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WAIRAKEI RESERVOIR ENGINEERING

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SUMMARY – The response of the geothermal reservoir at Wairakei to 40 years of production is described in this paper. Initially, rapid change in deep pressure was observed with consequent decline in mass flows and formation of shallow vapour dominated zones. Recharge to the reservoir by both deep and shallow fluids has led to the attainment of lower and relatively stable liquid pressures and temperatures in the major production aquifer. Production from the induced shallow steam zones has been undertaken. Future production is expected to be sourced from the Te Mihi area. Reinjection has commenced successfully and is expected to provide the major challenge to the management of the field for the next 40 years.

1. INTRODUCTION

The Wairakei geothermal field, part of the Wairakei-Tauhara geothermal system, was the first liquid dominated reservoir in the world to be developed. After 40 years of production the steamfield is still successfully supplying the power station. The knowledge acquired over this period has benefitted the management of the geothermal reservoir at Wairakei and many other geothermal fields around the world.

2 NATURAL STATE

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. Evaluation of sub-surface pressures before significant fluid withdrawal had taken place identifies a continuous liquid profile from -300 masl to the ground surface at about +400masl (Grant and Home, 1980). The pressure gradient exceeded the hot hydrostatic gradient by about 7%. Using this gradient, the natural mass throughput and the reservoir area, MacNabb (1975) estimated a vertical permeability of 8 millidarcy. The continuous pressure profile and large mass outflow of chloride water at the surface demonstrated that on a field-wide basis the reservoir was effectively uncapped (although over much of the reservoir the Huka Falls Formation does act as a caprock). Temperatures measured in the early wells indicated boiling point for depth conditions down to about 400m depth (-100 masl).

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 Borefield along the Wairakei Ignimbrite-Waiora Formation contact zone and the major fault structures, up through the Waiora Formation and then to the ground surface controlled by the structure of the Huka Falls Formation. Part of the flow is directed southward along the domed surface of the Karapiti Rhyolite and exits at the surface where the Huka Falls Formation thins out or disappears. Steam heated features are found at higher elevations (Karapiti thermal area) and liquid-fed features at lower elevations (along the Waikato river upstream of Huka Falls). In the Wairakei and Waiora Valleys, fractures and faults through the Huka Falls Formation provide paths for the deep geothermal fluid to reach the surface.

Several of the early wells completed into the Middle Huka Formation produced vapour or high enthalpy fluid (Banwell, 1957), indicating that mobile steam was present at this level in the natural state. All the other early investigation wells produced fluid corresponding to liquid at the measured downhole temperature. It is likely that two-phase fluid with mobile liquid was present just below the Huka-Waiora contact over much of the reservoir.

3. PERMEABILITY DISTRIBUTION

The Wairakei Geothermal Field is characterised by high horizontal permeability. This has been demonstrated by the small pressure gradients across much of the reservoir, by interference tests and indirectly by tracer tests. Almost all

