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RESPONSE OF WAIRAKEI GEOTHERMAL RESERVOIR TO 40 YEARS OF PRODUCTION

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ABSTRACT

Wairakei field has passed 40 years of production with its most recent year generating more electricity than any previous year. Pressure drawdown of up to 25 bars affected production during the first decade, and lateral inflow of cool water down the original outflow zone of the reservoir became evident in part of the borefield during the subsequent two decades. This has been largely overcome by cementing up the wells with shallow downflows of cool water. Temperature and pressure are now almost stable in the western production borefield, although a gradual chloride dilution trend is still present. Production for the Eastern Borefield has been replaced by production from Te Mihi in the west of Wairakei field. Here temperatures are close to the original undisturbed temperatures of 255 – 260ºC at 1 km depth. Since the late 1980s, replacement production has been achieved by tapping the high pressure steam zone at 300 – 500 m depth in Te Mihi. In the long term, deeper production from this area will sustain the power plant. Injection rates are presently over 40% of the separated water, and this will increase to 50% over the next few years. Most injection will occur near the eastern boundary of the field. Reservoir models confirm that production and injection is sustainable to beyond the year 2050, although some cooling of the reservoir is anticipated.

1. INTRODUCTION

The Wairakei geothermal field was the first liquid dominated reservoir in the world to be developed. Generation at the Wairakei Power Station commenced in November 1958. The station was operated until 1987 by the New Zealand government when ownership was passed to a State-Owned Enterprise (SOE), the Electricity Corporation of New Zealand Ltd (ECNZ). In February 1996 ECNZ was split up into two SOEs. Contact Energy Ltd, the smaller of the two was split off as a separate SOE. Wairakei was included in Contact's portfolio of generators. The New Zealand government has recently privatized Contact Energy. Edison Mission Energy are now the cornerstone shareholder, with a 40% shareholding.

A second power station was commissioned by Mercury-Geotherm Ltd on the western boundary of Wairakei Field (Poihipi Power Station, Fig.1). This plant commenced continuous operation in May 1997 and operated at levels of up to about 46 MWe peak load initially. This had declined to 36 MWe by early 1999. Mercury-Geotherm has recently been placed into receivership and the plant is for sale.

With 40 years of production behind it, the steamfield continues to successfully supply the Wairakei Geothermal Power Station. The maximum annual electrical energy generation from the field was produced during the 1998 calendar year (1354 GWh, Fig.2).

The Wairakei field has been sub-divided into a number of sectors for convenience and these are shown in Fig. 1, together with the well locations and the resistivity boundary zone. The natural state and characteristics of the permeability have been described previously (ECNZ, 1992; Clotworthy, 1998).

2. NATURAL STATE OF THE RESERVOIR

A contiguous area of low resistivity caused by geothermal conditions at 500 – 1000 m depth indicates that the Wairakei field covers an area of about 25 km^2. Before development, the Wairakei geothermal reservoir was a liquid-dominated system with a base temperature indicated by chemistry and physical measurements of about 260°C. The conceptual model of the field is that of deep hot fluid flowing upward into the reservoir in the west, then moving sub-horizontally into the Western and Eastern Borefields. The main surface outflow was at Geyser Valley near the northeastern boundary of the field but extensive areas of steaming ground existed from the northwest to the southern boundaries of the field. The total surface heat flow prior to development was estimated to be 400 MW_{th} (Allis, 1981).

Wairakei Field is characterised by high horizontal permeability. Almost all of the production comes from pumiceous breccias between 300 and 900 m depth or –500 to +100m above sea level (i.e. mostly in the Waiora Formation; Wood, 1994). Major northeast-trending faults cutting through the field also play an important role in directing fluid towards the northeast boundary. In the southwest of the field high permeability also exists in a rhyolite dome (Karapiti rhyolite). This has influenced southwards flow of steam towards the surface in the Karapiti area (Fig. 1).

3. PRODUCTION HISTORY

The earliest production was mostly from the Eastern and Western borefields, but with time, production has shifted westwards. The total field production history is plotted in Figure 3. The production history is divided into the main borefield (Eastern plus Western Borefields) and the Te Mihi area. Plots of mass flow and enthalpy for total field and Te Mihi area are shown in Figure 3. Since the late 1980's make-up wells have been drilled to keep the power station fully loaded. Mass withdrawal has been relatively constant for the last 20 years, but has increased again in 1999. Currently (July 1999) there are 53 wells producing into the steam collection system, with most of the production coming from the Western Borefield and Te Mihi areas. Two new dry steam wells are ready for connection.

