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Forty Years Sustained Production From the Wairakei-Tauhara System

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ABSTRACT

Wairakei field has passed 40 years of production with its most recent year generating more electricity that any previous year. Rapid 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 a problem in part of the borefield during the subsequent two decades. This problem 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 Production for the Eastern Borefield has been replaced by production from Te Mihi in the west of Wairakei field.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 – 250°C 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 30% of the total production mass, 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 this level of production and injection is sustainable to beyond the year 2050.

Introduction

The Wairakei geothermal field, part of the Wairakei-Tauhara geothermal system, was the first liquid dominated reservoir in the world to be developed. Generation commenced in November 1958. 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 1998 (1354 GWh). The natural state and characteristics of the permeability have been described previously (ECNZ, 1992; Clotworthy, 1998). The Wairakei-Tauhara system has been sub-divided into a number of sectors for convenience and these are shown in Figure 1, together with the well locations and the resistivity boundary zone. The extent of thermal activity and other geographic features are shown on Figure 2, overleaf.

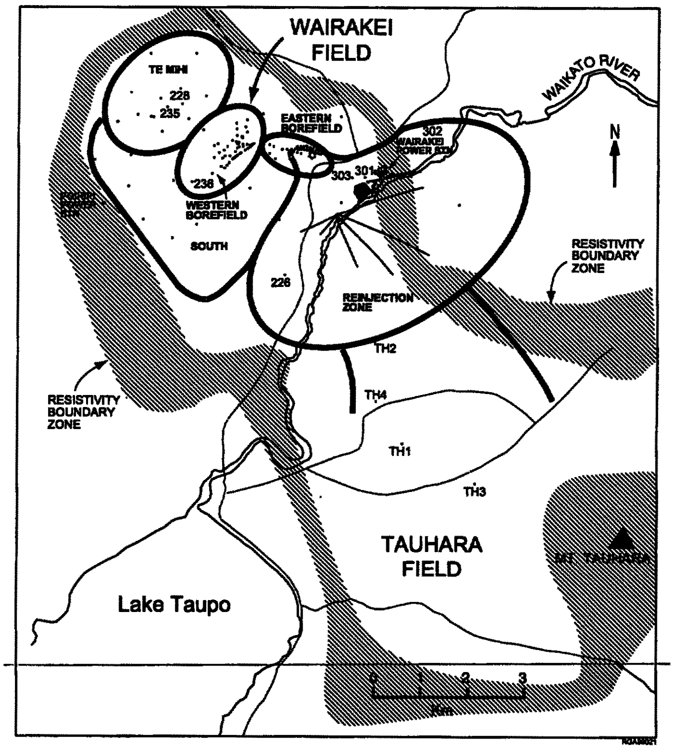

Figure 1. Major features of the Wairakei-Tauhara geothermal system referred to in the text. The resistivity boundary zone is an indication of the extent of geothermal conditions at 500 – 1000 m depth.

A contiguous area of low resistivity caused by geothermal conditions at 500 – 1000 m depth indicates that the Wairakei-Tauhara system could cover an area of the order of 50 km^2. Exploration wells drilled into northern Tauhara Field during the 1960s showed declining reservoir pressure due to production from Wairakei Field, confirming a permeable connection to at least the northern sector of Tauhara Field. The earliest production was mostly from the Eastern and Western borefields, but with time, production has shifted westwards. The field-wide production history is plotted in Figure 3a. Since the late 1980's

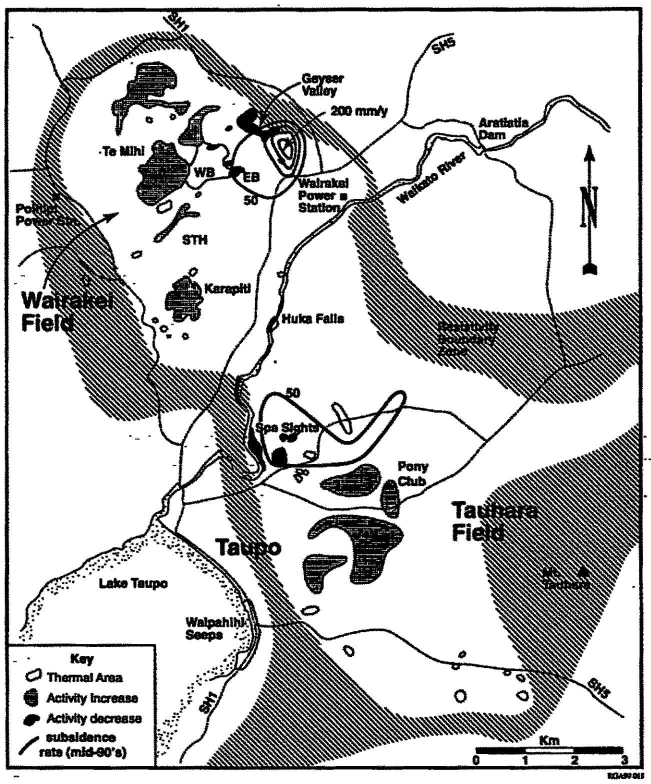

Figure 2. Distribution of thermal activity on the Wairakei-Tauhara system, with areas of significant change as a result of development highlighted.