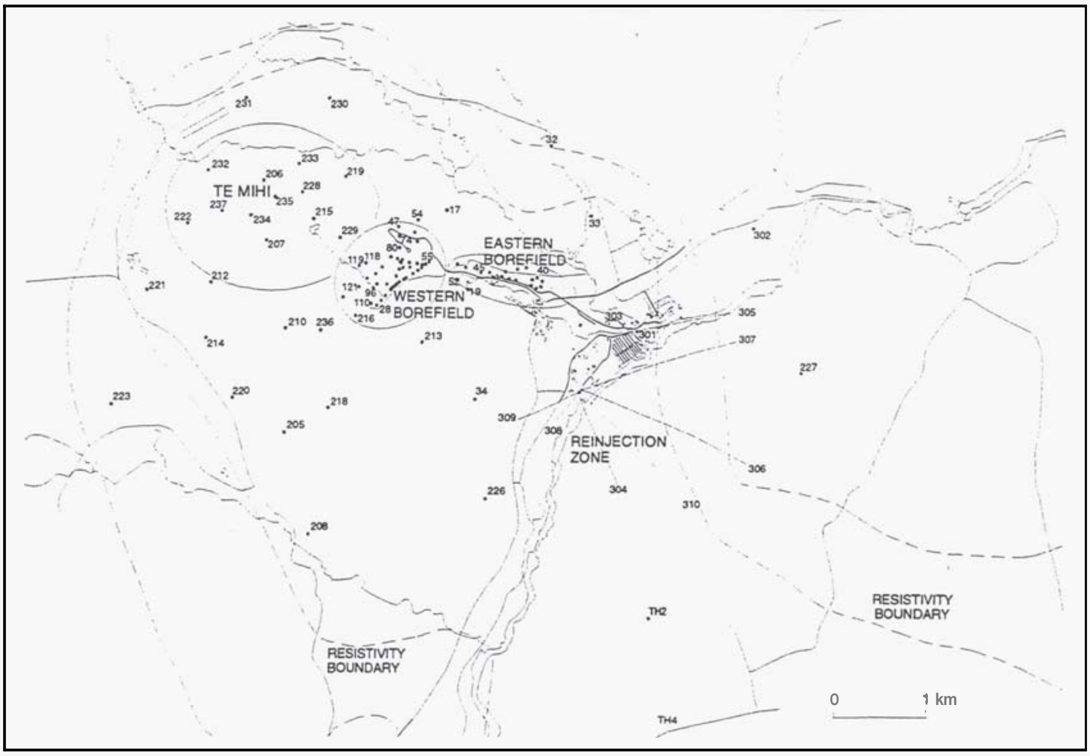

Figure 1 Wairakei Geothermal Field, showing well locations and resistivity boundary

production comes from the Waiora Formation, or other units interlayered within the Waiora. At earlier stages of development, some production was obtained from the Lower and Middle Huka Falls Formation in the Eastern Borefield, but these wells have now ceased to produce. Few wells penetrate significantly below the Waiora Formation and the production potential of deeper units has not been thoroughly tested.

Most production wells are cased through the Huka Falls Formation, and terminate in the Wairakei Ignimbrite. In the Western Borefield the bulk of the liquid production comes from a sub-horizontal zone at or just above the Waiora Formation and Wairakei Ignimbrite contact at about -150 masl. A shallower zone of permeability is found just below the Huka Falls Formation and Waiora Formation contact at 0 to +100 masl. This shallower zone now produces steam, but in earlier times also produced liquid. Wells with discharge enthalpies between that for liquid at reservoir temperature and steam, generally feed from a combination of deep liquid and shallower steam feeds, to produce the "excess" enthalpy of the total discharge, rather than a true two-phase feed direct from the reservoir.

In the west, the geology is not as simple as in the Western and Eastern Borefields and feed zones appear to be more randomly distributed with depth, but remain within the Waiora Formation and Karapiti Rhyolite where this is present. Major permeability here lies in the range -400 to **+100 masl.**

The Karapiti Rhyolite dominates the shallow ,hydrology to the south.

Pressure buildup tests in steam wells indicated **kh** values of 20-80 dm (Grant, 1978). In 1988-89 measurements made in monitor wells in the Eastern Borefield gave typical kh values of 100 - 500 darcy metres. Recent tests on wells at Te Mihi show high, but variable, permeability in the steam zone.

4. PRODUCTION HISTORY

Currently (August 1998) there are 53 wells producing into the steam collection system. The fieldwide production history is plotted in Figure **2.** The production history is divided into the main borefield (Eastern plus Western Borefields) and Te Mihi area, with plots of mass flow and enthalpy for total field (main borefield plus Te Mihi) and Te Mihi area.

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

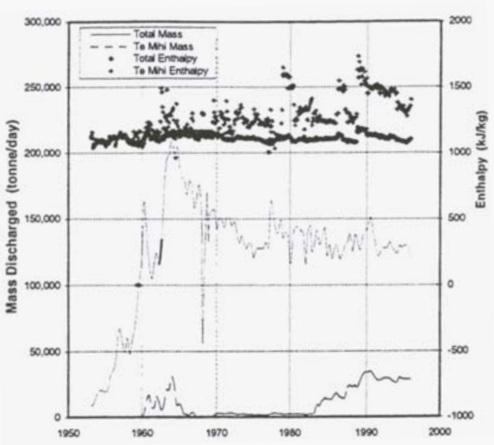

Figure 2 Trends for mass flow and field enthalpy and the field and Te Mihi.

