RESERVOIR ENGINEERING OF WAIRAKEI GEOTHERMAL FIELD

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1 INTRODUCTION

Wairakei was the first liquid dominated geothermal field exploited for major power production. As such many decisions were taken on an ad-hoc or experimental basis. In retrospect the choice of Wairakei was fortunate : with extensive shallow high permeability and major recharge it is an easy field to exploit.

This lecture describes the history of the field and the contribution of reservoir engineering to field management, and describes the reservoir as it is now understood.

2 THE FIELD

This section describes the reservoir as it is now understood. Figure 1 shows a map of Wairakei field and its link to the adjacent Tauhara field.

A line of section is shown on the map. Figure 2 shows geological structure along this section line. Figures 3 and 4 show isotherms in the undisturbed state of the field and in the early 1080's.

Significant geological units are:

- Huka Falls formation, impermeable except where fractured, and so forming a partial cap to the reservoir.
- Waiora Breccia, generally permeable, and extremely permeable at its contacts with the Huka Falls formation, and the underlying.
- Wairakei Ignimbrite and Karapiti Rhyolite.

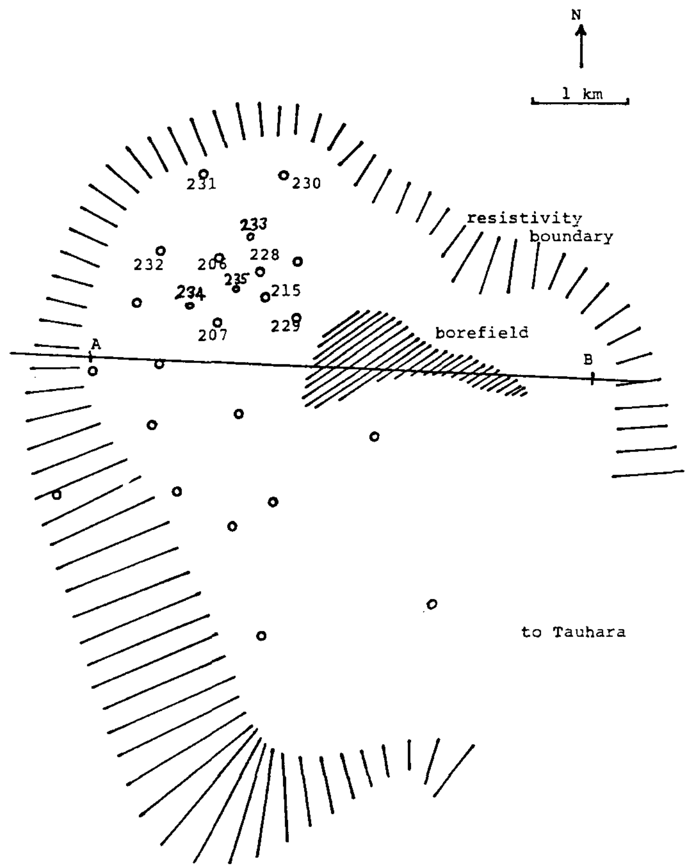


FIGURE 1. WAIRAKEI GEOTHERMAL FIELD, after Risk et al. 1984
Open circles denote '200 series' wells.

The principal permeability from which wells derive fluid is the contact between the breccia and the ignimbrite. Some shallow wells also draw on the mudstone-breccia contacts, and outlying wells (not in current use) on the breccia-rhyolite contact. On the reservoir scale, the uniformity of drawdown across the field shows that good permeability is horizontally continuous across Wairakei and Tauhara. A representative kh value is 30-300 darcy-metres, although production wells intercept local regions of markedly higher or lower permeability.

The faults constitute the principal vertical permeability of the field, giving an average k_v for Wairakei of about 5 md. Compared with the k_h value for the formation contacts and a reservoir of h of say 1 km, this indicates that one the gross scale the reservoir is anisotropic, with $k_h >> k_v$. As the principal vertical flow channels, the

FIGURE 2. Geological section, after Bolton 1982.