make-up wells have been drilled to keep the power station fully loaded. Mass withdrawal has been relatively constant for the last 20 years. Currently there are 53 wells producing into the steam collection system, with most production coming from the Western Borefield and Te Mihi areas.

The Wairakei Power Station was built and 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 a 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, Figure 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 was placed into receivership at the end of 1998.

Natural State of the Reservoir

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 (Figure 2). 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 the production comes from the pumiceous breccias between 300 and 900 m depth (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), and this has influenced southwards flow of steam towards the surface in the Karapiti area (Figure 2).

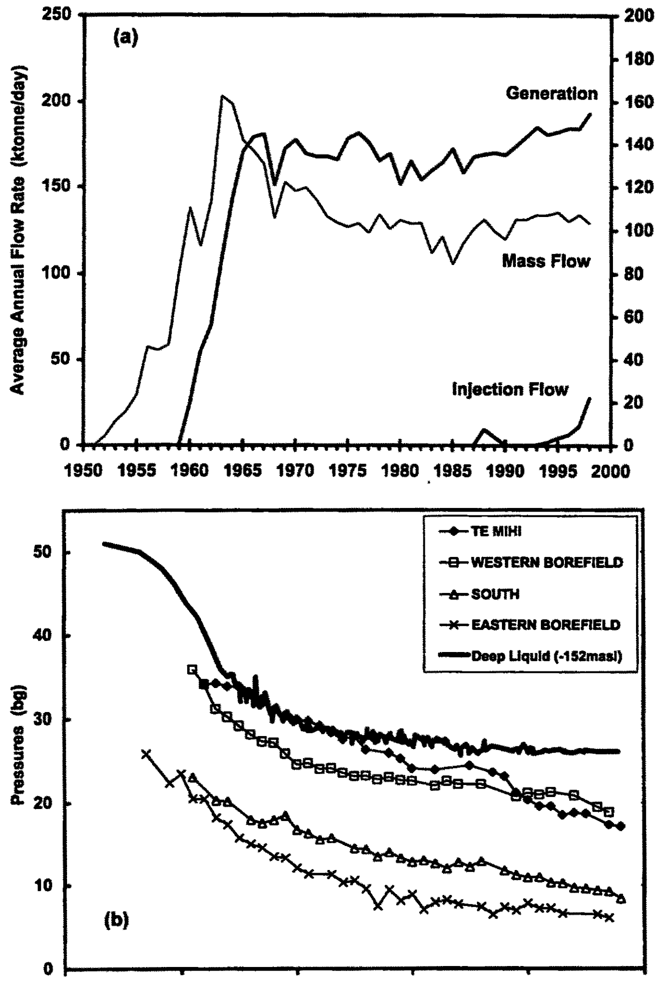

Figure 3. Upper graph shows the production history of the Wairakei power plant, along with the average annual production and injection mass flows. Lower graph shows the trend in pressure of the liquid reservoir at a datum approximately equivalent to 550 m depth (bold line), and the trends in steam-zone vapour pressure in different sectors of the field.

Reservoir Response To Production

Liquid Pressures

As a result of field development, deep liquid pressures have been reduced by 25 bar below the original undisturbed values, as shown in Figure 3b. 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 pressure boundaries close to the resistivity boundary. 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 4.

Deep liquid pressures in the Tauhara Geothermal Field have been affected by fluid withdrawal from the Wairakei reservoir, as shown by the –20 isobar contour in Figure 4. The data from the Tauhara Field indicates a continuous gradient is present from TH3 through TH1, TH2 and WK226 to Wairakei. Since 1964, pressures in the deep reservoir (-305 masl; ca. 750 m depth) at Tauhara have been falling at the same rate as at Wairakei (Allis, 1983). Pressures in TH1 and TH3 were about 7 bars higher than at Wairakei, and at TH2 about 4.5 bars higher. Because of both the lack of changes in thermal activity and lack of subsidence in the southern part of Tauhara Field, it has been suggested that this area may not have been affected by pressure drawdown from the Wairakei borefield Allis *et al.* (1989).