5. LIQUID PRESSURES

The geothermal reservoir fluids are stratified, with a deep liquid, a boiling zone, at least two distinct steam zones and an overlying groundwater system. These interconnected units are surrounded by, and connected to, a cold water system. The deep hot liquid in Wairakei field is interconnected with the nearby Tauhara field. All these units have responded over time to the development of the Wairakei reservoir.

As a result of field development, deep liquid pressures have been reduced by **25 bar** below the original undisturbed values, as shown in Figure 3. Pressures here are referred to **-152** masl.

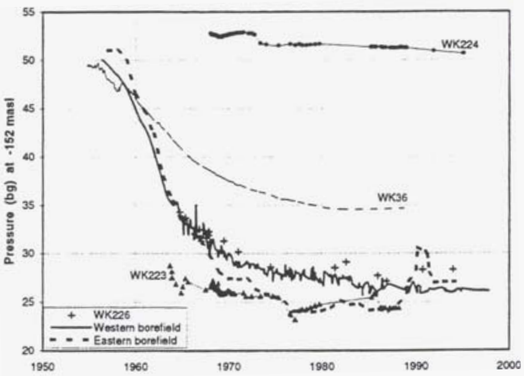

Figure 3 Trends of pressure in the deep liquid at **–152** masl (-500').

With the onset of production in **1958,** pressures in the deep liquid began to decline rapidly, reaching a maximum of 3 bar/year by **1960.** By **1967** the pressure decline rate had reduced and since **1990** pressure in the liquid zone has been relatively stable.

Eastern Borefield pressures have shown a slightly different trend.

The deep field pressure (average for Western Borefield) is plotted as a function of mass withdrawal in **Figure 4.** Initially there was a linear relationship indicative of draining of the water from the upper reservoir. After **1994** there is evidence of recharge to the system, and by **1985** external recharge appears to balance the mass produced.

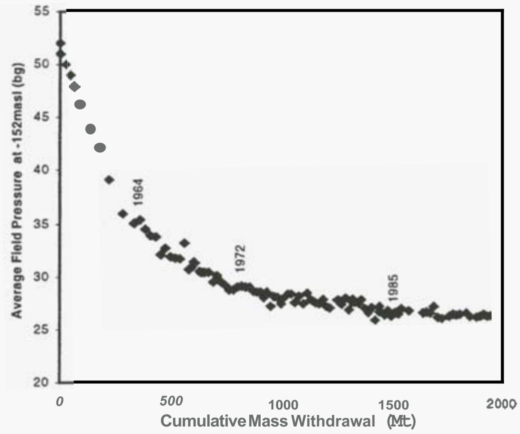

Figure **4** Average deep liquid pressure for field versus mass withdrawal.

The pressure response to fluid withdrawal has been almost uniform across the entire reservoir. Except for the Eastern Borefield which has followed a slightly different trend, the pressure trend for the hot reservoir can be represented by a single trend line within **±0.5** bar. 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.**

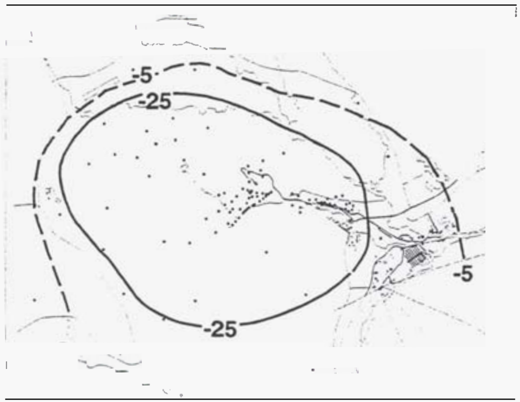

Figure 5 Pressure distribution map showing extent of liquid pressure drawdown, with contours outlining area of 25 and 5 bar decline.

Well WK223 located in the resistivity boundary zone at the south-western side of the field is the only deep cold well that may have some connection to the hot reservoir.