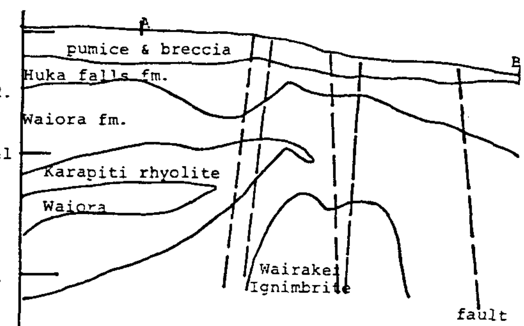


FIGURE 3. Isotherms in natural state

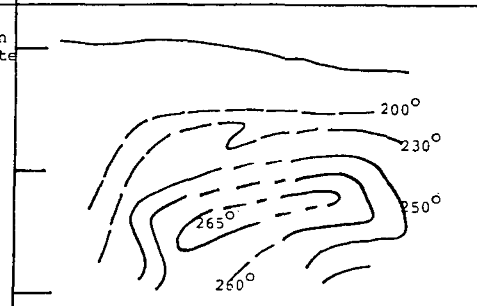
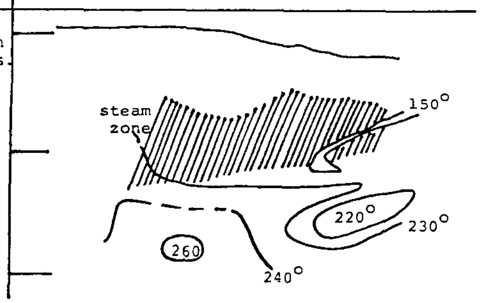


FIGURE 4. Isotherms in early 1980's.



faults strongly influence the pattern of the upflow in the natural state, and the downflow of surface waters induced by exploitation.

Figure 3 shows an isothermal section in the undisturbed state of the reservoir. The isotherms show that the natural flow originates as an upflow in the west of the field (to the north of the section). From this upflow there is an outflow almost due east, which, beyond the end of the section, manifests itself in the surface discharge at Geyser Valley.

The maximum temperature attained within the reservoir depths is about 265°C. In the natural state, this rising water boiled at 260-230°C, forming a liquid-dominated two-phase zone in much of the shallower parts of the reservoir.

Pressures in the natural state were those of a liquid-dominated reservoir. Reservoir pressures at feedpoints of early wells define a gradient some 7% above hydrostatic. This pressure excess is the gradient needed to drive the natural flow up through the reservoir, and it is from this that k_V = 5md is computed. No break in gradient or discontinuity is apparent so that there is, on the reservoir scale, no confining layer.

The changes in the reservoir following exploitation are conveniently discussed under three categories: pressure, fluid type, and temperature. Traditionally, pressure changes have been of greatest interest, but they do not fully characterise a geothermal reservoir. Figure 5 shows pressure and temperature profiles in one section of the field at different times in field history. (After Allis & Hunt, 1986)

There is now a shallow liquid-dominated region, not greatly disturbed by exploitation, and a deep liquid-dominated region in which pressures have fallen below the original trend. Between the two is a region of low gradient and somewhat variable pressures. The pressure drop in the lower "water" zone is fairly uniform across the field. Figure 6 shows pressure profiles along the section and it is this pressure that is referred to as the "field pressure", "reservoir pressure" or "deep liquid pressure". The history of this field pressure has been analysed in a number of simple and elaborate models of the reservoir from the first by Whiting & Romey (1969) to the elaborations of Frudkin et al (1982). In general good matches have been obtained by quite a wide range of models. Figure 7 shows the field history, with the changes in deep liquid pressure, discharge enthalpy, and the mass flow from the production wells.

The changes in fluid type correspond to the changes in pressure. In the undisturbed reservoir, there was a shallow two-phase zone. Mass withdrawal and pressure drop caused the two-phase zone to increase in depth and dryness. By 1962, enough water had drained for a vapour-dominated interval to form between two liquid-dominated zones.

