

IN THE MATTER

of the Resource Management Act 1991

AND

IN THE MATTER

of resource consent applications by Contact Energy Limited in respect of the Te Mihi Geothermal Power Station Proposal.

STATEMENT OF EVIDENCE OF JOHN GREGORY BLUM BURNELL

23 June 2008

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1. Introduction

- 1.1 My name is John Gregory Blum Burnell. I am a scientist in the Applied Mathematics Team, Industrial Research Limited.
- 1.2 I hold the degrees of BSc (Hons) in Mathematics (1979), Msc (1981), and a PhD in Applied Mathematics (1985) from Victoria University of Wellington.
- 1.3 From 1981 to 1985 I lectured in mathematics at Victoria University. In 1986 I joined the Applied Mathematics Division of the Department of Scientific and Industrial Research to undertake research and consulting in geothermal energy development. In 1992, DSIR was restructured and the Applied Mathematics Division became part of Industrial Research Limited. At Industrial Research my work involves modelling heat and mass flows in geophysical and industrial settings.
- 1.4 During the past 22 years I have been involved in many research and development projects on geothermal systems. The research has included: work on the theory of two-phase flow in porous media; incorporating chemistry into geothermal models; and pressure transient analysis. I have also undertaken consulting work, developing models of the Wairakei, Rotorua, Kawerau, Mokai and Rotokawa geothermal systems in New Zealand, the Lihir geothermal system in Papua New Guinea and the Kakkonda geothermal system in Japan. I am an advisor to Environment Bay of Plenty on matters relating to the Rotorua Geothermal Regional Plan. I am also the principal developer of the software suite GeoCad, which is a preprocessor for the TOUGH2 geothermal simulator. This software suite is used throughout the world.
- 1.5 I have read and agree to comply with the Code of Conduct for Expert Witnesses as contained in the Environment Court's "Practice Note on Alternative Dispute Resolution, Expert Witnesses and Amendment to Practice Note on Case Management." In particular, unless I state otherwise, this evidence is within my sphere of expertise and I have not omitted to consider material facts known to me that might alter or detract from the opinions I express.
- 1.6 I have undertaken geothermal modelling of the Wairakei/Tauhara geothermal system for Geotherm Group Limited between 2001 and 2004. In 2007, the Receivers for the Geotherm Group Limited commissioned me to assist with an assessment of utilisation of their resource.

Scope of Evidence

- 1.7 My evidence will consider the effects of Contact Energy's application on Geotherm Group's resource consents. The particular focus is on the effect of Contact's reinjection plans.
- 1.8 In this evidence I will:
- Describe general modelling principles and how these relate to Wairakei.
 - Summarise the geoscientific features of the Wairakei/Tauhara system relevant to the model.
 - Describe details of the modelling I have undertaken, including the match to measured data.
 - Present the results of 3 scenarios to consider the impact of Contact's application on any future operations of Geotherm.
 - Discuss Contact's application in light of these scenario results.
- 1.9 The model that I have developed will be seen to give a good match to the data available from Wairakei and I believe it can be used with confidence to assess impacts of the current proposals for development of the system.

2. Computational Modelling

- 2.1 A computational model of a geothermal system calculates the state of the field (pressure, temperature, outflows) before development, and in response to events such as withdrawal and reinjection. This is achieved by simulating fluid and energy flows using a computer program. The development of a model consists of two stages: a conceptual model, and a computational model.
- a. The conceptual model is the basis for the computational model. It summarises the data relating to the field and identifies the important processes that control the fluid, energy and chemical flows in the field.
 - b. The computational model is a realisation of the conceptual model in terms of mathematical equations and a computer program. These equations describe the flow of energy and mass through the field, and allow the state of the field (pressure, temperature, etc.) to be calculated.

Modelling Stages

2.2 The stages involved in developing a reliable and predictive computational model are:

- a. Construct an initial model.
- b. Solve the model using a geothermal simulator to calculate temperatures, pressures and flows.
- c. Compare model results with measurements from the natural state, and the response to production.
- d. Refine the model parameters to improve the comparison in Stage C.
- e. Repeat Stages B-D until a satisfactory match is reached in Stage C.

This process is illustrated in Figure 1.

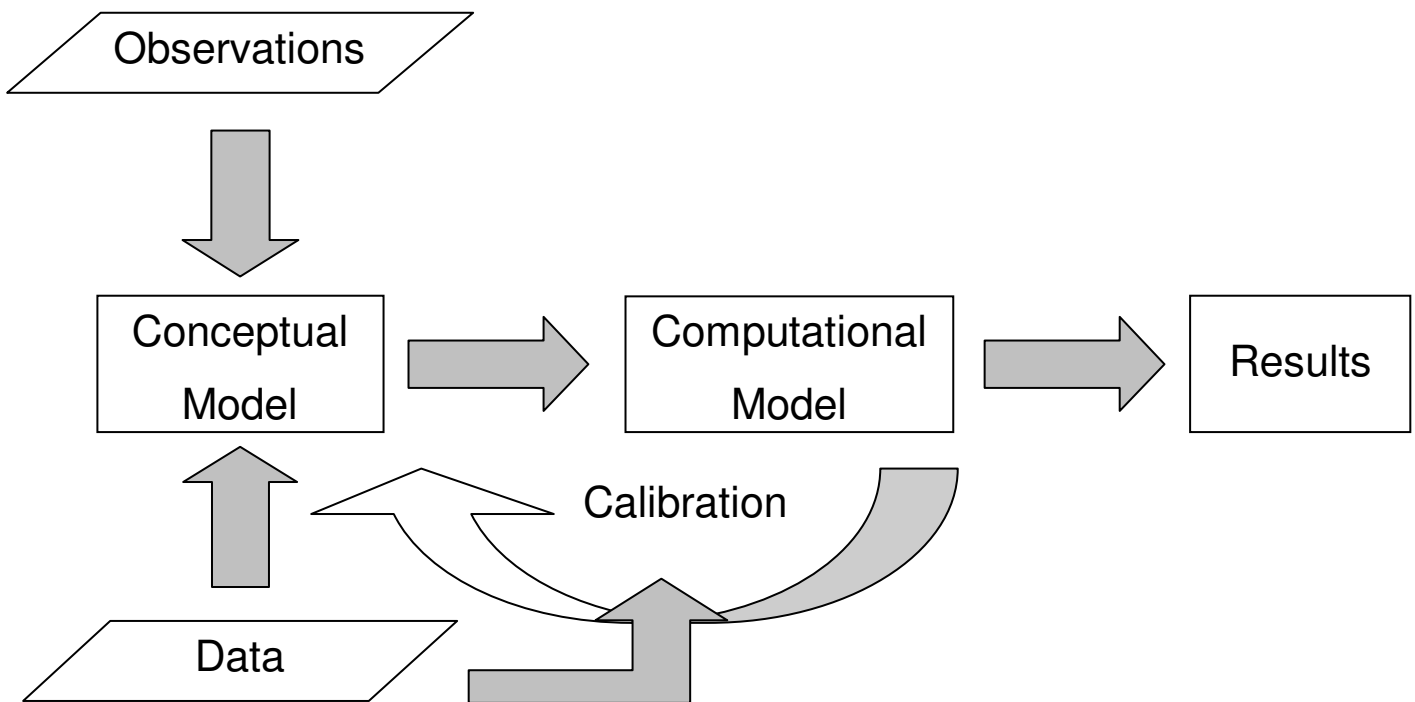


Figure 1: Flowchart showing modelling process

Modelling Principles

- 2.3 Geothermal fields have complex structures. Our understanding of these fields is based on the interpretation of data that can only be observed at certain points – for example in the wells, and at surface features. On the other hand, a model requires input parameters prescribed at all parts of the field. Since the parameters cannot be measured directly, an important part of the modelling process is deciding which parameters to include in the model and estimating their values. Parameter values are estimated by varying the parameter within reasonable limits until an acceptable match is found between model predictions and field data. The limits on the parameter values are determined from the conceptual model, measured data, and from measured and model values from similar geothermal systems.
- 2.4 Models can range from very simple ones containing only a few parameters to models with hundreds of parameters. One of the keys to modelling geothermal fields is to get the number of parameters “right”. Using too few parameters results in not including important processes in the model. On the other hand having a model with too many parameters may result in many of these parameters being poorly resolved – that is the model and data cannot distinguish between two quite different values of the parameter. When this happens then it is difficult to have any confidence in the ability of the model to predict the future. For example permeabilities in regions where little data has been collected may not be resolved very well by the past history.
- 2.5 In the modelling work undertaken for this project, a simple model (small number of parameters) was used in the beginning, and complexity (additional parameters) was added only when required to match the data. I believe that such an approach achieves the best balance between having too few parameters (omitting important processes), and too many parameters (resulting in poorly resolved parameters) in the model.

Model Verification

- 2.6 A key stage of the model development is verifying the model by comparing the model predictions with field measurements. Typically these measurements are from the natural state before production began in the field, and from the response of the field to production. For example, the important data from the Wairakei/Tauhara system that needs to be considered are:
- Surface heat flows in the natural state

- Temperature profiles in the natural state
 - The pressure response to production
 - The change in surface heat flow in response to production
 - The formation of steam dominated regions
 - Changes in temperatures
 - Production enthalpy
- 2.7 Comparing a model with a wide range of different aspects of the field data improves confidence in the model performance.

Modelling Terminology

- 2.8 I will now provide a brief description of some of the terminology I will use.
- 2.9 **Permeability** measures the resistance of rock formations to fluid flow. For a given pressure drop, larger permeabilities result in larger flow rates. Permeabilities are measured in darcies or milli-darcies. 1 darcy would be considered a large permeability.
- 2.10 **Porosity** measures the capacity of the rock to store water, and is measured as a fraction of the total volume.
- 2.11 **Enthalpy** measures the amount of available stored heat in rock or water. It has units of kilo-Joules per kilogram (kJ/kg)
- 2.12 Resistivity measures electrical resistance of the rock and water. Hot rock and water can often be identified by very low resistivities.
- 2.13 A **steady state** is one in which pressures, temperatures and flows do not change with time. That is, the system is stable and unchanging.
- 2.14 **Elevations** will be given as metres above sea level (m.a.s.l.). Over much of Wairakei the ground surface is between 400 and 450 m.a.s.l.
- 2.15 Unless otherwise specified, all heatflows are given in megawatts thermal.

3. The Conceptual Model of Wairakei

- 3.1 I will now summarise the key features of the Wairakei system that served as the basis for the conceptual model that was used in my modelling work.

- 3.2 A conceptual model of a geothermal field is a summary of the scientific data relating to the field. It serves as a basis for the computational model that is a mathematical realisation of the conceptual model. The conceptual model is a combination of measured data and interpretations by researchers. In order to develop a conceptual model it is necessary to take account of all the data and to form a self-consistent picture of the processes occurring which affect the state of the field.
- 3.3 Many people have worked on formulating the conceptual model at Wairakei for over 50 years. There are many common elements to the conceptual models that have been developed over this time, but some uncertainty still exists – especially in areas of the field where little data has been collected. Here I describe the common elements of these various conceptual models together with the consensus view for other elements.
- 3.4 Data that has been used in the development of conceptual models includes:
- geology
 - electrical resistivity
 - heat and mass flows from springs and streams
 - fluid chemistry
 - well temperatures
 - well pressures
 - regions where boiling occurs
 - changes in response to withdrawal

Key features from the data from each of these areas will now be summarised:

Reservoir Size

- 3.5 The resistivity boundary around the Wairakei/Tauhara system encompasses an area of approximately 75 km².

Geology

- 3.6 The geology of the Wairakei Geothermal Field has been the subject of many investigations. Some notable features are sketched in Figure 2 and include:

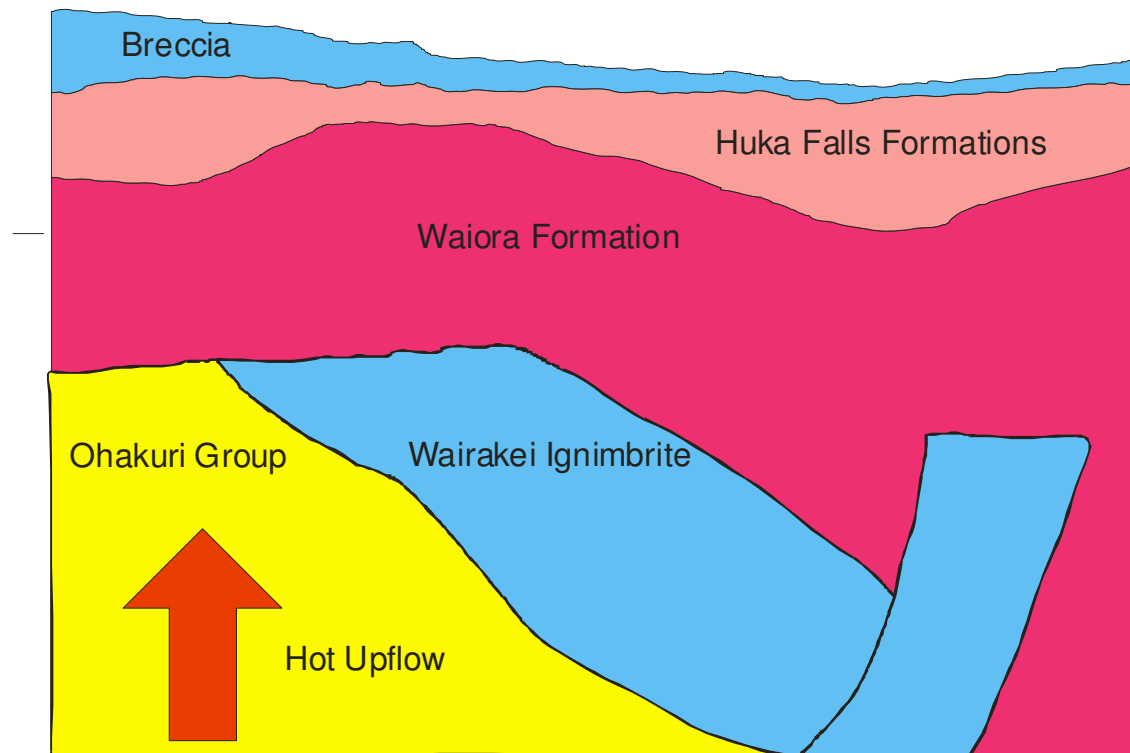


Figure 2: Schematic of geology (after Bromley et al, 2000) and upflows at Wairakei. The dash on the left represents 0 m.a.s.l.