Pressures to the east and south-east of the hot reservoir initially closely followed the average borefield trend, but after 1962 have followed an intermediate trend, probably reflecting a connection into the two-phase or steam zone in the Eastern Borefield (See Figure 3, WK36).

The pressure measured in WK301, after deepening in 1990, lies close to the reference pressure profile, whereas deviated wells drilled into the top of the Karapiti Rhyolite (WK308, WK309) have higher pressures.

Deep liquid pressures in the Tauhara Geothermal Field have been affected by fluid withdrawal from the Wairakei reservoir. 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) 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.

In the ground outside the resistivity boundary zone, pressures have shown a small response. Thus while there is a hydrological boundary, there is lateral flow of the fluids across the boundary from the cold surrounding formations into the hot reservoir.

6. VAPOUR PRESSURES

In the natural state the upper parts of the reservoir almost everywhere contained a liquid-dominated two-phase zone. The Middle Huka Formation above the Eastern Borefield was an exception, with mobile steam in a two-phase fluid. Development rapidly reduced deep liquid pressures in the period 1960-65 (Figure 3). As much of the upper reservoir was already at or close to boiling point, there was 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. In the Eastern Borefield this "steam" zone extended up into the Middle Huka Falls Formation.

Average vapour pressures measured in a selection of wells throughout the field are plotted in Figure 6 and the extent of the steam zones is plotted in Figure 7.

These plots show that at least two steam zones developed at Wairakei; a high pressure zone in

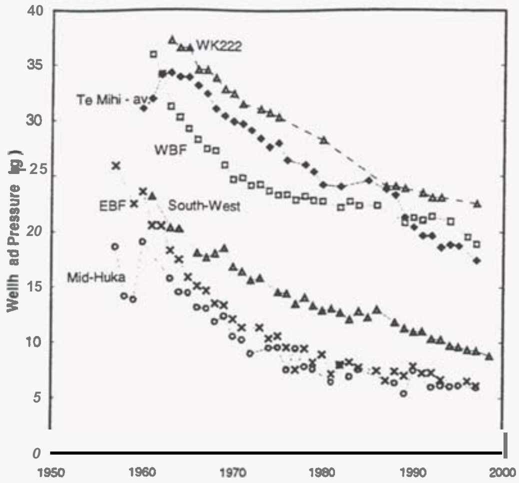

Figure 6 Trends of vapour pressures for various sectors of the field, reflected by shut-in wellhead pressures. (EBF, WBF- Eastern, Western Borefields).

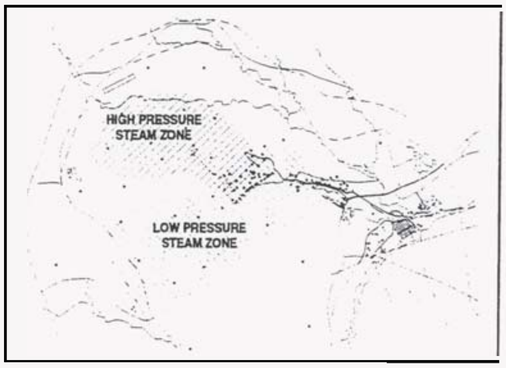

Figure 7 Map of field showing location of the high and low pressure steam zones.

the Te Mihi area and the Western Borefield and a lower pressure zone in the southwest and the Eastern Borefield. It is possible to further subdivide each of these zones, but this apparent difference is more likely to be an effect of development of part of the larger zones. In both cases there is little doubt that production wells in the Eastern and Western Borefields were taking at least part of their fluid from the "unexploited" zones further to the west.

The natural decline in pressure of the steam zones lead 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 been drilled in Te Mihi to date. WK236 was also drilled into the low pressure steam zone.

7. RESERVOIR TEMPERATURES

Feedwater temperatures measured in permeable, liquid-fed wells are plotted in Figures 8 and 9.

Western Borefield: In the period 1960-66 feed water temperatures in the Western Borefield 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.

