the plant model and the amount of brine increases due to the lower enthalpy in the separator.

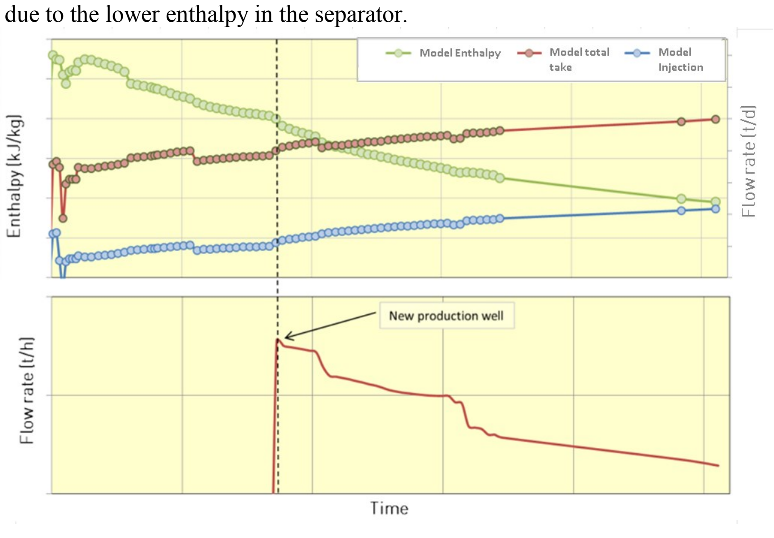


**Figure 13: Example of the field enthalpy evolution, total mas flow required, injection flow rate and automatic activation of one production well. Note just one new production well is shown in this figure.**

## 5. MODEL CALIBRATION

### 5.1. Natural state

5.1.1. Temperature

The initial state temperature distribution of the reservoir, shown in Figure 15 to Figure 17, is interpreted mainly from static measured temperatures in wells primarily taken prior to the start-up of the NAP power station. The hottest wells in the field are RK4, RK5 and RK17 with bottom-hole temperatures of at least 330 °C, suggesting that the deep upflow for the geothermal system lies near these wells. Bottom-hole temperatures decline to the north with ~310 °C in RK6 and ~280 °C in RK8. RK17 encountered the shallowest occurrence of 330 °C fluid at approximately -1500 mRL. In the west the fault intersected by RK17 influences the shape of the deep isotherms (see Figure 18), suggesting that it is a major conduit for upflow and that it defines the western boundary of the geothermal reservoir. With the exception of RK4, all wells show a temperature reversal above approximately -700 mRL.

The temperature matching is in general very good with the main mismatch in the Intermediate Aquifer of the south wells (injection area) where not enough cooling is achieved. An example is shown in Figure 14. The area within the field boundaries is characterized by relatively high permeability and high temperature (>300 °C) based upon temperature profiles of deep production and injection wells. This high permeability/temperature region is surrounded by a lower permeability envelope.