Any interpretation of field enthalpy changes with time needs to be made with care. Gradual changes in steam collection hardware have changed the accuracy of total flow measurement. The change in data processing to metric data in 1978 produced an apparent step change in discharge rates and additional discharge rate variation.

4. RESERVOIR RESPONSE TO PRODUCTION

4.1 Liquid Pressures

As a result of field development, deep liquid pressures have been reduced by 25 bar below the original pre-development values, as shown in Fig. 4. Pressures here are referred to -152 masl (metres above sea level; datum is -500 ft asl, or approximately 550 m depth), corresponding to the base of the Waiora Formation in the Western Borefield. Deep liquid pressure declined slowly after 1972 and stabilised after 1985.

The pressure response to fluid withdrawal has been almost uniform across the entire Wairakei reservoir with relatively sharp iso-pressure lines close to the resistivity boundaries. A reference line was plotted to represent the best match to the 1994-1998 vertical pressure profile found in the Western Borefield wells. Pressures measured in other wells were then compared with this profile to construct an isobar map of the reservoir for years 1994-98, plotted in Figure 5.

Where wells have been drilled outside the Wairakei resistivity boundary zone, pressures have shown a small or zero response to production. Thus while the resistivity boundary in general is also a hydrological boundary, there have to be at least local zones of lateral fluid flow across the boundary from the cold surrounding formations into the hot reservoir. The stabilisation of pressure despite constant mass production and declining chloride concentration in parts of the borefield both indicate increased inflow of both cool and hot water due to pressure decreases caused by production.

4.2 Vapour Pressures

In the natural state, the upper parts of the reservoir almost everywhere contained a liquid-dominated two-phase zone. As much of the upper reservoir was already at or close to boiling point, production caused extensive boiling throughout the reservoir above a level of about -200 masl and the development of a steam-dominated two-phase zone just below the Huka Falls Formation over much of the Field. Average vapor pressures measured in a selection of wells throughout the Field are plotted in Fig. 4 and the extent of the steam zones is plotted in Fig. 5.

At least two steam zones developed at Wairakei: a high pressure zone in Te Mihi area and the Western Borefield and a lower pressure zone in the southwest and Eastern Borefield. The natural decline in pressure of the steam zones led to the decision to tap the high pressure zone in Te Mihi for production with shallow wells. WK228 commenced production in March 1986 and six shallow steam wells have subsequently been drilled in Te Mihi. WK236 was drilled into the low pressure steam zone in 1995. The 18 - 20 bar steam pressure in Te Mihi steam zone and locally very high permeability at 100 – 200 masl elevation has resulted in highly productive wells being drilled in this part of the field during the last 10 years. In mid-1999 40% of Intermediate Pressure (5 bar gauge) steam is produced by dry steam wells.

The low pressure steam zone has been tapped by the Poihipi Power Station located on the western margin of the Wairakei field. Pressures in the southern steam zone are now about 8 bar g.

4.3 Reservoir Temperatures

Feedwater temperatures measured in permeable, liquid-fed wells are plotted in Fig. 6. In the Western Borefield for the period 1960-66, feed water temperatures declined in proportion to the pressure-temperature saturation curve from the natural state values of about 255°C as the deep liquid pressure declined. This was followed by a period of slow but steady decline at about 0.5°C per year, until 1980. Since that time the decline appears to have slowed for most wells.

Some cooling and chemical dilution has been a characteristic feature of shallow-cased wells at the northeastern end of the Western Borefield. The wells most affected by this cooling all have shallow production casing (above +100 masl, or 300 m depth) and the level of cooling occurs between +50 and +200 masl. This is within the upper part of the Waiora Formation. Temperatures measured in wells most affected by this cooling are also plotted in Fig. 6. This shows a consistent rate of cooling from 1960 through to 1990. Since 1990 most of these wells have been cemented up to stop internal flows into the deep reservoir and measurements are no longer possible. Where wells are cased deeper than 0 masl, there has been little cooling.