FIGURE 5. Pressure and temperature in Western borefield, from Allis & Hunt, 1986. Dotted sections denote steam zone

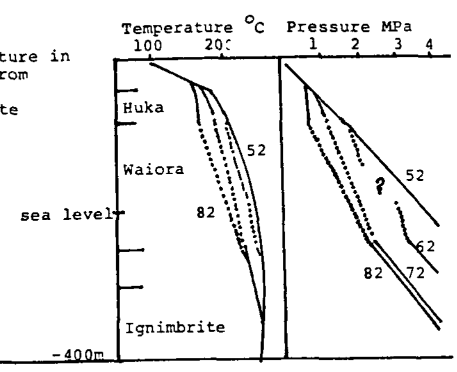


FIGURE 6. Pressure profile across field, in liquid, from Bolton 1982.

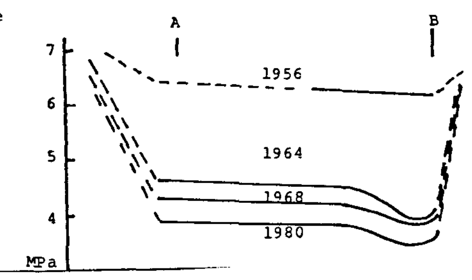
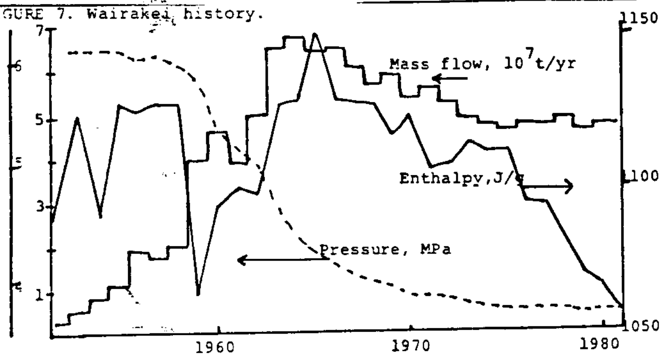


FIGURE 7. Wairakei history.



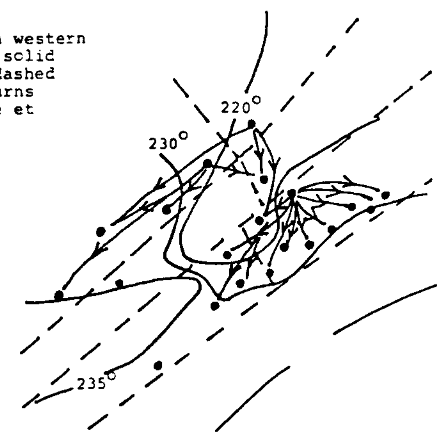
This is the region of reduced gradient in Figure 5. Feedpoints in this steam zone generally supply high-enthalpy fluid, or "dry" steam (saturated, not superheated). Two-phase fluid may also be discharged from the upper liquid-dominated zone, and from the top of the lower; but the bulk of production derives from liquid water further down.

The previous paragraph assumed that all temperature changes are caused by boiling: that two-phase conditions occur everywhere pressure has fallen below saturation corresponding to the original temperature. In general this is true, but there has also been some cooling of the reservoir by the entry of cooler water. Figure 4 shows the 1981 conditions for the same section as Figure 3. In the west, the extent of 260°C water is unclear. Internal flows are now so frequent in wells that it is very difficult to construct isotherms, and 260°C water may occur extensively, disguised by downflows. The temperatures in the west reflect the changes caused by boiling. In the production field intrusions of colder water are present. One shallow intrusion (<150°C) is very localised, but carries several hundred tonnes per hour of water, and was responsible for downflows or temperature inversions in WK 31, 107 and 57. A more extensive area of cooling at greater depth is shown by inversions in WK 48 and 121. It is possible that this zone of cooler water derives from the upper intrusion, by downflows in wells.

Figure 8 shows a plan view of the western production area. Isotherms at RL-200 m are shown, as are faults and the pattern of returns in a number of tracer tests. There is a strong correlation between the pattern of the isotherms, the pattern of flow as indicated by radioactive tracer (McCabe et al., 1981), and the predominant SW-NE fault direction. Colder water is entering the reservoir from the New Zealand, along the paths where there was once outflow to surface discharge. The connection to surface is further confirmed by the fall in groundwater level in this area of the field. Figures 4 and 8 also show hot inflow to the production area, slanting upward and flowing almost due east from the west of the field.