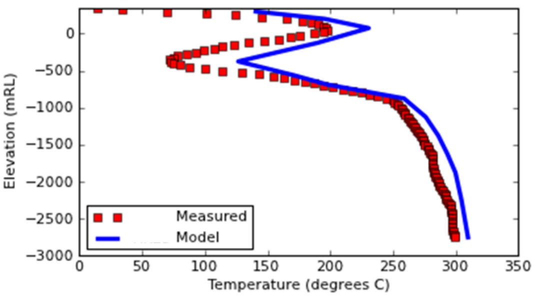


**Figure 14: South east well**

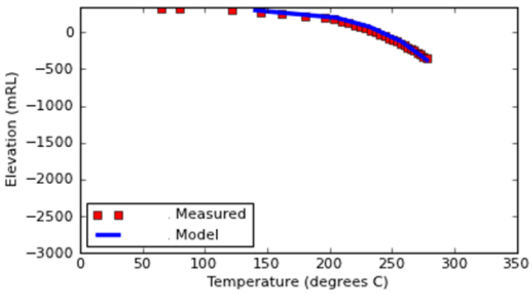


**Figure 15: Shallow central well**

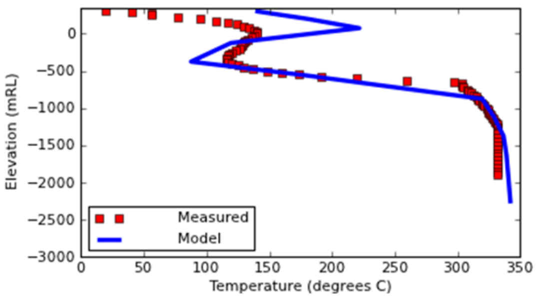


**Figure 16: Eastern production well**

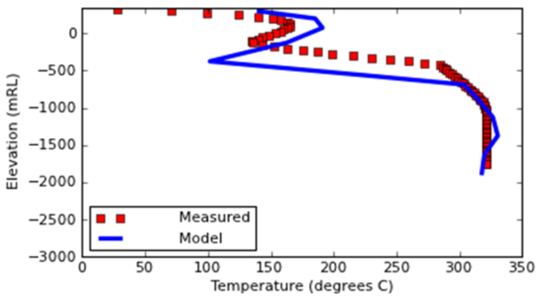


**Figure 17: North production well**

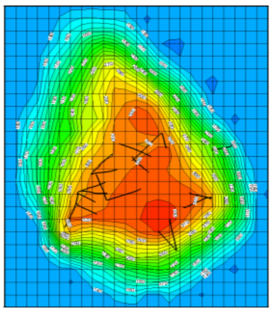

**Figure 18: Interpreted temperature distribution at -2000m RL**

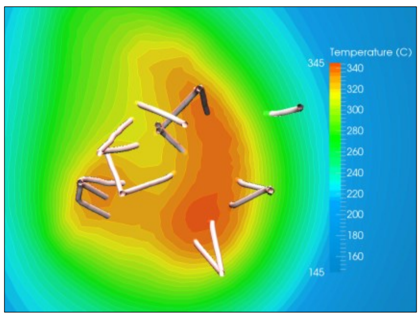


**Figure 19: Model temperature at -2000 mD in 1997**

5.1.2. Pressure

The pre-production pressure gradient in the field has been interpreted from measured static pressures at fluid entries of early wells. These included deep wells RK4, RK5, RK9, and shallow wells RK1, RK1/X, RK11 and RK12. According to this gradient the pressure at -4050 mRL is approximately 315 bar. The natural state pressure was defined by a few initial wells but there seems to be around 10 bar over pressure at -750 mRL associated with the cap of the deep reservoir. The entire southern part of reservoir seems well connected.

### 5.2. History match

History matching of pressure and enthalpy is especially challenging due to the large heterogeneity of structures found in Rotokawa. Four years after the 132 MW increase of generating capacity was installed, the pressure drawdown range is 38 bar and the production enthalpy range is 550 kJ/kg. The full period of production from first generation covers the interval between 1997 and 2014 in the model.

### 5.2.1. Pressure

The large variation in pressure change across production wells does not follow a clear pattern, but wells can be grouped in compartments according to chemical distribution, tracer returns, feed zone locations, static temperature and pressure drop.

The model obtains a very good match of pressure in the main production area (west) with the correct magnitude of initial decline, stabilization, and recovery during plant shuts. The production wells in the center part of the field (Figure 22) have a lower pressure drawdown due support from the injection area.