The Eastern Borefield wells have been diluted by cool inflows and this, combined with reinjection testing in the Eastern Borefield has now generally reduced temperatures in the +100 to -200 masl levels to less than 200°C.

In the western wells of the Te Mihi area, liquid temperatures have changed little from pre-development times. Shallow temperatures in this area have been declining as a result of steam zone formation and subsequent pressure reductions. Well WK235, which has a deep feed zone has shown no change in temperature (Fig. 6). Fig. 5 shows the approximate location of the 240°C temperature contour at –400 masl. At greater depths in this area the temperature is expected to be higher. There are no deep wells near the Western Borefield area that are accessible for temperature surveys below the depth of current production, to confirm the extent of the higher temperatures or the maximum temperatures in this area.

5. WELL PRODUCTIVITY

It is difficult to determine the decline in steam flows for the field because of the de-rating and other changes on surface plant to improve the efficiency of utilization of the steam produced. The bulk of the production has come from a group of 36 Western Borefield wells which are still in operation. Figure 7 plots the theoretical total steam flow available from these wells assuming a separation pressure of 5 bg. The individual well flows are based on allocation of flash plant flows to individual wells. The methods of measuring these flash plant flows have varied over the years. Nevertheless, it can be seen that there was an almost linear decline in available steam flow from 1964 to the early 1970s of almost 3% per year. Since then the decline rate has reduced and is now below 1% per year.

The output of these production wells has been predominantly affected by pressure drawdown and stabilization in the deep liquid feed zones in the Waiora Formation. The average enthalpy for these wells declined slowly after 1980 and has stabilized recently at 1020 kJ/kg (Clotworthy,1998).

6. RESERVOIR CHEMISTRY

The major change in liquid chemistry for Wairakei has been dilution by cooler dilute water. The trends in reservoir chloride levels for three different areas of the field are shown in Fig. 8 from Glover (1998). The Eastern Borefield was most affected and shows the greatest decrease in chloride concentration. The Western Borefield has shown a steady decline since 1960. The Te Mihi wells have shown little evidence of dilution.

The non-condensable gas levels were low initially (17.5 millimoles/100 moles of steam in deep fluid; Glover, 1998) and declined again after a brief rise during the period of maximum pressure drawdown and the formation of the shallow steam zone. The shallow steam production wells drilled in Te Mihi have higher gas contents (up to 1300 millimoles CO_2/100 moles steam) and so the gas flow into the power station has increased to about 0.6 wt% in the steam.

7. INJECTION

Investigations and injection testing began at Wairakei about 1978. Tracer tests, reinjection trials, geophysical investigations and the drilling of injection investigation wells were all undertaken. WK301 was drilled in 1984 near the Wairakei Power Station. This was followed with two nearby wells, WK302 and WK303, in 1989. WK302 confirmed permeability outside the field to the north-east. WK303 investigated shallow permeability in the mid-Huka formation near WK301. In June 1990, WK301 was deepened to explore the deeper reservoir to the east. It encountered permeability just below the original bottom hole and indicated high temperatures at depth (260ºC at 2 km).

Following this work, a series of injection wells was drilled during 1995. Two wells were drilled as highly deviated (70° from vertical) wells to the southeast, inside the field. Three wells were drilled to explore permeability outside the eastern field boundary. Two additional wells targeted the Karapiti Rhyolite to the southwest.

To date, up to five injection wells have been in service. A total of 18.9 Mt was injected between 1993-98. Short-term tracer tests have been conducted but no returns have been detected. A long-term tracer test is currently in progress.

8. FUTURE DEVELOPMENT

It is anticipated that the Wairakei field will continue to supply steam sufficient for the current level of generation for at least the next 40 years. Computer modelling conducted at the University of Auckland (O'Sullivan et al. 1998) has indicated that the current level of generation can be maintained until year 2050. The scenario that was modelled assumed that 60,000 tonne per day of separated water would be injected (60% of present separated water flow) as this is the level for which a legal consent has been granted. Future production wells were assumed to be drilled in the Te Mihi area where temperatures have not changed. Figure 9 shows the predicted future trends for temperatures and pressures in the deep production blocks of the reservoir. This shows that the reservoir can sustain this level of production into the foreseeable future. Field enthalpy is predicted to decline from over 1100 kJ/kg at present to about 1000 kJ/kg in 2050.