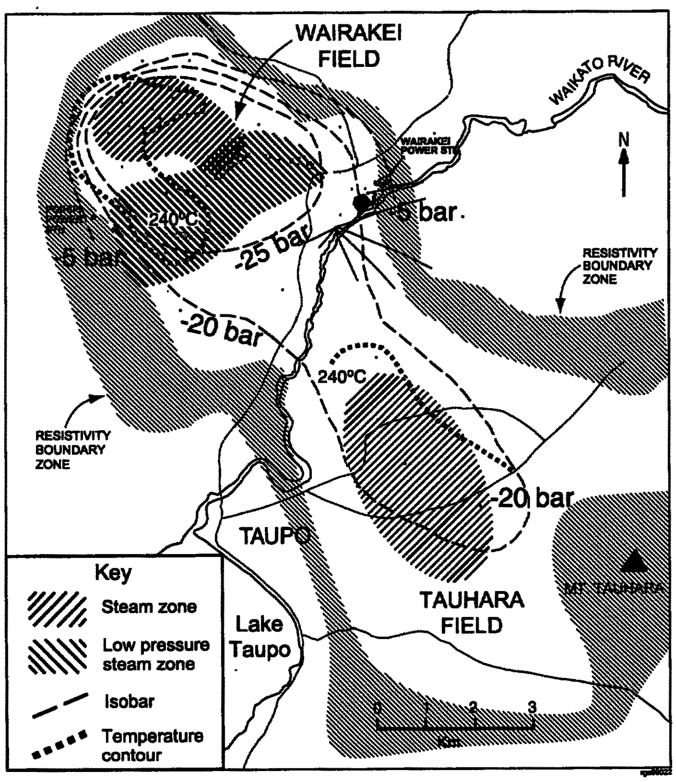

Figure 4. Compilation from the mid 1990s of the extent of pressure decline in the liquid reservoir, the known areas of highest temperature at about 800 m depth (> 240ºC at -400 m asl), and the locations of the steam zones which have formed as a result of the pressure decline.

Where wells have been drilled outside the Wairakei-Tauhara resistivity boundary zone, pressures have shown a small or zero response. Thus while the resistivity boundary in general is also a hydrological boundary, there has 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 point to increased inflow of cool and hot water due to production.

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 Figure 3b and the extent of the steam zones is plotted in Figure 4.

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 300 – 400 m depth has resulted in highly productive wells being drilled in this part of the field during the last 10 years.

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.

Reservoir Temperatures

Feedwater temperatures measured in permeable, liquid-fed wells are plotted in Figure 5a. In the Western Borefield for the period 1960-66, feed water temperatures declined from the natural state values of about 255°C, according to saturation conditions 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 Figure 5a. 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 and so 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 at Te Mihi, 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 (Figure 5a). Figure 4 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 greater. 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 240°C contour.

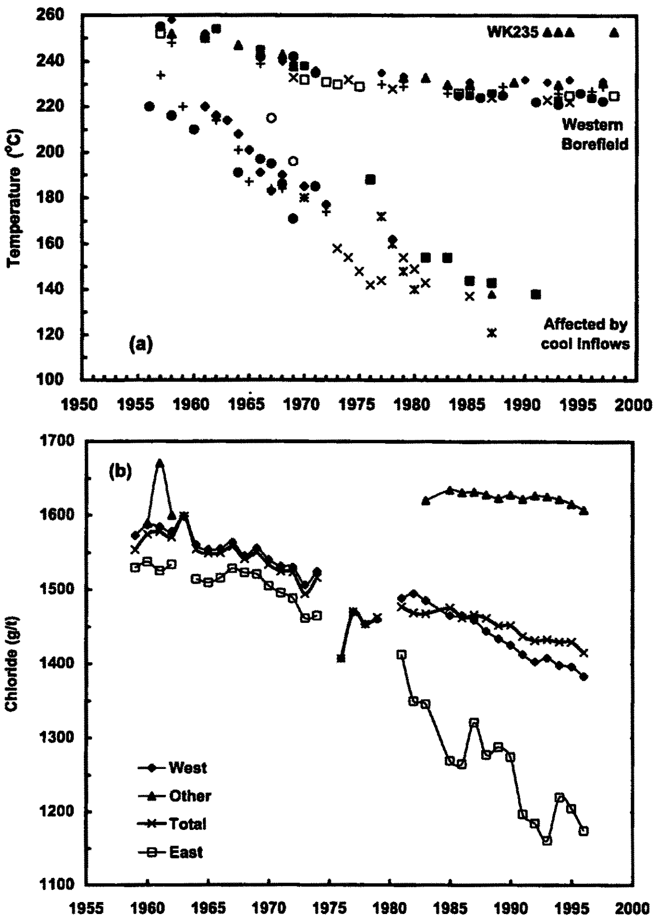

Figure 5a. Trends in average temperature from liquid feedzones in Wairakei production areas; **b.** Trends in average corrected chloride concentrations from the Wairakei production areas (from Glover, 1998).