- A surface formation of pumice and Wairakei breccia, containing the shallow groundwater aquifer, which is typically 100m thick.
- Below this is the Huka Falls Formation, often regarded as a caprock for the geothermal aquifer, but containing paths between the aquifer and the groundwater aquifer – possibly through fractures and faults. The typical thickness is in the range 50 to 150m. The Huka Falls Formation is absent at Karapiti.
- The highly permeable Waiora Formation from which most production currently occurs. The typical thickness is in the range 350 to 750m.
- Several rhyolite flows within the Waiora Formation, a notable one being the Karapiti Rhyolite in the southwest which appears to be more permeable than the Waiora Formation. The Karapiti Rhyolite is around 500m thick in places.
- The Wairakei Ignimbrite lies underneath the Waiora Formation. This is more than 900m thick in places, and generally has low permeability except where fractured by faulting.

- The Ohakuri Group lies beneath the Wairakei Ignimbrite and contains units similar to those in the Waioara Formation. In the west, the Ohakuri Group may lie directly under the Waioara Formation.
- Within all these formations, faults and fractures are widespread. The reservoir contains many northeast trending faults that are believed to be paths of high permeability within the reservoir. In addition, local fracturing is also believed to provide permeable paths within the reservoir.
- Recent deep drilling by Contact in the Te Mihi region is providing new insights into the geology at depth. This recent information has not been included in my model to date as I have not had access to the full details and it is unlikely that this information will influence the results of this work on assessing the impact of further Contact reinjection on Geotherm's operations. The reason being that Contact's likely reinjection sites and the Geotherm property are in a different part of the reservoir to the area where recent deep drilling has taken place.

Heat Sources

- 3.7 It is generally believed that the surface heat flow from the Wairakei area in the natural state was around 400 MW – although estimates vary from 340 MW to 600 MW (Allis, 1981 and Fisher, 1965).
- 3.8 The output from the surface in the natural state is believed to be matched by recharge to the reservoir. Most of the recharge is hot upflow at depth within the reservoir, probably from depths below 2km.
- 3.9 The chemistry suggests that the source of deep hot upflow into the reservoir is 260°C water. The upflow is generally believed to be underneath the Te Mihi region. If the natural, that is pre-production, state represented a steady state of the field then the upflow approximately matched the surface heat flow. Converting a heat flow of 400 MW to a mass flow gives an upflow of 360 kg/s in the Wairakei area.
- 3.10 Since production started at the field this deep upflow has changed. As a result of production, a significant pressure drop occurred which stabilised after the production rates stabilised in the 1970s. This suggests that the total flow into the reservoir now matches the total surface heatflow of 400 MW plus production of 1,500 kg/s. Clearly this recharge flow will be more than 1,500 kg/s, which is significantly more than the natural-state upflow.

- 3.11 The reservoir has shown no evidence of widespread cooling as a result of production, so we can conclude that most of this recharge flow is hot. The size of this hot recharge can then be estimated. If the surface heat flow is matched by a recharge of 260°C water then the total recharge today is approximately 1850 kg/s. Some of this recharge will be cold groundwater, but this calculation gives a ballpark figure of the total hot recharge.

Natural State

- 3.12 Some measurements were made at Wairakei before production started – for example temperatures, pressures, heat flows and chemistry. Notable points about the pre-production state are:

- The surface heat flow is approximately 400 MW.
- The reservoir is liquid dominated with base temperatures of 260°C.
- Boiling point for depth conditions exist down to about –100 m.a.s.l.
- Some two-phase fluid with mobile steam existed in the Middle Huka Falls Formation.
- Most wells showed liquid enthalpies.

Response to Production

- 3.13 The response of the reservoir to production provided a great deal of information on the reservoir properties. The behaviour of the field before the mid 1980s has been studied extensively in many publications. Reports from 2000-2004 have shown some of the changes that occurred through the 1990s.

- 3.14 The notable changes to the field in response to production were:

- Liquid pressures reduced by 25 bars from the natural state to the late 1980s where they remained unchanged through the 1990s until reinjection started in 1997. There was an increase in deep liquid pressures of approximately 2 bar from 1997 to 2000.
- Liquid pressures reduced by about 18 bars at Tauhara. This provides strong evidence that the Wairakei and Tauhara fields are linked.
- Extensive boiling in the reservoir resulted in steam zone formation below the Huka Falls Formation. In the Te Mihi region to the north (High Pressure Steam Zone) the steam pressures are approximately 12 bars higher than in the south

(Low Pressure Steam Zone or LPSZ). From 1960 to 1990 pressures in both steam zones fell by about 12 bars.

- Temperatures at depths where boiling has occurred have fallen as pressures fell. This temperature decline is the result of the pressure drop not cold water influx; heat in the water and rock is used to boil the liquid to form steam. In the liquid fed wells in the Western Borefield at around –150 m.a.s.l. this has resulted in a temperature drop of about 30°C from 260°C to 225°C over the period 1960 to 2000. In the Te Mihi region and to the south there has been little change in liquid temperatures at greater depths of around –400 m.a.s.l.
- As a result of the boiling that occurred in the reservoir, there was a large increase in the surface heat flow, with more steam escaping to the upper groundwater aquifers and atmosphere. Allis (1981) reports the heat flow increasing from 400 MW in the natural state to 800 MW by 1965, reducing to about 600 MW in 1979. The most notable change in heat flow occurred at Karapiti where the heat flow increased from about 40 MW to about 400 MW in 1964, before decreasing to a level of about 200 MW in 1979. Recent surveys have suggested that there has not been much change within limits of measurement at Karapiti since then.

In the Tauhara area, the natural state heat flow was about 100 MW (Fisher, 1965). This had increased to about 200 MW by 1980.

4. Model Description

- 4.1 The model described here was solved using a modified version of the TOUGH2 reservoir simulator (Pruess, 1981). This program was originally developed at Lawrence Berkeley National Laboratory in California, and has been used throughout the world to model geothermal and groundwater systems. The program solves the equations describing the flow of heat and mass in a porous medium. Modifications were made at Industrial Research Limited to improve the handling of large grids. This modified version of TOUGH2 has been tested against a suite of test problems.
- 4.2 The simulations described here use a module that allows water in its liquid and vapour phases, as well as heat and air to flow through rock. The simulation model requires the following input:
 - a computational grid covering the system;

- upflows and downflows that occur in the system;
- boundary conditions;
- injections or withdrawals that are imposed on the system.

Computational Grid Structure

4.3 A computational grid is essentially a set of boxes which cover the region of interest. The grid for this model covers an area that encloses the geothermal fields at both Wairakei and Tauhara, and extends to a depth of 3km. The model is built from 21 horizontal layers as shown in Figure 3.

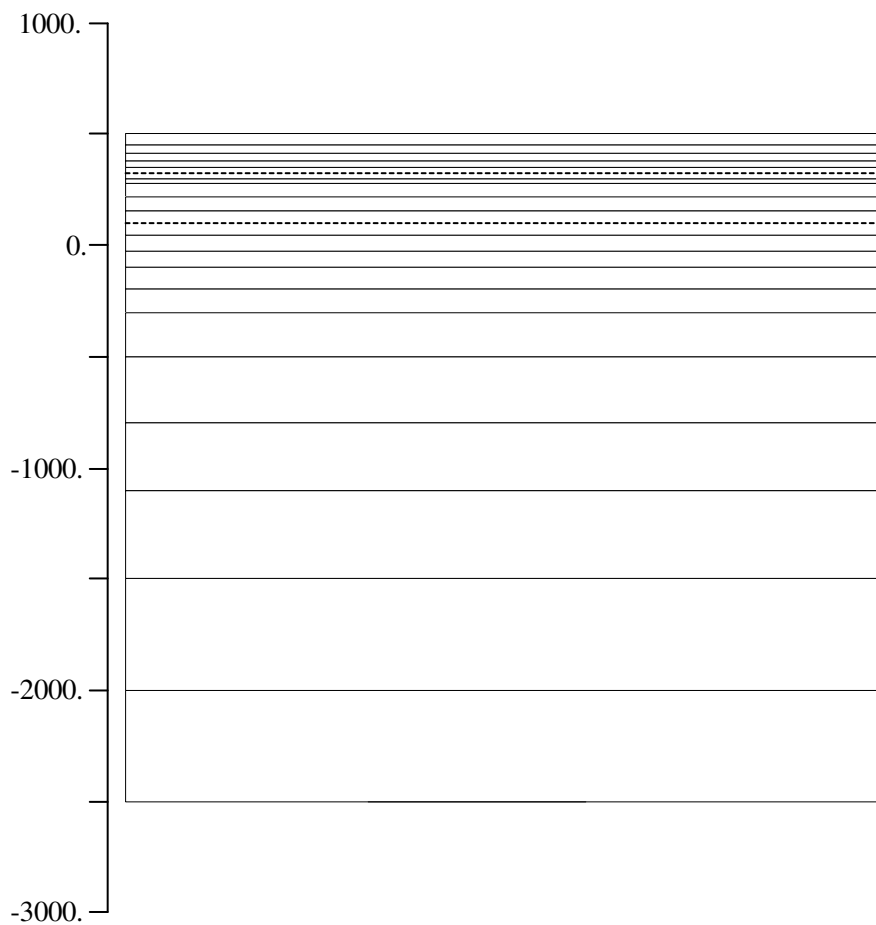


Figure 3: Vertical structure of the model. The vertical axis shows levels in m.a.s.l.

4.4 In each of these layers a horizontal grid of 406 grid blocks is defined. The grid is identical on each layer, and is shown in Figure 4. The total number of grid blocks in the model is 8,526.

4.5 A simple approximation to the surface topography is included in the model. This is achieved by connecting grid blocks in the model to an air layer. Over most of the model the ground surface is at 450 m.a.s.l., but in the low-lying areas it is at 400 m.a.s.l., and in higher areas it is 500 m.a.s.l.

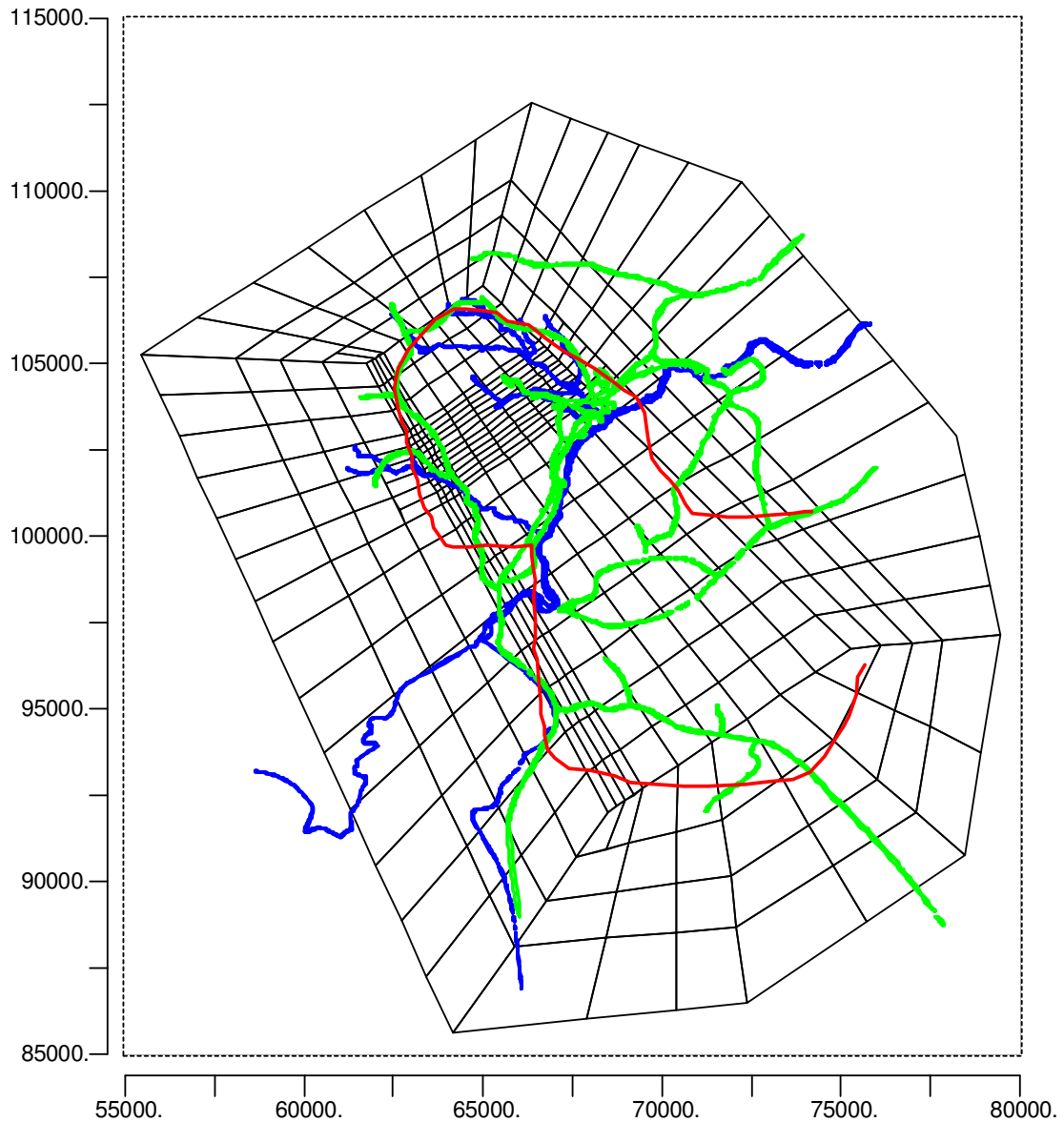


Figure 4: Grid structure in a horizontal layer. The coordinates are relative to the Maketu Grid – with (60,000, 190,000) on the diagram corresponding to (260,000, 590,000) on the Maketu Grid. The blue lines show river and streams, the green lines are roads and the red line indicates the location of the resistivity boundary.