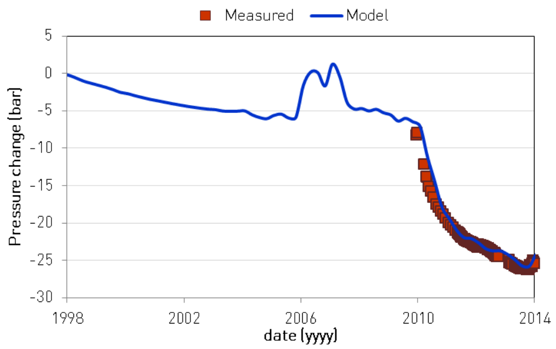


**Figure 20: Downhole pressure change in monitoring well in the west production area**

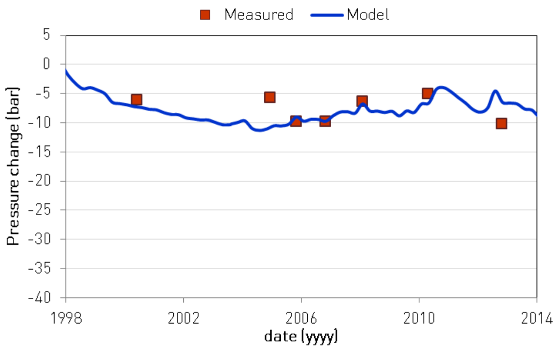


**Figure 22: Downhole pressure change in a central production well**

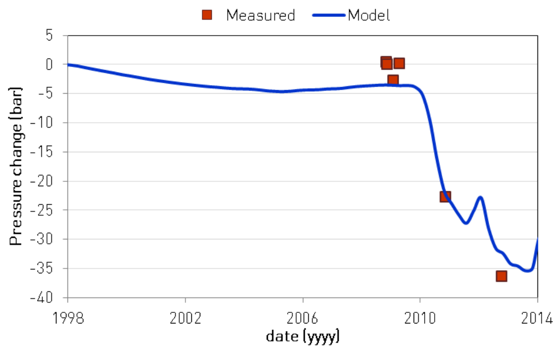


**Figure 21: Downhole pressure change in an east production well**

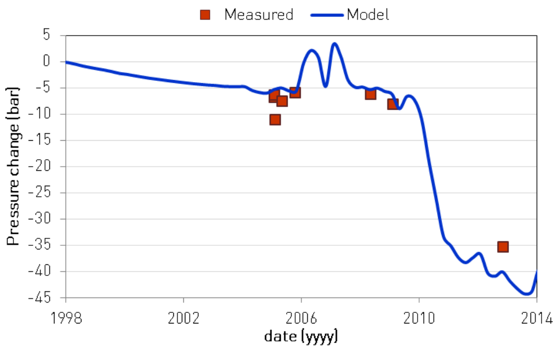


**Figure 23: Downhole pressure change in a northwest production well**

Two wells were initially assigned in the same compartment due to a similar pressure drawdown in 2012 and similar natural state temperature profile, but results from tracer tests first in 2011 and after that in 2013 suggested a strong connection between the main injector with one of the wells. This theory is supported by the low pressure drawdown since natural state and by the chloride results. The model was updated excluding this well from the compartment, connecting it with the injection area. The permeability was matched to obtain the correct pressure support without affecting at the temperature profile as shown in

Figure 24.

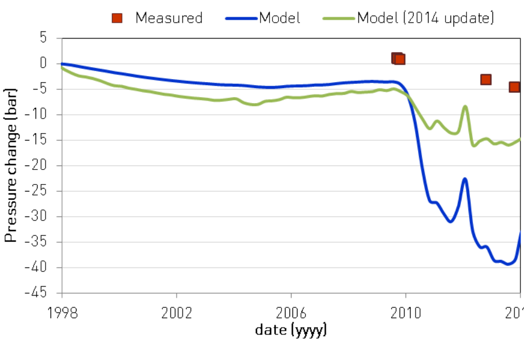


**Figure 24: History match of the pressure drop in the 2012 model and its review in 2014**

### 5.2.2. Enthalpy

Enthalpy matching in the field is generally good with some cases of excessive boiling (see Figure 27). Most of the Rotokawa wells follow a similar trend with an initial increase in enthalpy after one year of production from Nga Awa Purua and a slow decline over time.