The most recent make-up production wells have mostly tapped the shallow steam zone at Te Mihi. Future production wells will target the deeper liquid aquifer in Te Mihi as shallow steam pressures decline. It is evident that there are large volumes of permeable rock which are hot and are potential future drilling target areas.

Future injection wells are proposed away from the existing wells to enable greater dispersion of injected water. It is anticipated that a significant proportion of the separated water will be injected outside the geothermal field. This has been a successful strategy for managing injection at the Ohaaki field.

In the past there has been one large power station at Wairakei field. There are currently two power stations. Management of multiple users on a single system is controlled by the Resource Management Act, which has an emphasis on sustaining the potential of natural resources to meet the reasonably foreseeable needs of future generation and avoiding, remedying or mitigating adverse environmental effects. The New Zealand government is currently promoting a policy of competition between electricity generators in order to reduce the price of electricity. Contact's Wairakei operation has demonstrated over the last 40 years that geothermal energy is a viable energy source for electricity generation. Wairakei is capable of sustaining production for many decades into the future. Wairakei will have an important role as a relatively clean source of power in the "new" New Zealand electricity environment.

ACKNOWLEDGMENT

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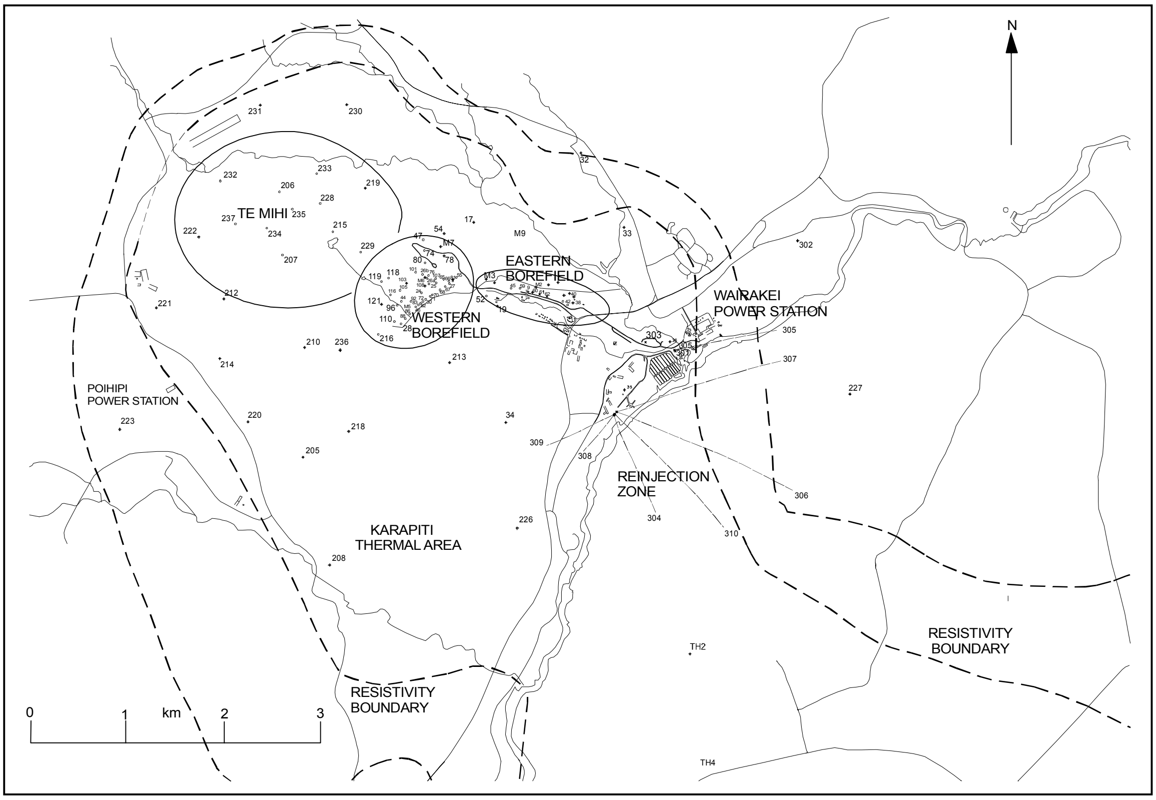