Boundary Conditions

4.6 Geothermal fields are often subject to boundary conditions that control aspects of the flow within the field. For example, the water table surface is connected to the

atmosphere, which maintains a pressure of 1 bar and temperature under 20°C. Within TOUGH2 such boundary conditions are modelled by connecting the boundary blocks with blocks where the state (pressure, temperature, saturation) does not change throughout the period of the simulation.

- 4.7 Changes in atmospheric pressures and temperatures are small in comparison to the pressure and temperature changes which occur within the field – the pressure varies with depth by hundreds of bars, and the temperature by hundreds of degrees. So, the atmosphere can be included in the model by connecting a large block containing air at 1 bar and 20°C to all the surface blocks. This allows movement of water and steam and heat from the reservoir, simulating springs, geysers, fumaroles etc.
- 4.8 Apart from rainfall infiltration and the deep upflow I discuss below, all the other boundaries in the model are closed. That is, there is no flow exchanged over these boundaries between the model and the surroundings.

Sources and Sinks

- 4.9 The deep upflow in the natural state is represented in the model as an injection of hot water in the base at Te Mihi, the Western Borefield and at Tauhara. The modelled hot upflow under Wairakei was 472 MW, and 226 MW at Tauhara. The sizes of these upflows were adjustable model parameters. In addition to these specific upflows, a conductive heat flow of 37 MW is applied uniformly across the base of the model corresponding to the terrestrial thermal gradient.
- 4.10 Infiltration of rainfall is represented in the model by injection of cold water in all the surface blocks. The rainfall injection rate was a model parameter, chosen to be 1.8 kg/s/km². This corresponds to an infiltration fraction of 6% of the annual rainfall of about 1000 mm/year. This fraction was adjusted during the development of the model to help improve the model performance.

Recharge

- 4.11 As I mentioned earlier, the pressure and temperature response to production suggests that the geothermal reservoir is subject to considerable hot recharge. In addition to the fixed hot natural state upflow, recharge was implemented in the model by connections at the base of the model to blocks at 270°C where the pressure and temperature does not change. The pressures in the recharge blocks were chosen so that they contributed little recharge in the natural state, and the

flow from the recharge blocks was varied until the model matched the measured response.

Production and Reinjection

4.12 Production was incorporated into the model by placing groups of wells in appropriate blocks within the model. The overall production history from the reservoir was approximated by the curve shown in Figure 5. Production was divided between the various production wells in the Eastern and Western Borefields, at Te Mihi and in the South.

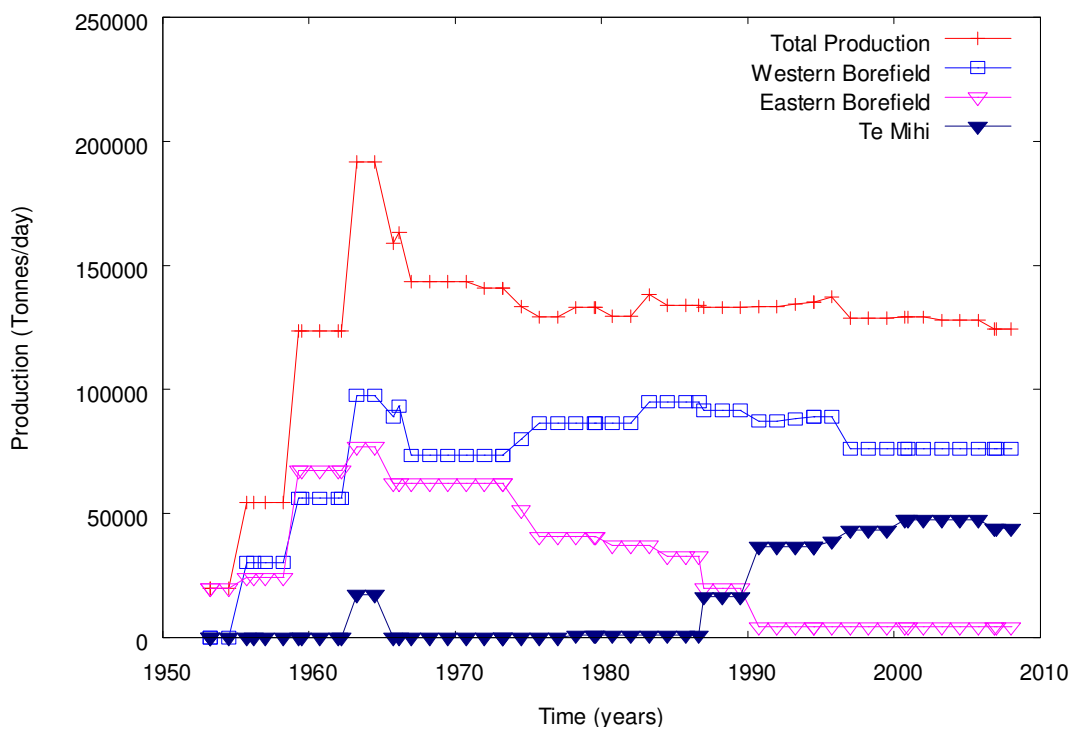


Figure 5: Approximate Wairakei production history used as model input.

5. Model Verification

- 5.1 The initial part of model verification is to match the natural, pre-production, state to ensure that the model correctly simulates observed conditions.
- 5.2 To this end, the model was run until an unchanging, steady, state was reached – that is pressures and temperatures did not change with time. This state should correspond to the natural state of the reservoir. The model results can then be compared with measured pre-production temperatures and heat flows from previously published work.

Natural State Temperatures

5.3 The model temperature profiles against depth, below the Western Borefield and Te Mihi are shown in Figure 6 and Figure 7. These profiles compare well with the measured temperatures.

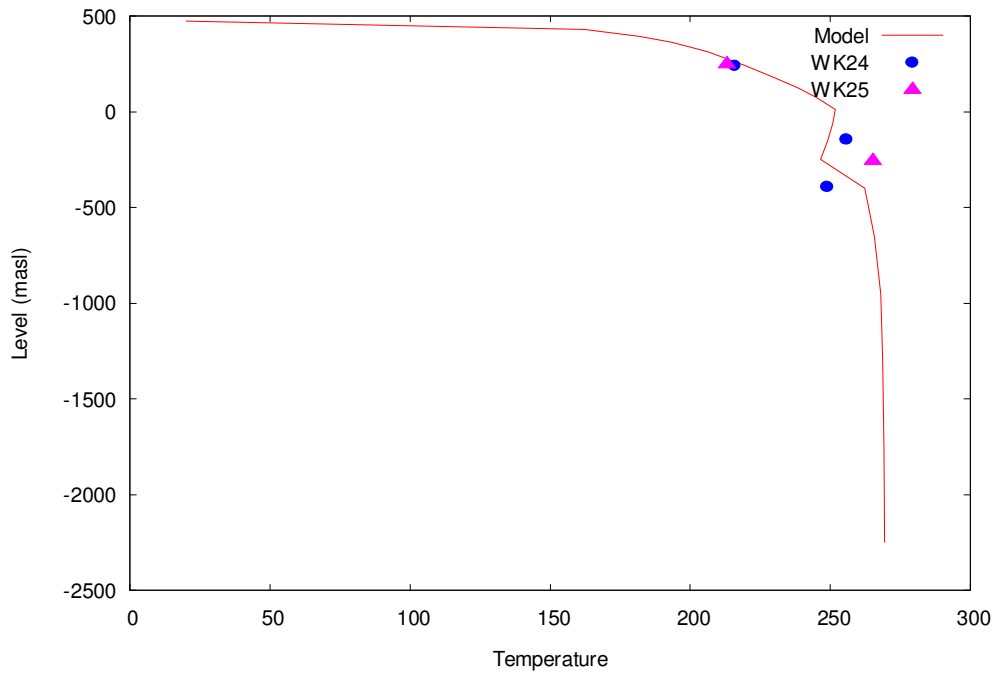


Figure 6: Natural state temperature profile with depth in the Western Borefield.

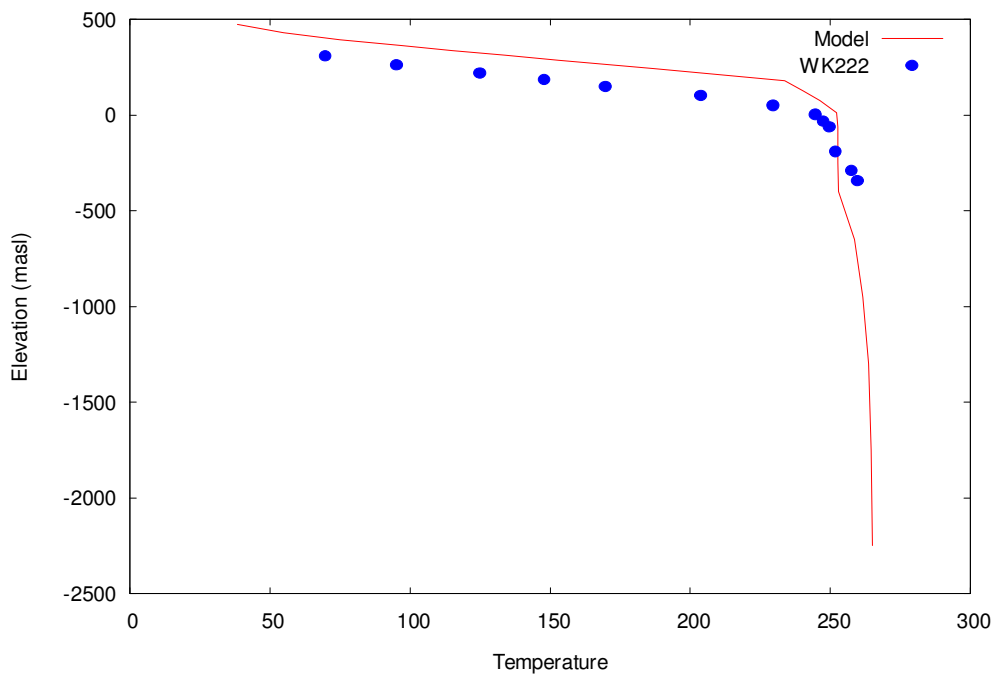


Figure 7: Natural state temperature profile with depth at Te Mihi.

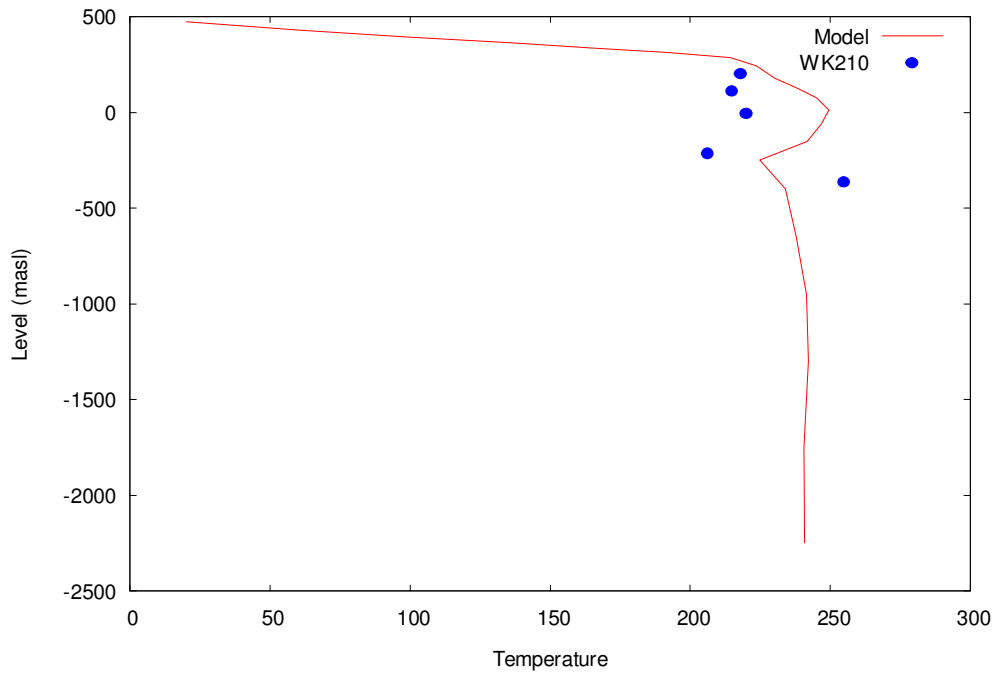


Figure 8: Natural state temperature profile with depth beneath the Low Pressure Steam Zone.