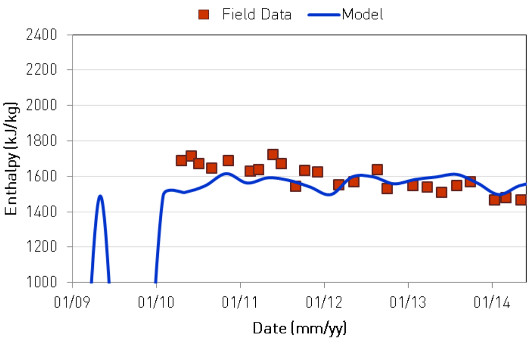


**Figure 25: West production well**

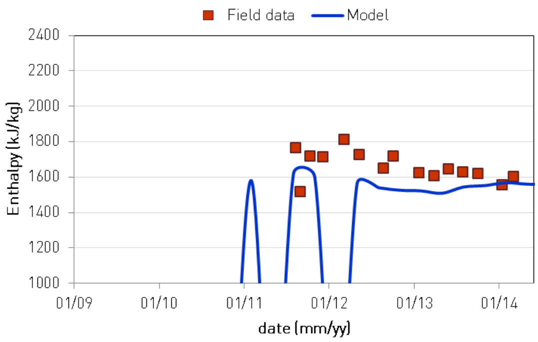


**Figure 26: Central production well**

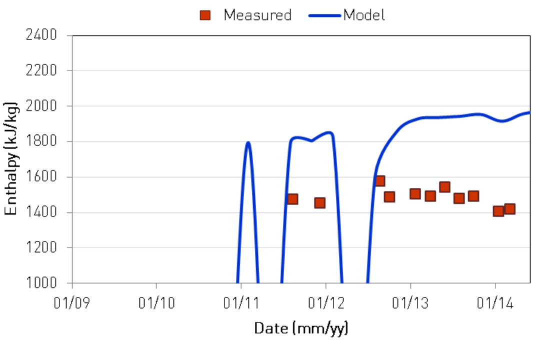


**Figure 27: Northwest production well**

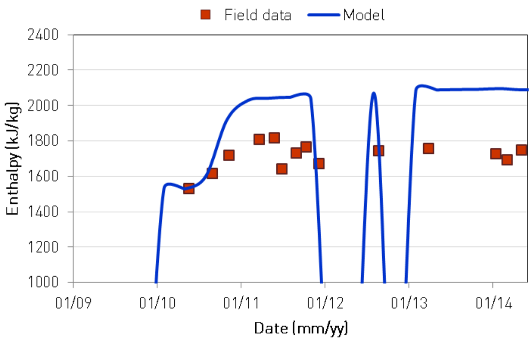


**Figure 28: East production well**

5.2.3. Micro Gravity

The approach to calculate microgravity changes from the model was to use the variations in density from each block of the numerical model and compute gravity from them. Any significant mismatches were then identified and the model was adjusted to obtain a better match.

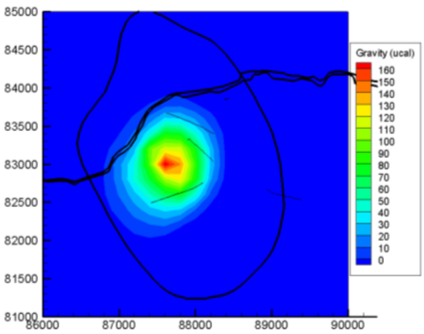


**Figure 29: Modeled gravity change in 2009, measured in micro-gals.**

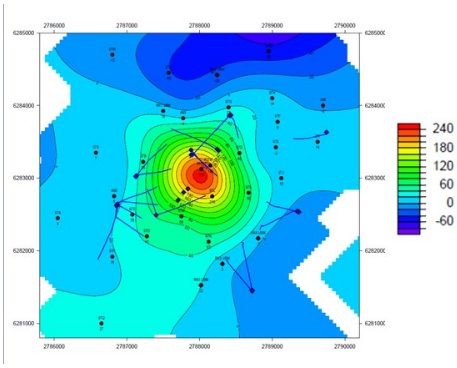


**Figure 30: Measured gravity changes in 2009**

5.2.4. Sensitivity analysis

A process model (simpler model with 1560 grid-blocks) was developed by MRP (Clearwater, 2012) to be as simple as possible but still reflect the major conceptual model elements. Particular model parameters were varied above and below base values to test sensitivity in the output. This study only sampled a limited region of the parameter space but provided important insights to the model. The key findings from the sensitivity testing were:

- The pressure dependent recharge did not affect the natural state pressure or temperature, but removal of it caused ~ 5 bar additional drawdown up to 2011 and an increase in enthalpy associated with greater pressure drawdown and more boiling.

- When the recharge was moved to the north it did not affect natural state temperature or pressure, but it caused lower pressure drawdown in the north (~ 2 bar) and slightly more pressure drawdown in the south.

- The temperature of recharge did not impact natural state temperature or natural state pressure, but hotter recharge caused less drawdown probably due to either density differences or two-phase development. It had minimal impact on mass flow, steam flow or enthalpy.

- Fracture permeability in the reservoir had significant impact on natural state temperature as flow paths changed. Natural state pressures were much higher with low fracture permeability, but high fracture permeability was similar to the base case. Mass and steam flow were much lower in low permeability case. The matrix permeability did not impact natural state conditions, but low matrix permeability had a larger drawdown with an associated reduction in mass flow and a minor increase in enthalpy.