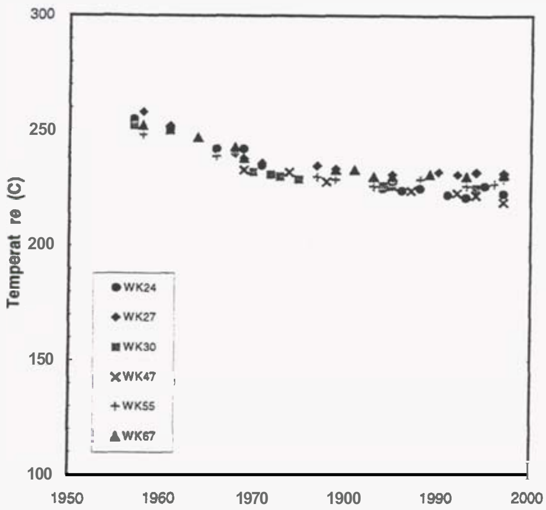

Figure 8 Flowing temperatures for typical Western Borefield wells.

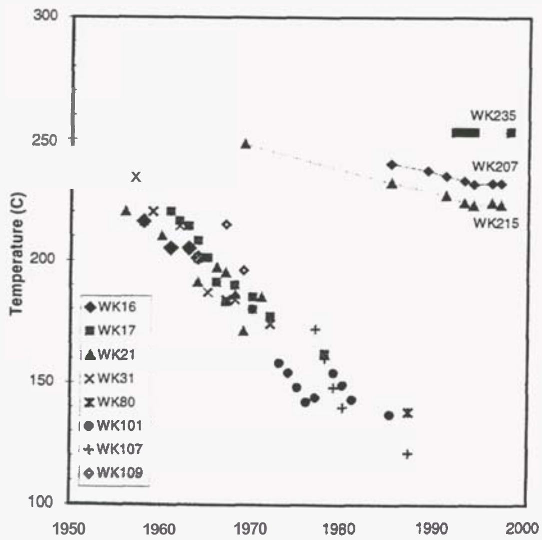

Figure 9 Feed temperatures for wells affected by cool inflows and for Te Mihi wells (WK207, 214 & 235).

Eastern Borefield: Reliable reservoir temperatures for the Eastern Borefield are not available. Due to the generally poorer permeability in the Eastern Borefield, wells have frequently not recovered from production when downhole surveys run. There also has been a more extensive development of two-phase conditions here compared with the Western Borefield. The Eastern Borefield wells have suffered dilution 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.

Te Mihi: 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 and associated temperature reductions. Well WK235 which has a deep feed zone has shown no change in temperature (Figure 9).

South: In the southern part of the field liquid temperatures in the Karapiti Rhyolite have shown little change, except in well WK208 to the south, where a reduction of 20°C, indicating an influx of cooler waters into the hot reservoir via the rhyolite, has occurred.

Cooling in Production Areas: 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) 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 are plotted in Figure 9. This shows a consistent rate of cooling from 1960 through to 1990. Since 1990 most of the affected wells have been cemented up to stop internal flows and so measurements cease. Pressures are about 5 bar greater in the cool zone than would be expected from wells connected into the deep liquid (Wainwright, 1969; Bixley, 1990). Thus where a well allows communication between the cool fluid and the deep reservoir, an internal downflow commences.

The three-dimensional distribution of cool fluid indicates a tongue, sloping gently from northeast to the southwest within the Waiora formation, penetrating into the upper part of the Western Borefield. Where wells are cased deeper than 0 masl, there has been no dramatic cooling, although chemical monitoring indicates more rapid dilution of deep producers in this part of the field than elsewhere.

The higher pressure and lack of invasion by the cooler fluids shows that an aquiclude of some sort must be present at about 0 masl to limit the vertical movement of fluids in this area. Sealing off the downflows in some wells appears to have at least reduced the rate of temperature decline in the liquid producers over the last ten years (Figure 8).

8. 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 Western Borefield wells which are still in operation. Figure 10 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.