- 5.4 The model temperature contours at -400 m.a.s.l. are shown in Figure 9, and exhibit the temperature behaviour that is known to exist at Wairakei. The temperatures are a little cooler in the southern part of the field.
- 5.5 All the model temperatures compare favourably with actual measurements from the field.

Natural State Surface Heat Flows

- 5.6 Another important aspect of the natural state is the surface heat flow across the field. The measured and modelled results are:

Area	Measured	Model
Wairakei	430 ± 100 MW	522 MW
Karapiti	44 ± 40 MW	115 MW
Tauhara	100 ± 20 MW	92 MW

- 5.7 Note that there is considerable uncertainty in the measured natural state heat flows that affects all models. However the model results presented here give acceptable agreement with the measured flows.

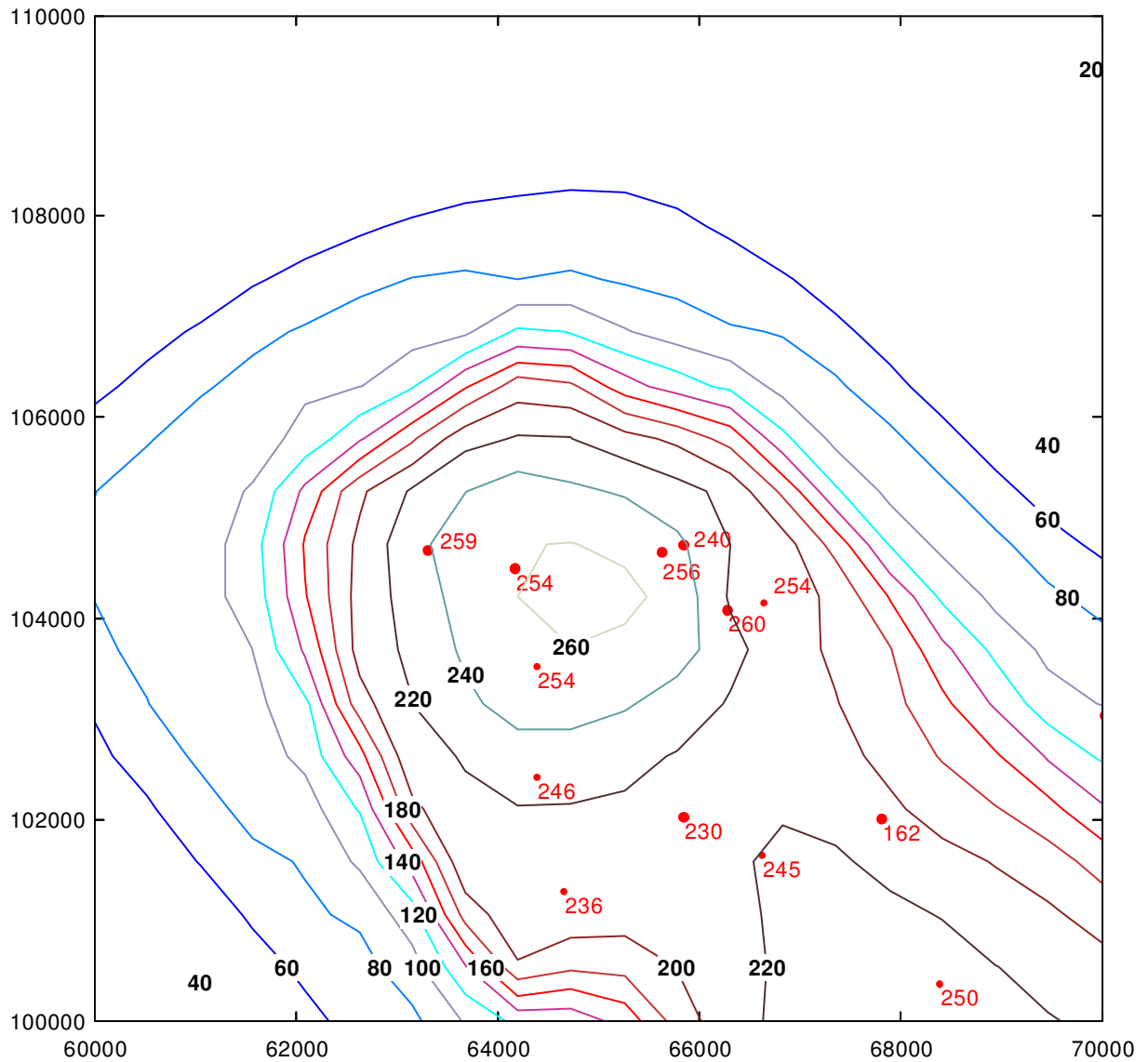


Figure 9: Natural state temperatures at -400 m.a.s.l. The red points and circles show temperature measurements, and the lines are model temperature contours.

Comments

5.8 In addition to the temperatures and heat flows, other features of the natural state model that agree, or are consistent, with observations are:

- The reservoir is liquid dominated.
- A small amount of steam is present with steam saturations less than 0.14.
- There is fluid at boiling point in some areas.

5.9 The model gives good agreement with the observed natural state in the Wairakei region. The agreement at Tauhara is not as good, but I consider it to be acceptable for the requirements of the model.

History Matching

- 5.10 After matching measurements from the natural state, the next stage of the model verification is to compare recorded changes in the geothermal reservoir with model results. To do this we run the model past the natural state, which we take as the state in 1952, and add the production history shown in Figure 5. In addition to the production for Wairakei Station we have included:
- Reinjection of 40,000 tonnes/day of 130°C water in the southeast in the vicinity of WK308 from 1997.
 - Production for Poihipi Station. This was taken to be 4,800 tonnes/day from the Low Pressure Steam Zone with 1,800 tonnes/day of condensate reinjected in WK680 commencing in 1997.

Deep Pressure Response

- 5.11 One of the most notable changes that occurred in the reservoir was the pressure response to production. The deep liquid pressures initially declined by 3 bars/year, but this decline had almost ceased by 1980. The pressure drop from the natural state to the mid 1980s was about 25 bars. Further, the pressure drawdown spread uniformly and rapidly across the Wairakei field.
- 5.12 In Figure 10 the model pressures in the Western Borefield are compared with measured pressures at –150 m.a.s.l. This shows good agreement between the model and measurements. Good agreement is also seen with deep pressures at Te Mihi and below the LPSZ in Figure 11 and Figure 12.
- 5.13 As mentioned, the pressure drawdown spread uniformly across the field, and also affected Tauhara. Figure 13 shows the model pressure drawdown below Tauhara and gives good agreement with the observed drawdown.
- 5.14 Overall the model gives good agreement with the observed deep pressure response across the field.

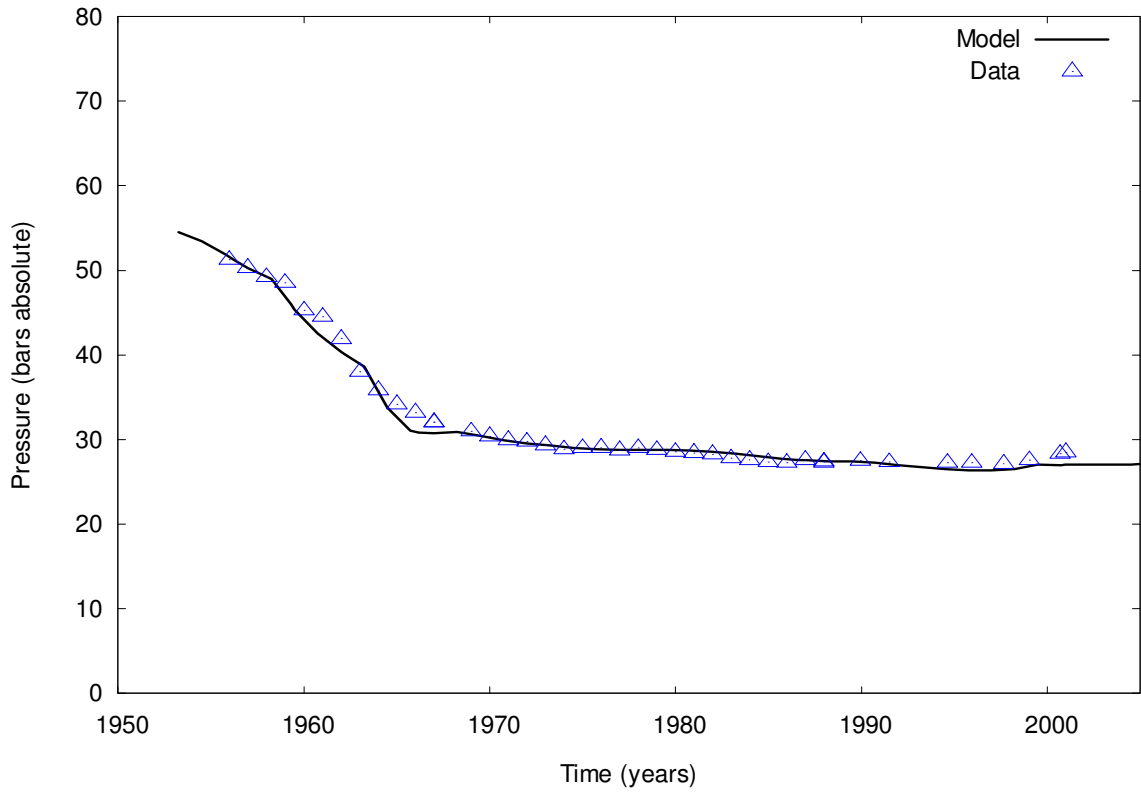


Figure 10: Deep pressure response to production at -150 m.a.s.l. underneath the Western Borefield.

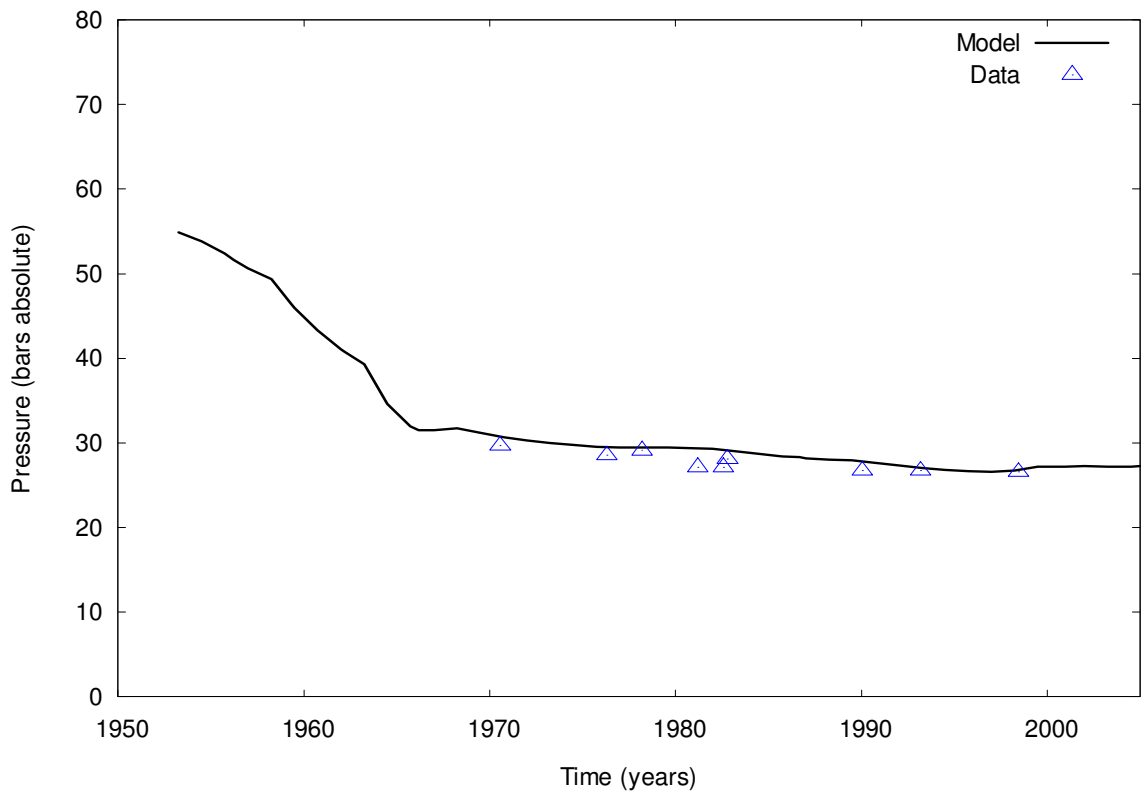


Figure 11: Deep pressure response to production at -150 m.a.s.l. underneath Te Mihi.