Figure 1 Wairakei Geothermal Field, showing well locations and resistivity boundary

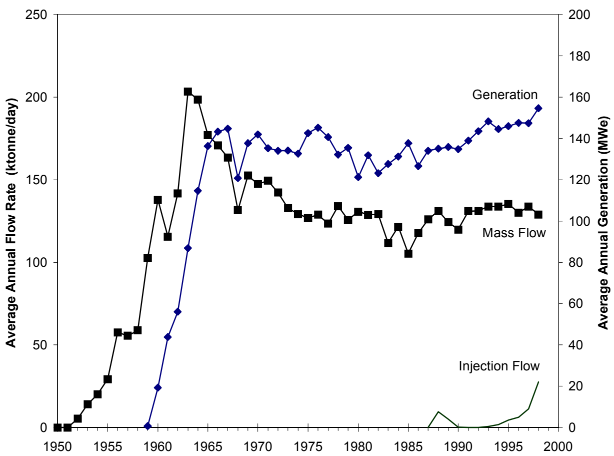

Figure 2. This figure shows the generation history of the Wairakei power plant, along with the average annual production and injection mass flows.

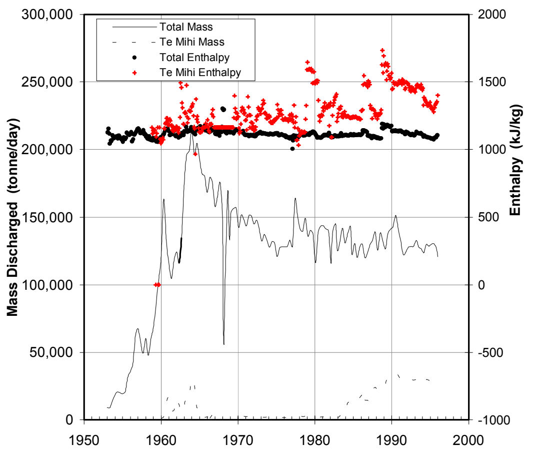

Figure 3. Trends for mass and enthalpy for the Wairakei field and the Te Mihi area

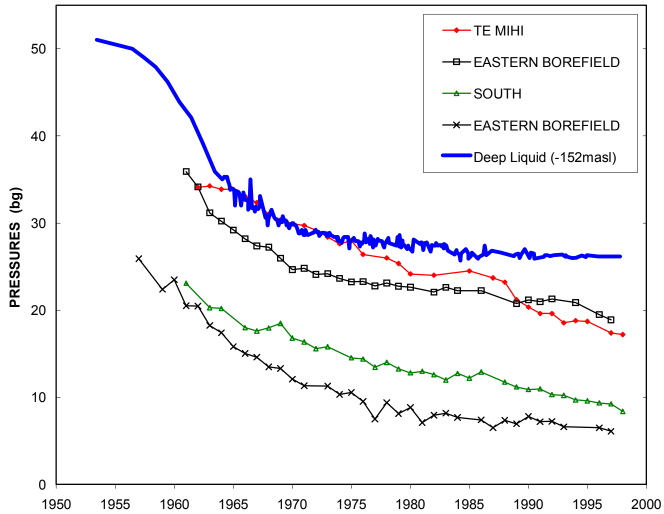

Figure 4. Graph shows the trend in pressure of the liquid reservoir at a datum approximately equivalent to 550 m depth (bold line), and the trends in steam-zone vapour pressure in different sectors of the field.

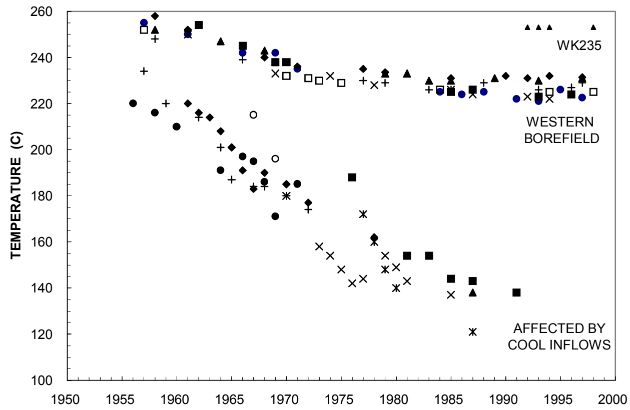

Figure 6. Trends in average temperature from liquid feedzones in Wairakei production areas.