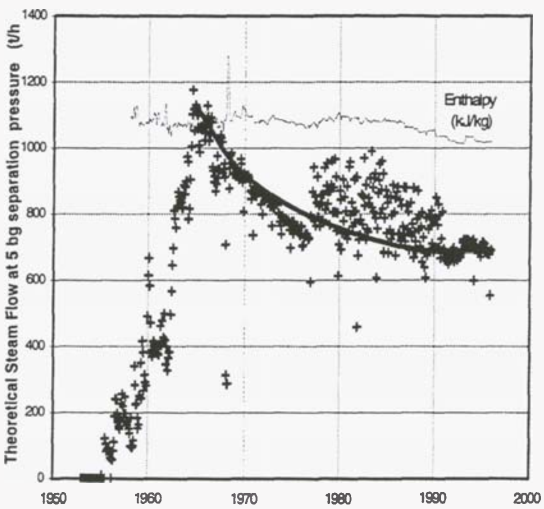

Figure **10.** Theoretical steam flow at 5bg separation pressure for core group of Western Borefield wells still in operation, calculated from test enthalpies and flows allocated from measured flash plant flows. Average enthalpy of these wells is also shown.

9. INJECTION

During **1980-1984** six injection trials were conducted using wells located outside the production borefield or disused production wells at rates of up to **200 t/h of 95°C** geothermal water. A trial injection at 580 **t/h** of **130°C** separated water into Eastern Borefield well **WK62** for **13** months followed in **1988-89.**

An integrated monitoring program covering production wells and chemical and geophysical measurements showed that, although reinjection was feasible, there was significant potential for damage to the geothermal resource and production well flows.

Tracer testing using radioactive tracers have been conducted on a number of wells (McCabe et al, **1983)** and revealed a complex hydrological system where flows were locally influenced strongly by the faulting system, but dispersion over a wider area was also observed after **2-3** weeks. Tracer movements of up to **22m/h** and high cumulative returns have been observed for some wells.

Drilling injection wells commenced in June **1990.** Well **WK301** was deepened to explore the deep reservoir to the east. It encountered permeability just below the original bottom hole and encountered high temperatures at depth. **WK302** confirmed permeability outside the field to the north-east. **WK303** investigated shallow permeability in the mid-Huka formation near WK301.

A range of geophysical surveys was performed in the potential reinjection areas near the eastern margin of the field. Seismic reflection, aeromagnetic, gravity and resistivity surveys were performed during **1989-1991**. These surveys were designed to locate the boundary between the geothermal field and surrounding cold aquifers more precisely and to locate potential reinjection targets. Magnetic and geological information showed the extent of the Karapiti Rhyolite dome, which has good permeability at the top and bottom contacts. Sesimic reflection profiles suggested targets associated with the Aratiatia Fault Zone, outside the field.

Wells **WK304** and **310** were drilled as a highly deviated **(70°)** wells to **the** south-east, inside the field. Wells **WK305**, **306** and **307** were drilled to explore permeability outside the field boundary. **WK308** and **309** targeted the Karapiti Rhyolite.

To date up to five injection wells have been in service. A total of **8.8** Mt was injected during **1993-97.** Short term tracer tests have been conducted on **WK308** and **WK304**. **No** returns have been detected.

10. CONCLUSIONS

The remarkable milestone of **40** years of operation of the Wairakei field is reached on **15** November **1998.** The field is well placed for a long productive future.

The major problem has been intrusion of cool ground water flowing back along the path of the original outflow zone. This problem has been successfully managed by a program of cementing up wells with downflows of cooler water.

Deep liquid pressures have stabilized, after an initial rapid decline, at a level 25 bar below the original value. Liquid pressures are almost uniform over an area of **14** km^2. Fluid has been extracted over this area and also from another **15** km^2 extending into the Tauhara field.

Vapour zones formed underneath the Huka Falls Formation cap rock as a consequence of the draining of the upper layer of the hot geothermal resource. The two major steam zones have both shown a decline in pressure due to heat losses and condensation. Production from the high pressure steam zone commenced in 1986.

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

Reinjection wells were sited after investigations to find permeability which was not well connected to the production sectors. Reinjection has commenced and only small pressure responses have been detected, with no evidence of returns of injected water.

Future production will focus on the Te Mihi area.

The management challenge for the next **40** years is the operation of reinjection.

11. ACKNOWLEDGEMENTS

Much of this paper has been summarized from ECNZ documents. I thank Contact Energy Ltd for enabling publication of this material at this **40** year generation milestone. I wish to pay tribute to the pioneering work of engineers and scientists who set the understanding of the reservoir at Wairakei on firm foundations.

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