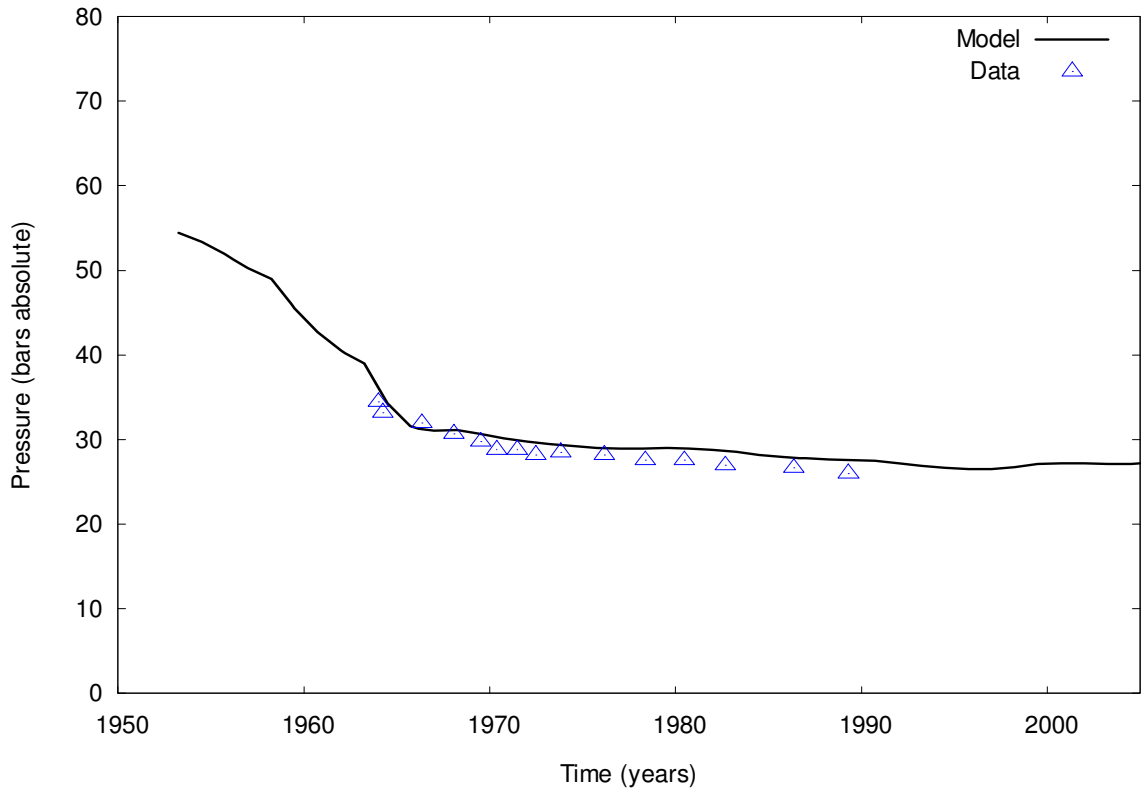


Figure 12: Deep pressure response to production at -150 m.a.s.l. underneath the LPSZ.

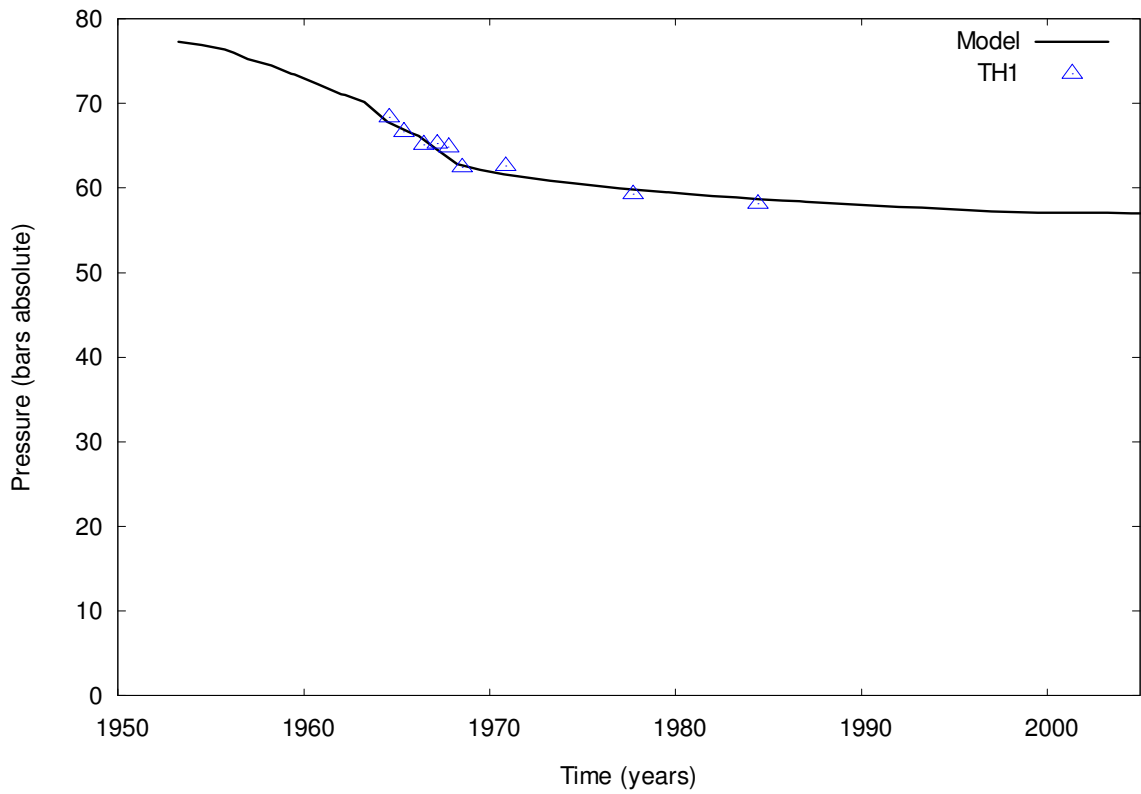


Figure 13: Deep pressure response to production at -400 m.a.s.l. at Tauhara

Steam Zone Pressure Response

- 5.15 In addition to the deep pressures, the pressure response of the steam zones has been measured. These steam zones formed as the result of the extensive boiling and drainage that occurred as the deep pressure reduced. Two steam zones have been identified – a high pressure one in the Te Mihi region; and a low pressure one in the southwest. The high pressure steam zone had a pressure in 1960 of 36 bars, and in the low pressure steam zone that pressure was 24 bars. The pressure in both zones fell by about 12 bars from 1960 to 1990.
- 5.16 In the model, a large steam dominated region formed between the southwest and Te Mihi – see Figure 16. Model steam zone pressures are shown in Figure 14 and Figure 15. The pressures in the LPSZ give acceptable agreement with the data, but the Te Mihi pressures are too low. However the model does show the correct changes in steam pressures that result from Wairakei production, so it can be used to predict changes in the future.

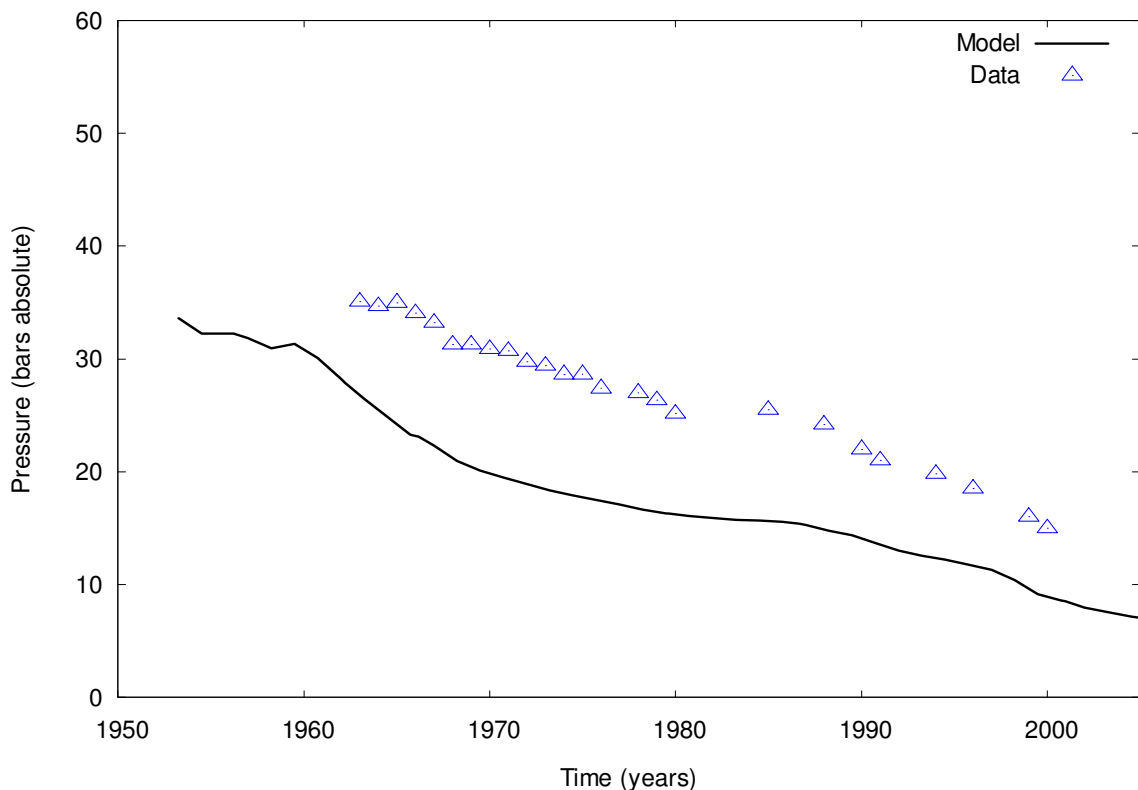


Figure 14: Model steam zone pressure response at Te Mihi

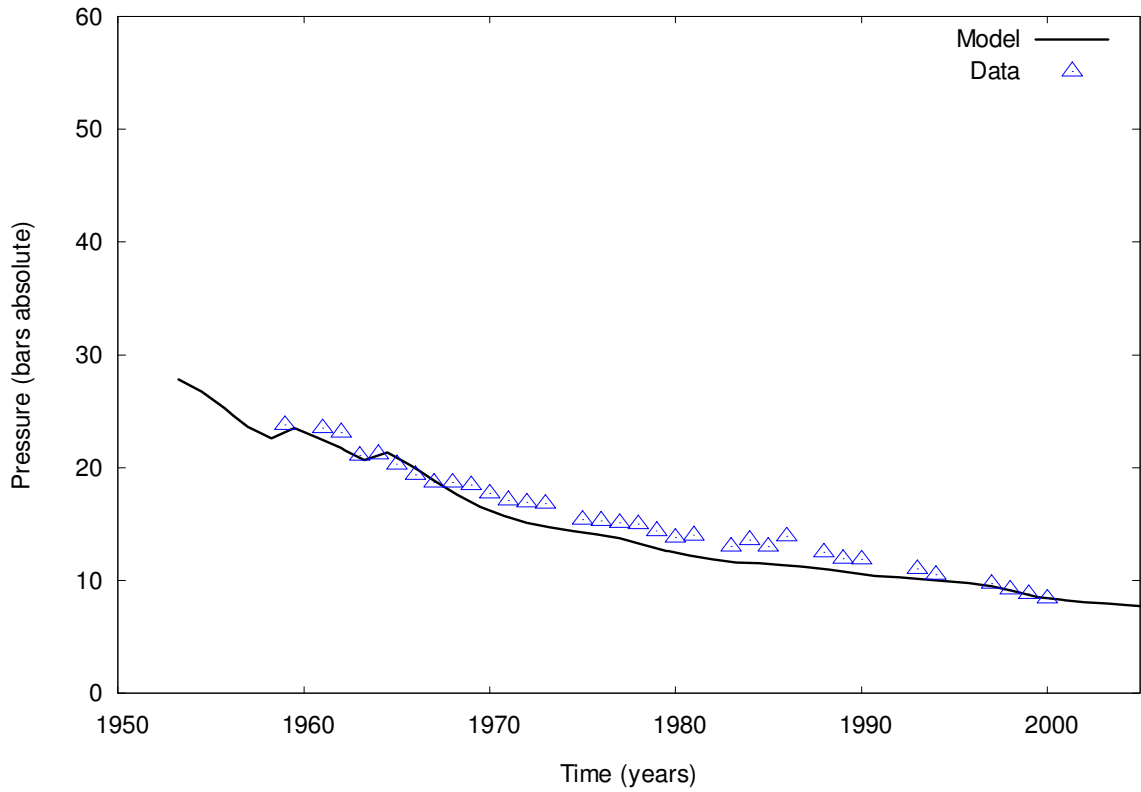


Figure 15: Model steam zone pressure response in the LPSZ.