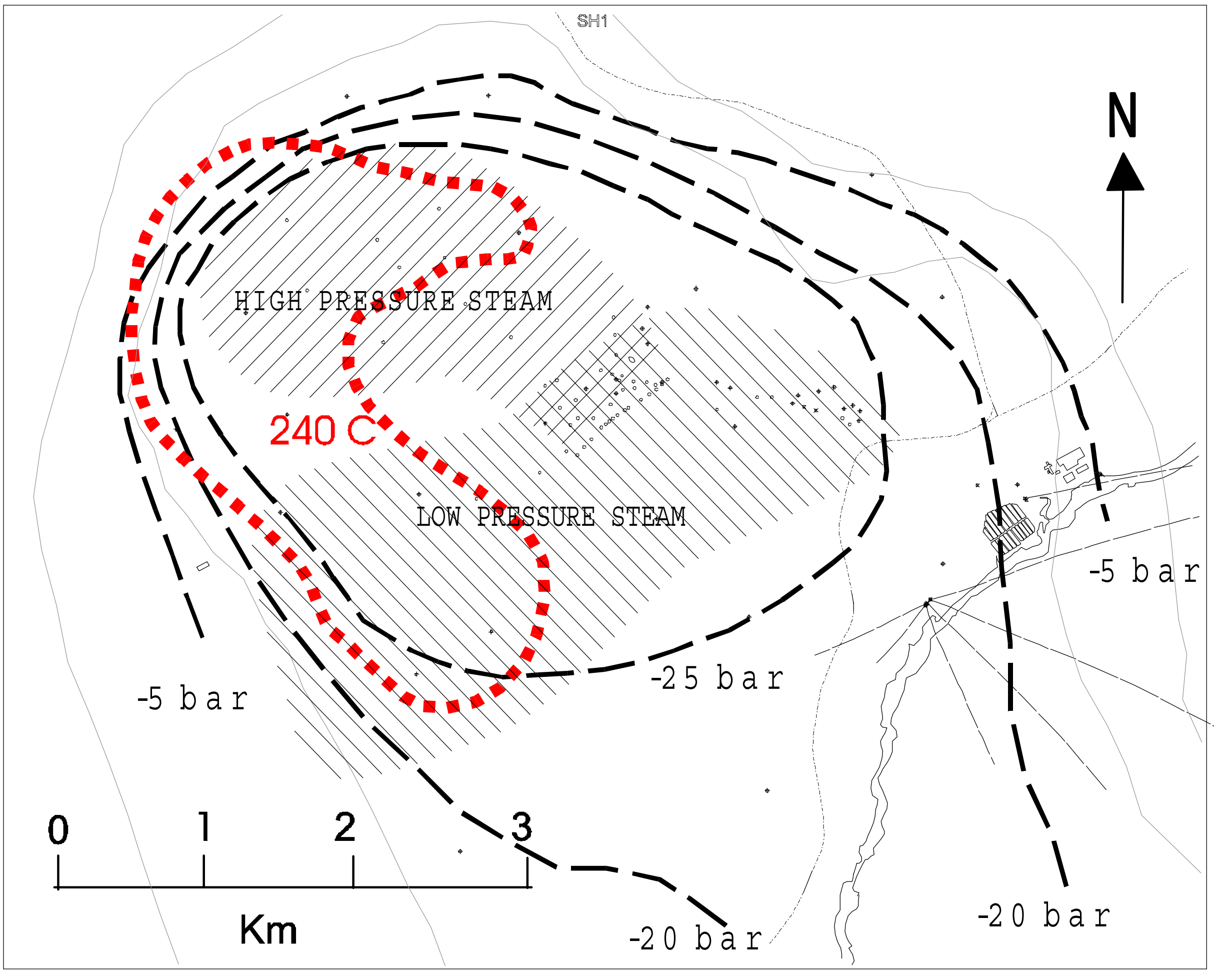

Figure 5. Compilation from the mid 1990s of the extent of pressure decline in the liquid reservoir, the known areas of highest temperature at about 800 m depth (> 240ºC at -400 m asl), and the locations of the steam zones which have formed as a result of the pressure decline.