- Fracture spacing had negligible impact on natural state conditions. Higher fracture spacing had a greater transient pressure response (by ~ 5 bar) but reverted to similar total drawdown by 2030; it also showed a reduction in steam flow and a 40 kJ/kg decrease in enthalpy.

- Fracture porosity had no impact on natural state temperatures or pressures. It increased transient drawdown (in response to NAP), but drawdown stabilizes to approximately the same level by 2030. There was a minor impact on mass flow, steam flow and enthalpy.

- Matrix porosity had no impact on natural state conditions. Lower matrix porosity caused slightly (> 2 bar) more pressure drawdown in response to production, but negligible impact on mass flow, steam flow and enthalpy.

- Additional MINC layers had negligible impact on natural state, response to production or mass and steam flows. Moving to a single porosity system changed the natural state by up to 5 °C and the pressure response by several bar. In general the single porosity system experienced greater drawdown over the RGEN period but lesser transient drawdown when NAP was switched on (although both models reach a similar stable level of drawdown by 2030). There is negligible impact on mass and steam flow, but the enthalpy is reduced in the single porosity system.

## 6. NUMERICAL MODELLING FOR RESERVOIR MANAGEMENT

The numerical model has been used by MRP for reservoir management/optimization and for testing theories about the dynamic evolution of the reservoir. In particular the following scenarios were simulated:

### 6.1. Production strategy

- Make-up wells required: Potential new production wells are tested assessing the risk of thermal breakthrough or interference with nearby wells. The results from decision analysis models (based in decline curve analysis) are consistent in the short term (5 years) with the numerical model results. The numerical model coupled with the wellbore model obtains better results in the long term (50 years) because it accounts for elements like interference between production wells, thermal breakthrough or boiling that the decision analysis cannot handle. The total number of make-up wells required to maintain the current generation level is one of the variables utilized to find the optimum production/injection strategy for the long term (+50 years).
- Optimum make-up well location: A number of scenarios were run by changing the order in which the make-up wells were activated measuring the time when the next (second) make up well would be required.

### 6.2. Environment and sustainability

The influence of the production in the main thermal features in Rotokawa (Ed's Spring, Rotokawa Fumarole, Explosion Crater Spring, New West Pool and Parariki Stream Spring) has been simulated. The approach adopted was to treat each one of the grid elements containing the thermal features as "wells" on deliverability (production according to the pressure in the grid-block) with a total depth of 300 mD. In the period 1997-2014 the field data available do not show any effect on the spring flow rates because the pressure drop in the model in these grid-blocks was 2 bar. In the next 50 years an additional 4 bar is shown in the numerical model.

### 6.3. Injection strategy

Injection strategy has also been addressed using the numerical model. The objective is to investigate the optimum location of injection with the aim of providing enough capacity to allocate brine and condensate and enough pressure support to the reservoir to compensate for the voidage while avoiding thermal breakthrough in the production area. Figure 31 shows the sensitivity of the production enthalpy to different injection scenarios.

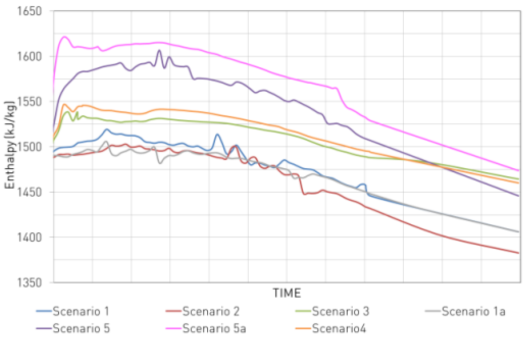


**Figure 31: Field enthalpy projections of different injection strategies**

- Injection tracking: The numerical model has been validated against the tracer tests by using ECO2N as the equation of state, where CO2 is present (as in EOS2) and using NaCl as the tracer in the model. The model shows injection return in the same wells as the measured data, however the time of arrival differs due probably to the level of discretization in the model. Figure 32 shows the impact of each of the major injectors in the production area, by running three scenarios and tracking the injection in each well.