Well Productivity

The output of the Western Borefield 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). Production from the Western Borefield and liquid-producing Te Mihi wells is declining at less than 1% per year.

Reservoir Chemistry

The major change in liquid chemistry for Wairakei has been dilution by cooler dilute water. Figure 5b (Glover, 1998) shows the trend in reservoir chloride levels for three different areas of the field. 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 "Other" trend line refers mainly to Te Mihi wells, which have shown little evidence of dilution.

The non-condensable gas levels were low initially (17.5 millimoles/100 moles of CO_2 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.

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 303, 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 higher temperatures at depth (260°C 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 in progress. After 5 months there are indications of low level returns to wells in the Western Borefield.

Environmental Impacts

There have been some environmental impacts resulting from development of the Wairakei field. The chloride water outflow to the Geyser Valley (Figure 2) ceased during the 1960s. The original springs and geysers were replaced by steam-heated thermal features. Similarly, the chloride springs and geysers north of Taupo in the Tauhara field ceased to flow and were gradually replaced by steam-heated thermal features during the 1970s. During the initial period of pressure decline in the 1960s and early 1970s the total heat output from the thermal areas of Wairakei and Tauhara approximately doubled and then reduced to about 50% above the original level. There was an increase in thermal activity in the Karapiti thermal area near Wairakei, where the expanding steam zone in the south of the field could vent freely to the surface. The thermal areas at Tauhara likewise exhibited an approximate doubling if total heat output due to increased steam flow to the surface, but this was delayed by about 10 years compared to that occurring at Karapiti. The part of Taupo township adjacent to northern Tauhara field has benefited from this "heat pulse" with increased opportunity for heat energy to be extracted through shallow wells.

An area of subsidence developed at Wairakei, centred between the Eastern Borefield and Geyser Valley. This lead to the need for cutting and welding of steam pipelines to allow for differential movement, repairs to roads, and adjustments to transmission lines. The local tourist hotel has shown signs of differential movement but no major problems have been reported. A much smaller area of subsidence has developed at Tauhara, near the original surface outflow.

For most of the 40 year development history of Wairakei separated water has been discharges into the Waikato River via the Wairakei stream. The amount of this discharge is now decreasing as a progressively increasing proportion of the water is reinjected (30% of total production mass in late-1998; Figure 3a).

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 by 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 mass flow) as this is the level for which a consent has been granted. Future production wells were assumed to be drilled in the Te Mihi area where temperatures have not changed. Figure 6 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 a little over 1100 kJ/kg at present to about 1000 kJ/kg in 2050.

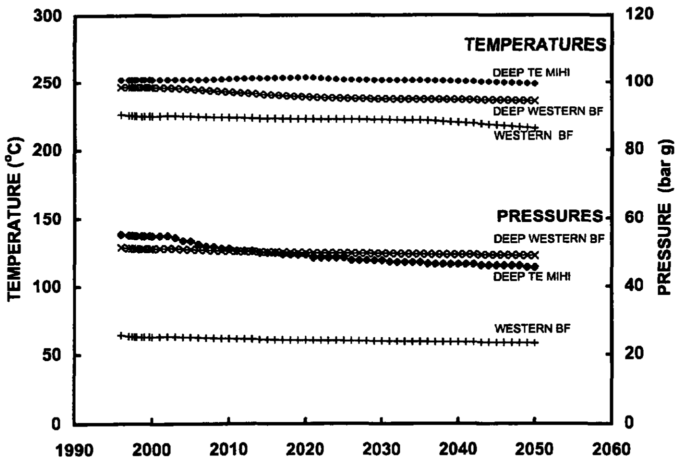

Figure 6. Model prediction of the future production trends at Wairakei assuming 60% of the production mass in injected, and make-up production wells are located in Te Mihi. The model is by O'Sullivan *et al.* (1998).

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 steam pressures decline. It is evident that there are large volumes of rock which are hot and are potential future drilling target areas.

Future injection wells are proposed to be sited 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.

Future development of the adjacent Tauhara field must take into account the need to demonstrate that surface effects are minimal, because of the close proximity of the town of Taupo. There are two current proposals for development at Tauhara which are proceeding to the Environment Court. The Contact Energy proposal is to use existing wells TH1 and TH2 to supply a 15MW turbine and local industry with steam. The second proposal is for a power station to be located to the south of the field, on the southwestern flanks of Mount Tauhara.

In the past there has been one large station at Wairakei field. There are currently two power stations and in the future there could potentially be four. 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 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.

Acknowledgement

We thank Mike O'Sullivan and Warren Mannington for supplying the modeling scenario used as Figure 6.

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