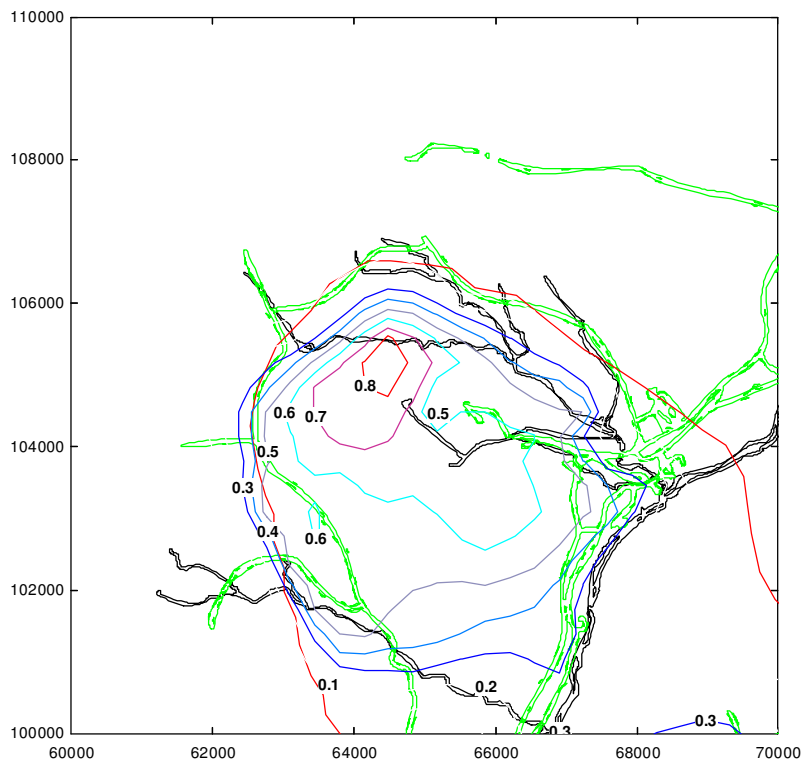


Figure 16: Vapour saturation contours at 125 m.a.s.l. in the year 2000. The numbers represent the volume fraction of steam present, e.g. a vapour saturation of 0.5 means that half of the fluid is steam.

Surface Heat Flows

- 5.17 Modelling the changes in surface heat flows has been difficult in all modelling to date – even Contact’s recent models have not managed to match all the changes that were observed. The major problem is that the heat flow in the Karapiti region underwent such a dramatic change from 40 MW in the natural state to 400 MW in 1965 and has remained essentially constant at 200 MW since 1979.
- 5.18 My model also has difficulty with reproducing the magnitude of the changes observed at Karapiti. The modelled total heat flow and Karapiti heat flow are shown in Figure 17. The changes in the model total heat flow are consistent with observed values – increasing from 400 MW in the natural state, to about 1050 MW in the mid 1960s, and declining to 450 MW in 1976. But the model Karapiti heat flow does not manage to reproduce the peak of 400 MW in the mid 1960s, and instead the model gives a peak of about 235 MW in 1959. However the model shows similar trends to the data with a large increase in the 1960s and a slow decline since 1980.

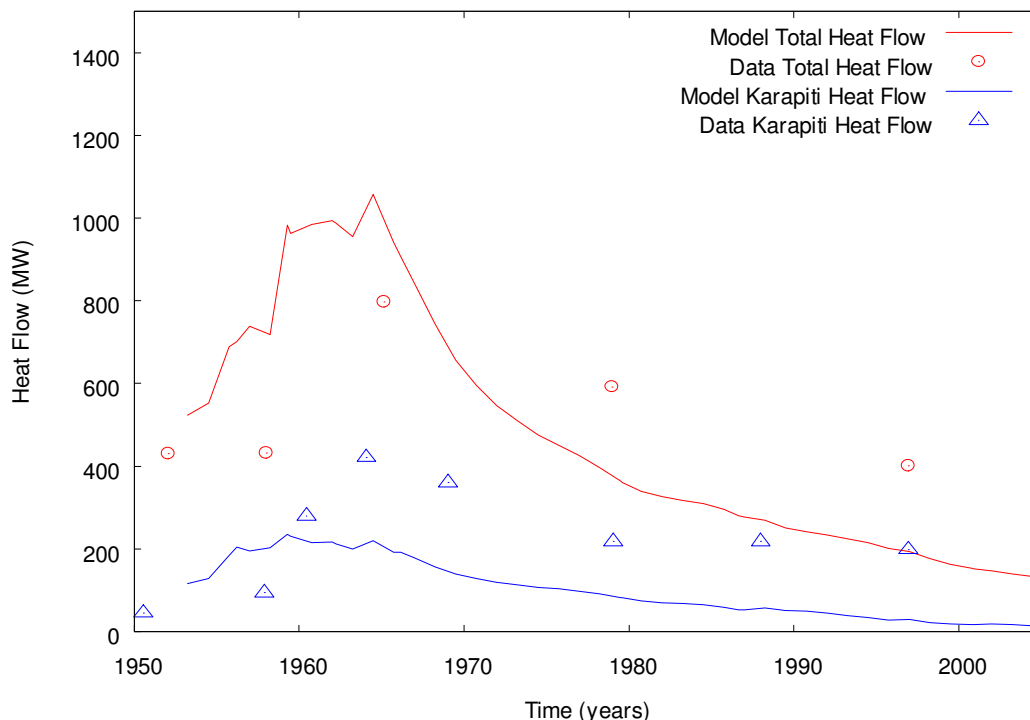


Figure 17: Heat flow changes due to production. Comparison of model and measured heat flows at Karapiti and the total heat flow from Wairakei

Production Enthalpy

5.19 The model production enthalpy is shown in Figure 18, and compares reasonably well with the measured enthalpies. The enthalpy does not show the correct trends in the 1990s, but it is likely that this is the result of a lack of detailed data available to me on production rates after the mid-1980s.

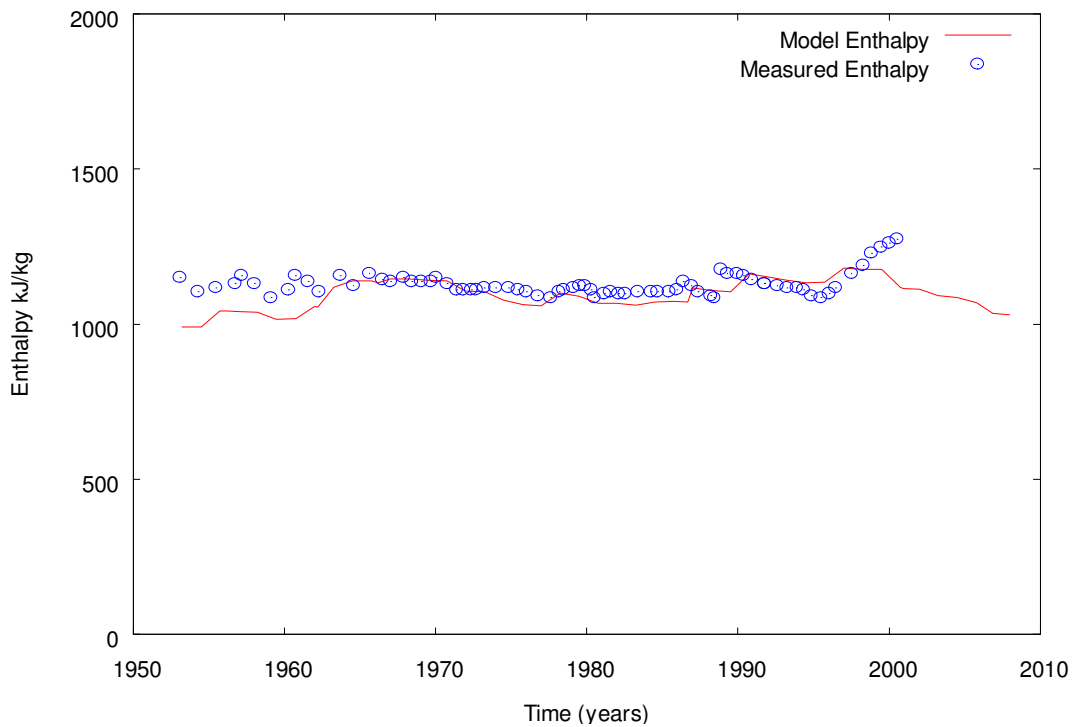


Figure 18: Modelled total production enthalpy at Wairakei.

Comments

5.20 Apart from the flow to Karapiti, the model gives a good match to the changes that have taken place in the field since production began. Pressure drops of the right size are predicted in the deep liquid and steam zones in different regions of the field. Boiling occurs over a significant volume of the reservoir, producing steam zones and an increased surface heatflow. The Karapiti results show the correct trends but the magnitude of the changes is not large enough.

6. Future Scenario Modelling

6.1 Once a model has been developed, calibrated and verified against the natural state and the response to production, it can be used to predict the effects of future developments - both for planning purposes and to assess any possible impact. To

do this, a detailed description of production locations, depths and rates, and reinjection locations, depths and rates is required. This information is incorporated into the computer model and the response of the system for a certain number of years is simulated. From these simulations, predictions of pressures and temperatures throughout the system are available together with surface flows and any recharge flows into the system

6.2 The Wairakei/Tauhara model that I have developed has been used to examine the impact of Contact's application to reinject 95,000 tonnes/day into the Wairakei/-Tauhara system.

6.3 It has been difficult for Geotherm and its consultants to decide upon some realistic scenarios to consider. The issue is that Contact has not stated in the application where the 95,000 tonnes/day will actually be injected into the reservoir. The June 2007 report by Professor O'Sullivan for the Assessment of Environmental Effects gives one scenario for the distribution of the reinjected fluid. However, there are a large number of other possibilities that are consistent with Contact's application.

6.4 The purpose of this evidence is to consider the possible impact of Contact's application on Geotherm's future operations. To do this I have considered the following three scenarios:

- **Scenario 1:** The existing environment baseline
- **Scenario 2:** Professor O'Sullivan's TM2 application scenario
- **Scenario 3:** Injecting most of the 95,000 tonnes per day into the two injection areas nearest the Geotherm property identified in Professor O'Sullivan's report. Since the Contact application does not specify injection rates in different areas, it was felt necessary to consider the impact of a scenario where most of the reinjection takes place in the reinjection areas nearest to the Geotherm property specified in Professor O'Sullivan's TM2 scenario

Scenario Details

6.5 Details of Contact's production and reinjection were taken from O'Sullivan's 2007 report. In all the scenarios Contact's production is maintained at the maximum consented levels. These levels are:

- Total production for the Wairakei/Te Mihi and Poihipi power stations of 211,000 tonnes/day from 1/7/2007 to 31/12/2011, 215,000 tonnes/day from 1/1/2012 to 30/6/2013 and 245,000 tonnes/day from 1/7/2013.
- Tauhara production begins in 2007 at 6,500 tonnes per day increasing to 20,000 tonnes/day at the beginning of 2009

6.6 Contact's reinjection varies in the three scenarios. ReInjection amounts for Scenarios 1 and 2 follow the respective scenarios TM1 and TM2 of O'Sullivan, 2007. Contact's current and future reinjection areas are shown in Figure 19, and follow the naming scheme used in O'Sullivan's report. In all scenarios, there is injection of 5,200 tonnes/day from 2007 to 2009 and then 16,600 tonnes/day after 2009 from the Tauhara project.

- **Scenario 1:** Separated geothermal water is injected infield into Area 5. The rates are: 60,000 tonnes/day from 2007 to 2009; 85,000 tonnes/day from 2009 to 2010; 105,000 tonnes/day from 2010 to 2013; 120,000 tonnes/day from 2013 to 2036; and 130,000 tonnes/day after 2036. These rates are shown in Figure 20.
- **Scenario 2:** Separated geothermal water is injected infield into Areas 1, 2, 3, 4 and 5 and condensate into Areas X and Y. The amounts of total injection are: 60,000 tonnes/day from 2007 to 2009; 85,000 tonnes/day from 2009 to 2010; 105,000 tonnes/day from 2010 to 2013; 165,000 tonnes/day from 2013 to 2015; a rate varying between 160,000 and 173,000 tonnes/day from 2015 to 2055. The rates used in the model are shown in Figure 21
- **Scenario 3:** In this scenario, 79,000 tonnes/day is injected into Areas 1 and 2. This includes up to 25,000 tonnes/day of condensate. The reason that this scenario does not consider injection of the full 95,000 tonnes/day into Areas 1 and 2 is that Contact has stated a goal of injecting in the Tauhara area to provide pressure support and this was included in the scenario. The totals for the various regions are shown in Figure 22.