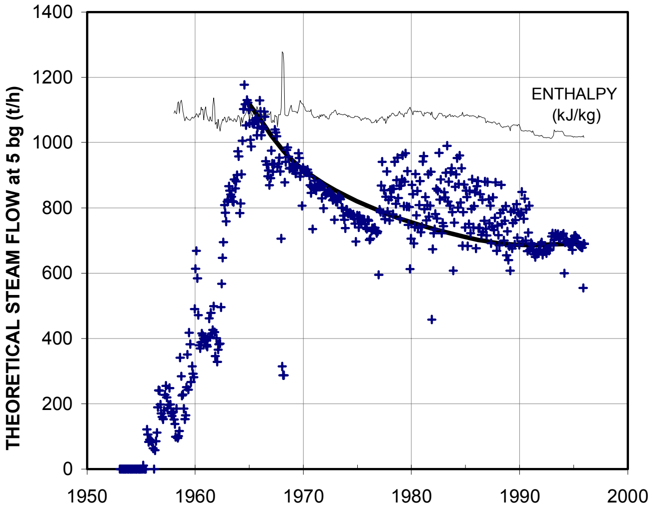

Figure 7. Theoretical steam flow at 5bg separation pressure for core group of 36 Western Borefield wells, which are still in operation, calculated from test enthalpies and flows allocated from measured flash plant flows. The average enthalpy of this group of wells is also shown.

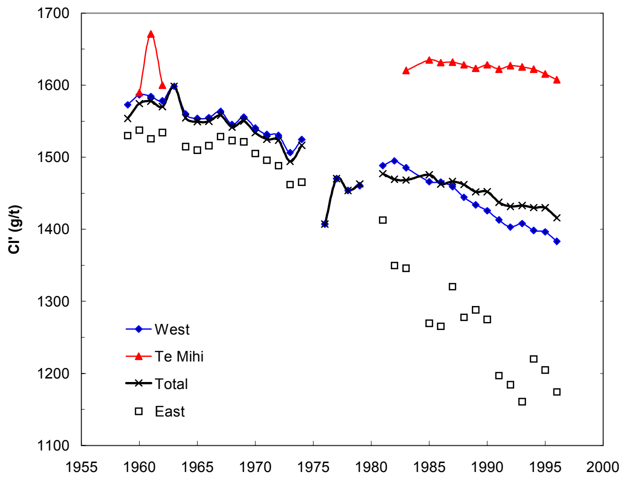

Figure 8. Trends in average corrected chloride concentrations from the Wairakei production areas (from Glover, 1998).

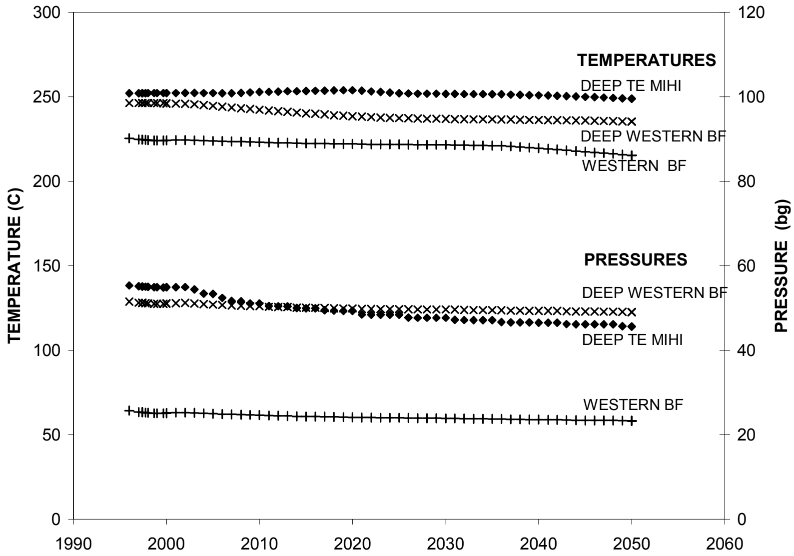

Figure 9. Model prediction of the future production trends at Wairakei assuming 60% of the production mass in injected, and make-up production wells are located in Te Mihi. The model is the same as that presented by O'Sullivan et al. (1998).