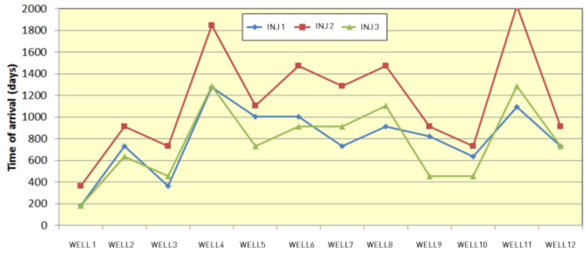


**Figure 32: Simulated injection time of arrival from the major injection wells to all production wells**

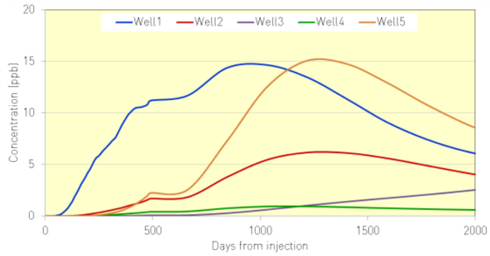


**Figure 33: Simulation of the tracer test in Rotokawa as return curves in the main production wells**

- Conversion of injection wells into production: The numerical model can reduce the uncertainty of predicting well capacity after converting an injection well into production. A flowing test to the surface is a very expensive operation with a high risk that the well is not going to be ready for production. Bi-annual shut PTS surveys in production wells can help to calibrate the thermal transfer around the well and the model can be used to forecast the thermal recovery. Figure 35 and Figure 34 show an example of temperature recovery in a well after injection stops and the expected enthalpy over time, highlighting the period when it is suitable for production to a plant at Rotokawa.

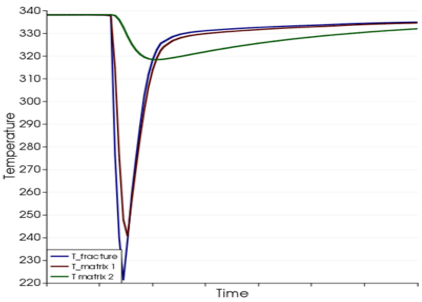


**Figure 34: Temperature evolution in the MINC layers of an injection well converted into production**

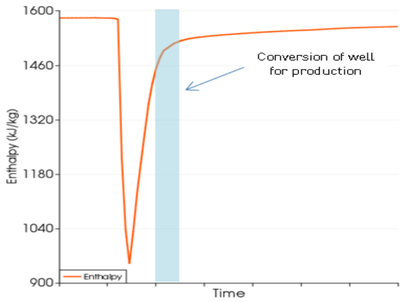


**Figure 35: Enthalpy evolution of an injection well converted into production**

## 7. CONCLUSIONS

The 2012 Rotokawa numerical model is a good representation of the Rotokawa system, the result of the work of a multidisciplinary team and an effort to combine conceptual understanding from multiple disciplines. The in-house utilization of the model has proved to be of great value in reservoir management and has allowed for the continual update of field data in the model (production, injection, wellbore model tables and plant models) and conceptual model elements. The coupling of wellbore and plant models has been crucial to gaining confidence in the use of the model for reservoir management and decision making. Future efforts will be directed to a full coupling of a dynamic wellbore model to replace the tables and the use of Monte Carlo analysis for uncertainty estimation.

## 8. ACKNOWLEDGMENT

The authors wish to thank the Rotokawa Joint Venture Ltd. (Mighty River Power Ltd. and Tauhara North No.2 Trust) for their permission to publish this work.

## 9. REFERENCES

Pruess, K., Oldenburg, C., and Moridis, G.: TOUGH2 User's Guide, Version 2.0. Berkeley: Earth Sciences Division, Lawrence Berkeley National Laboratory. (1999).

Winick, J., Powell, T., Mroczek, E.: The Natural State of the Rotokawa reservoir. New Zealand geothermal workshop, 2011.

Bowyer, D. and Holt, R.. “Case Study: Development of a Numerical Model by a Multidisciplinary Approach, Rotokawa Geothermal Field, New Zealand” Proceedings World Geothermal Congress 2010. Bali, Indonesia. April 25-29, 2010.

Sewell, S., Cumming, W.: Rotokawa conceptual model elements from geophysics; Mighty River Power internal memo, 2011.

Wallis I., Bardsley J., Powell S., Rowland J. and O’Brien J.: A structural model for the Rotokawa Geothermal Field. New Zealand Geothermal Workshop, 2013.

Clearwater, J.: Rotokawa Process Model. Mighty River Power internal report, 2012

Vinsome, K.: TETRAD user manual. Dyad Engineering, Calgary, Alberta, Canada, 1990