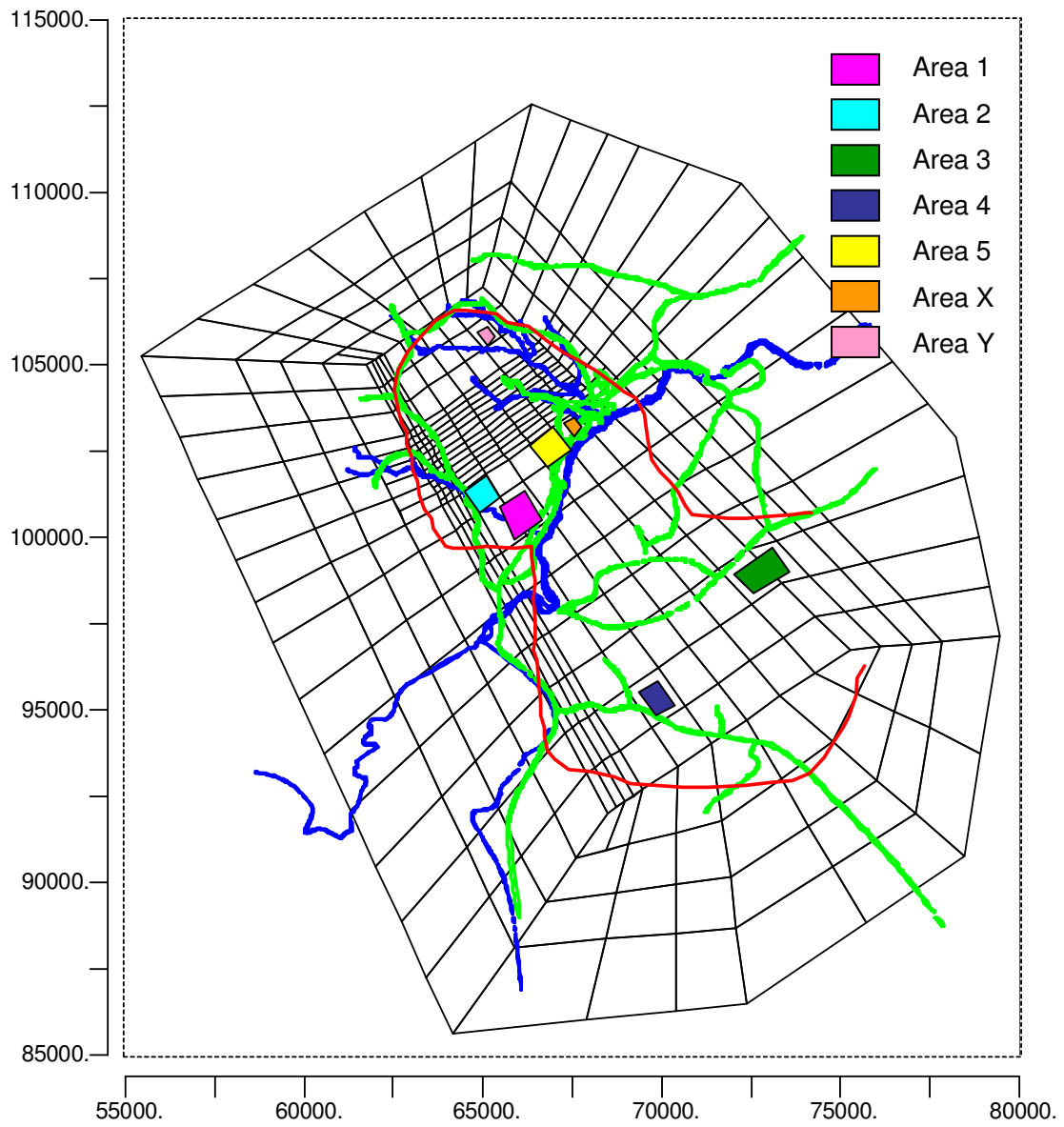


Figure 19: Locations of Contact injection areas 1, 2, 5, X and Y. The naming scheme follows O’Sullivan’s report.

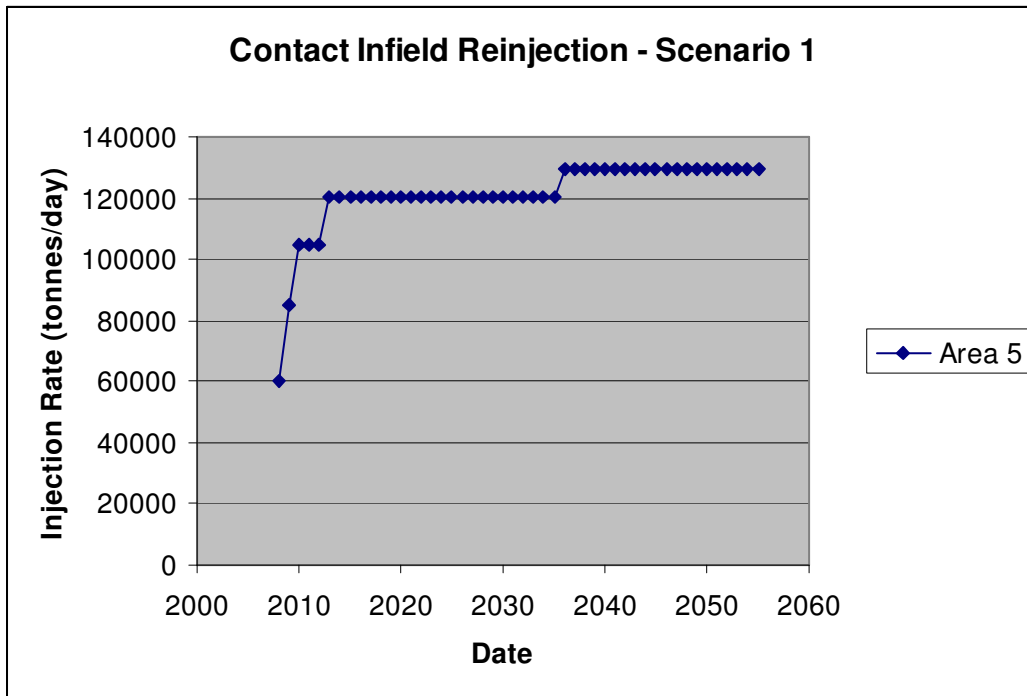


Figure 20: Injection rates used in the model for Scenario 1

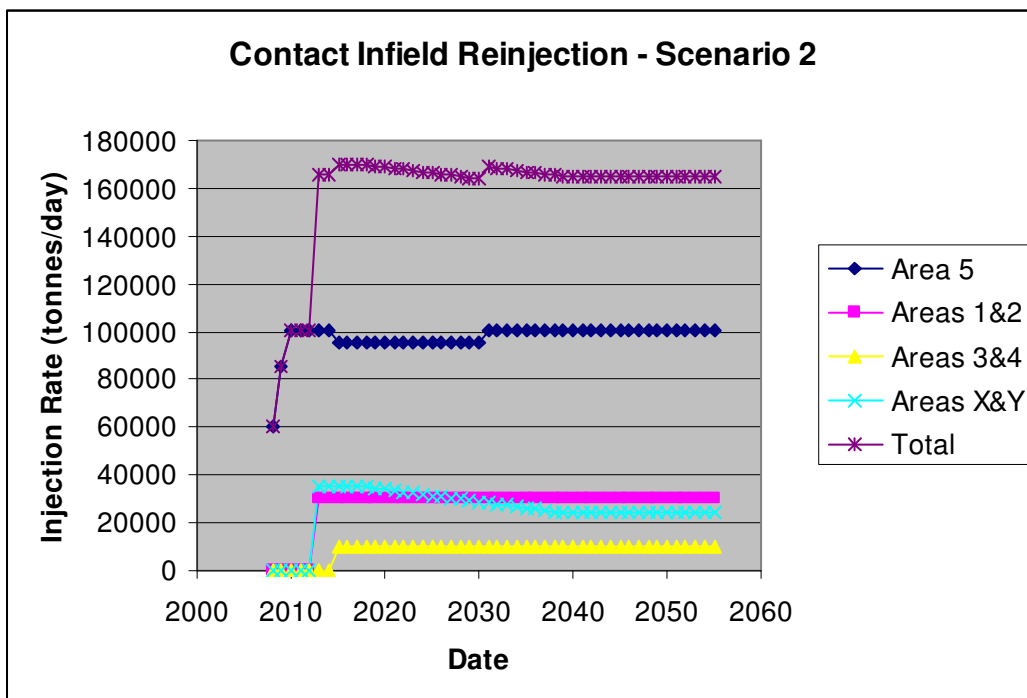


Figure 21: Injection rates used in the model for Scenario 2

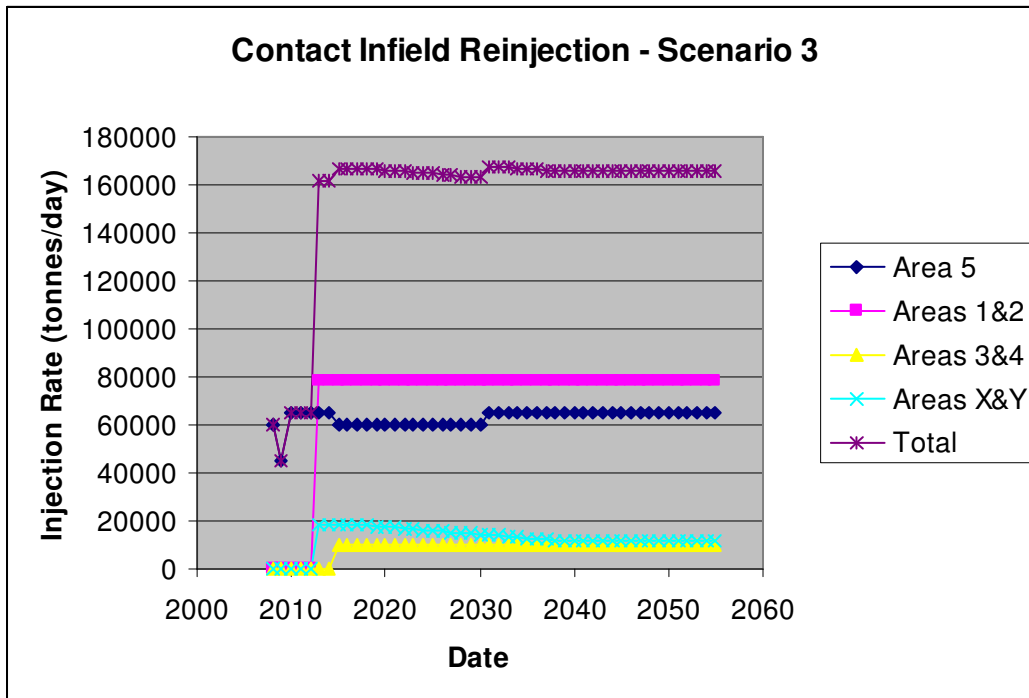


Figure 22: Injection rates used in the model for Scenario 3

Scenario Results

- 6.7 Production and reinjection was simulated through to 2055. Even though the existing consents for Contact and Geotherm expire in 2026, the model was run to 2055 to assess the impact if all the consents were renewed.
- 6.8 Geotherm production was assessed by using wells on deliverability. As conditions change in the reservoir, the model calculates the production rates from the Geotherm wells. In particular as reservoir pressures decrease (increase), well production rates will decrease (increase).
- 6.9 The results for Scenarios 2 and 3 were compared to the baseline Scenario 1 to assess the impact on Geotherm. These results are summarised in Figure 23 to Figure 25.

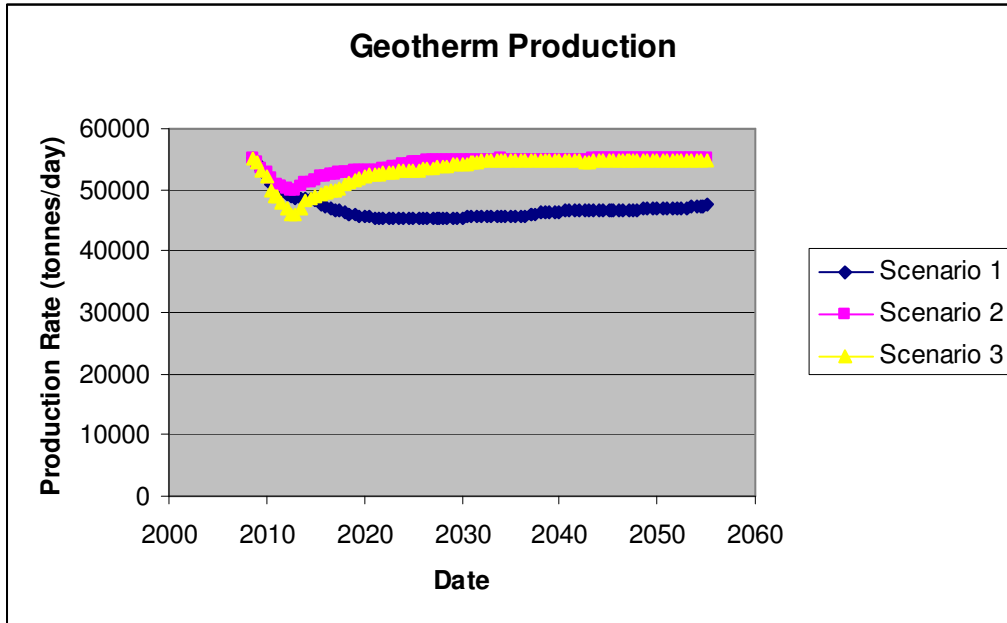


Figure 23: Comparison of Geotherm mass production rates for the three scenarios.

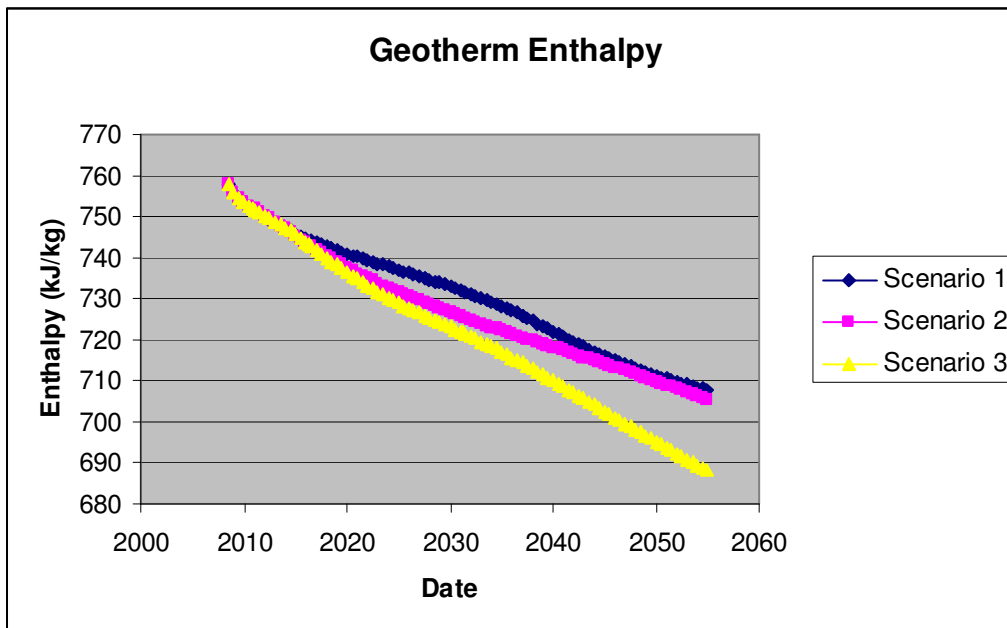


Figure 24: Comparison of Geotherm production enthalpy for the three scenarios.

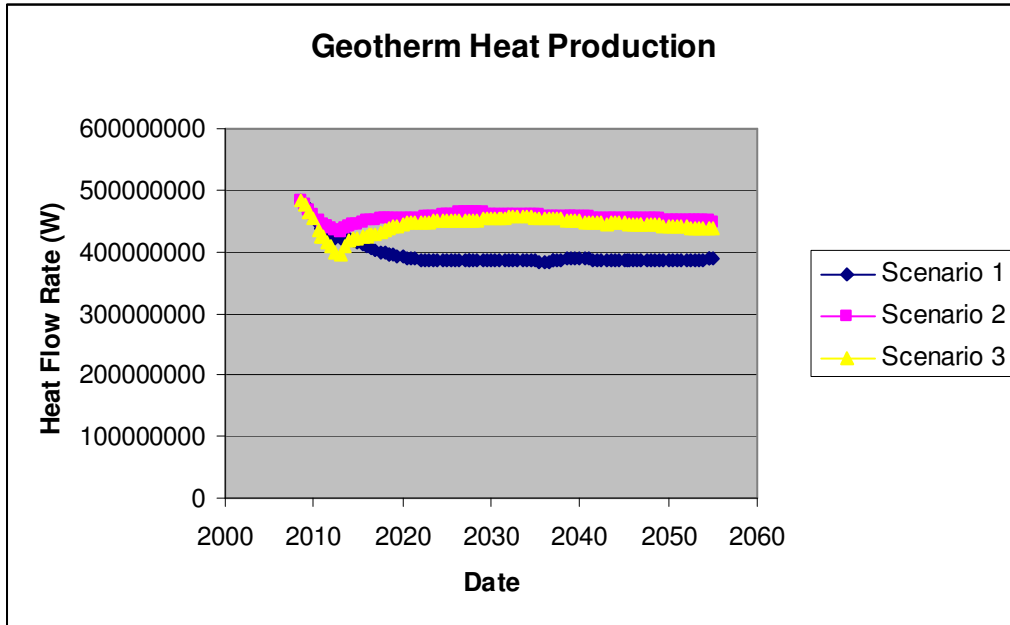


Figure 25: Comparison of Geotherm total heat production rates for the three scenarios.

Discussion

6.10 The results show that Contact’s reinjection increases Geotherm’s mass production, but has a negative impact on enthalpy. The reason for the increase in mass production is that the reinjected fluid helps to maintain the fluid pressures. Figure 26 shows the pressure changes in the Geotherm property at -250 m.a.s.l. for Scenario 1 (the existing environment). There it can be seen that pressures in the Geotherm property fall to around 26 bar. The reason for the pressure decline is that Contact extracts an extra 110,000 tonnes/day from the reservoir, but only reinjects an extra 75,000 tonnes/day. For wells at this depth, once the pressures fall to 20 bar then production falls off significantly. As the Geotherm pressures fall to around 26 bar in Scenario 1, Geotherm production rates decline and are sensitive to the further pressure changes. For Scenarios 2 and 3, the extra reinjected fluid results in higher pressures and hence higher Geotherm production rates.

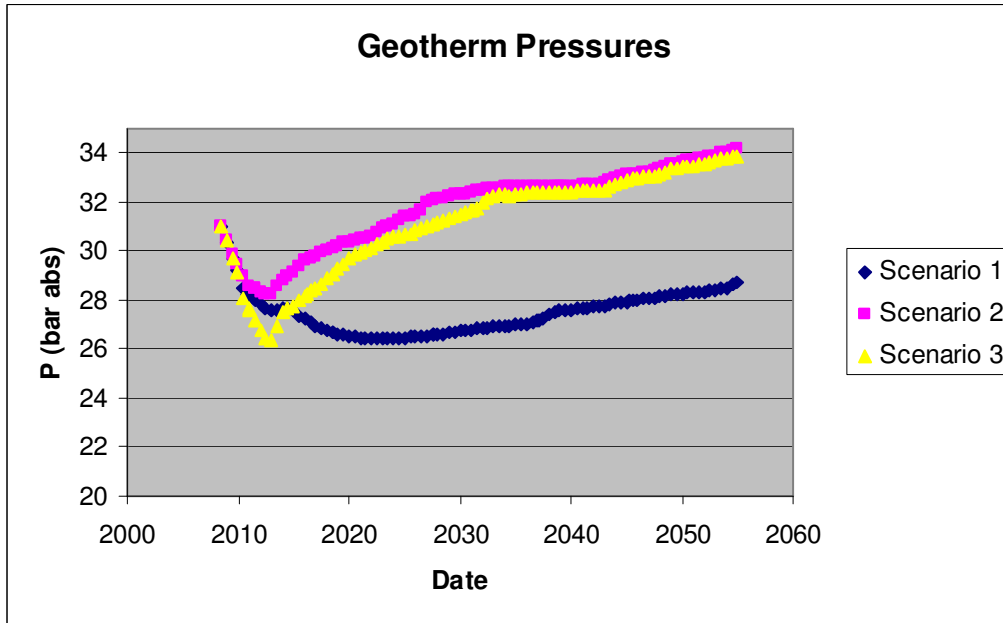


Figure 26: Geotherm pressures at -250 m.a.s.l. for Scenarios 1 (the existing environment), 2 and 3.

- 6.11 Although the effect of further reinjection is to increase reservoir pressures and consequently production rates, there is also a negative impact on the fluid temperature in the Geotherm wells. The fluid which is reinjected into Areas 1 and 2 is considerably colder than the surrounding fluid. For example in Scenario 3, the reinjected fluid is around 114°C. Over time, this colder fluid will cool the volume between the injection area and the Geotherm property. The effect of this cooling can be seen in Figure 24, where the production enthalpy is a measure of the temperature of the fluid produced from Geotherm’s wells. In both Scenarios 2 and 3 Geotherm’s production fluid is cooler compared to the baseline Scenario 1.
- 6.12 On the other hand, the impact of this cooling is offset by the increase in the amount of fluid produced in Scenarios 2 and 3. In these scenarios a greater amount of fluid is produced, but at colder temperatures. To illustrate this effect, Figure 25 shows the total heat flow rate produced from the Geotherm wells. There it can be seen that Scenario 3 has an initial negative impact, but after that both Scenarios 2 and 3 have a positive impact on the total heat flow rate produced by Geotherm. Whether the increase in total heat offsets the lower production enthalpy is unclear, as the exact details of the project will be decided by the new owners.
- 6.13 Overall, based on the assumed location of the proposed reinjection, Scenarios 2 and 3 suggest a marginally positive impact on Geotherm’s operations. However it is important to realise that these results are sensitive to the model details and

parameters. For example, in paragraph 31 of Professor O'Sullivan's evidence he states: *"For two scenarios, one with full infield injection (Scenario 12) and one with a small amount of infield injection (Scenario 11), my 2006 model showed production by Geotherm decreasing rapidly. For Scenario 12 full infield injection maintained production at around 10,000t/day up to 2014 and then it declined rapidly to zero. In other words, a greater level of infield injection was of marginal short term benefit, but hastened the decline of production in the medium term."* The point that he was making is that some of the model parameters were different in his 2006 model and that model gave slightly different results for a reinjection scenario.

- 6.14 A consequence of this sensitivity to the model parameters, is that in areas where there is less calibration data there is less certainty about the model results. Another important factor is the amount of model detail in the area of interest. These factors will be discussed in the following paragraphs.

Other Effects

- 6.15 It is important to realise that the models developed by Professor O'Sullivan and myself may not represent local effects of reinjection very well. The reason is that the model blocks can be very large and so cannot represent the details of local features such as large fractures or faults. For instance, the reinjection blocks in Professor O'Sullivan's model are approximately 800m by 1000m in horizontal extent, whereas large fractures may only be centimetres wide. If a large fracture connected the reinjection area to the Geotherm property, this would result in the flow of colder reinjected fluid directly along that fracture to the Geotherm wells. However the models are not able to represent this behaviour.
- 6.16 In addition it is my opinion that there is some uncertainty about the conditions that will be found in the region between ReInjection Areas 1 and 2 and the Geotherm Property. Geothermal systems are complex natural systems, and in areas where there are few wells and only small amounts of production or reinjection has taken place, the ability to accurately predict the future reservoir behaviour is limited. For this reason I believe that we can only use the results from the reservoir models as indicators of what might happen in the future, rather than certain predictions.
- 6.17 Avoiding direct returns of cold reinjection fluid is one of the challenges in designing a reinjection system. International best practice is to locate reinjection wells in a manner that provides a long and/or complex hydraulic connection between reinjection and production zones to allow the reinjected fluids to heat up to an acceptable temperature before reaching the production zone. It appears that

Contact has sited ReInjection Areas 1 and 2 to provide a long hydraulic connection with the production areas at Te Mihi. However the proximity of the reInjection areas 1 and 2 to the Geotherm property means that there is a chance that these direct returns will occur.

- 6.18 My opinion is that ReInjection Areas 1 and 2 may not provide a long enough hydraulic connection to Geotherm's production wells. Further, part of the reInjection area of Contact's application (Exhibit SGD2, Schedule One – Plan 124922-RC01) is directly adjacent to the Geotherm property. In my opinion, reInjection into that area could have a significant negative impact on Geotherm's production.
- 6.19 Given the potential for a negative impact on Geotherm's production and the uncertainty around the reservoir properties between ReInjection Areas 1 and 2 and the Geotherm property, it is my opinion that Contact should not be allowed to reInject within a certain distance of the Geotherm property to provide a buffer zone for Geotherm. A distance of 1.5km allows injection into ReInjection Area 1 and some of ReInjection Area 2 and reduces the likelihood of short hydraulic connections. Further, as the connection between these reInjection areas and the Geotherm property is untested, it would be prudent to consider some monitoring and mitigation conditions such as proposed by Richard Matthews in his evidence.
- 6.20 Given the size of the area to which Geotherm's resource consents apply, it cannot use a horizontal separation between its production and reInjection wells to provide a long hydraulic connection. Geotherm's proposed development looks to achieve long hydraulic connections vertically with its proposed reInjection wells drilled to a significantly greater depth than its proposed production wells.
- 6.21 In addition to a buffer zone for reInjection of separated geothermal water, I believe that a similar buffer zone should be required for condensate reInjection. The condensate buffer zone should be larger as the injected fluid is much colder than the separated geothermal water. In Professor O'Sullivan's model, the condensate injection areas X and Y are approximately 4km from the Geotherm property. In view of this, a buffer zone for condensate injection of 3km around the Geotherm property would seem reasonable.

7. Conclusions

- 7.1 A model of the Wairakei/Tauhara geothermal system has been developed. The model gives an acceptable match to the natural state and historical data.

- 7.2 The model was used to consider 3 scenarios relating to reinjection for the Te Mihi power station.
- 7.3 The model results that relate to Contact's application show that further injection increases Geotherm's mass production, but cools the produced fluid.
- 7.4 The scenarios considered are only two possibilities of where the reinjection could take place. The application allows reinjection to occur over a very large area.
- 7.5 Reservoir models with large blocks may not represent local behaviour such as direct flow along a fracture from a reinjection well to a production well.
- 7.6 International best practice is to separate production and reinjection by long hydraulic connections, which can be achieved by horizontal or vertical separations.
- 7.7 To counter uncertainty about possible direct flow of cooler fluid along fractures from the reinjection to production areas, it would be prudent to consider a buffer zone between the reinjection areas and the Geotherm production wells.
- 7.8 Monitoring and mitigation conditions are also required.

8. References

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Signature:



John G B Burnell

Date: 23 June 2008