It should be stressed that the area affected by cold inflow is, so far, fairly small - about 1 km^2 of the reservoir. A heat balance shows that cold inflow does not yet form the dominant part of the Wairakei recharge and most of the reservoir is little affected by it. However the production area is so affected, and this has had significant effects on the performance of wells. Despite this deterioration, there remains a very large heat store at Wairakei, in a reservoir of proven permeability. Production, possibly through replacement wells further west, can be maintained for a long time to come.

FIGURE 8. Isotherms in western borefield at RL-200m (solid lines) major faults (dashed lines) and tracer returns (arrows). After McCabe et al 1981.



3 HISTORY 1953-1980

The preceding summary contains much relatively recent data and interpretation. Actual decisions were made in the light of the available data and concepts.

Major drilling began in 1953, after some preliminary shallow wells. Wells were drilled at sites determined on geology. If successful, they were left to discharge. Lacking any other basis, the proven potential was taken as the total output of the wells. The extent of the field was not known and in fact drilling covered only a fraction of the field.

Banwell (195) made stored heat calculations, and demonstrated that the heat reserve was large. Interference was measured between two wells, and a downhole pressure transient measured by gas purge, but these results were not pursued.

Wellhead pressures were measured and downhole temperature profiles. After 1960 downhole pressures were also measured. The wellhead pressure data show drawdown began in 1952-53. For political reasons (denial of effect on surface activity) this observation was ignored. Generation and full production began in 1958 and with it major pressure drops.

The station was designed to include a heavy water separation plant. Although this was cancelled, design parameters remained set. In particular the operating wellhead pressures was set at what is now regarded as a high value of 15 bar.

After commissioning the first two stages of the station to a total capacity of 192MW, the fall in pressure was so obvious that Stage III was abandoned. Through the first half of the 1960's further exploration wells ('200 series') were drilled that by about 1965 had roughly delineated the field. A first resistivity survey now also gave an indication of field size. Many pressure transients were recorded at this time but nothing was made of them. In retrospect, they are dominated by wellbore thermal and flow effects.

Part of the 200 series were drilled to northwest of the production borefield at Te Mihi. It was thought this might be a separate resource capable of supporting another new station. However the same (draw down) pressures were found and so it was concluded that this area was effectively exploited by the existing borefield. This inference is the first application of reservoir engineering to field management.

In 1965, the first reservoir engineering study of Wairakei was commissioned, later published as Whiting and Ramey (1969). The field was modelled as a sealed reservoir of compressed liquid, and the model validated by a regression fit to pressure-discharge history. The volume of liquid found was enormous, and implied a field capacity of 2000 MW. After some interesting discussion, the conclusions were rejected. However the study permanently influenced the development of concepts of Wairakei, and in particular the later series of simple models fitted by regression.

Uncertainty about the field capacity continued. Through this period and up to the early 1980's decisions about field management were taken by engineers on a practical basis. Estimates of field capacity at this time ranged from 2000 MW down to claims that the field would not sustain the existing plant for more than a few years longer. In the face of this uncertainty it was decided to finally abandon plans to expand the station. The danger of depletion was also guarded against. A sequence of exploration wells were drilled in 1965-66 in a number of other fields. Two were drilled at Rotokawa, the nearest field to Wairakei. Having found steam here, the field was then abandoned. It was in fact being left aside as an informal "reserve" to pipe steam to Wairakei power station if necessary.

Four wells were also drilled at the adjacent Tauhara field, which, like Te Mihi, proved to be linked to Wairakei.

Drilling stopped at Wairakei in 1966. Over the next 15 years field management consisted of a series of engineering improvements and the connection of idle wells. The engineering improvements resulted in doubling the thermal efficiency. Actual output was maintained fairly steady at 140-150MW. Continued drawdown of the reservoir meant that operating wellhead pressures had to fall progressively with time.

Original reservoir engineering contributions began to appear by the mid 1970's. McNabb developed the technique of interpreting reservoir pressure and plotting this against depth to determine reservoir pressure distribution, a technique now standard in New Zealand. From this and the natural flow he deduced the vertical permeability. McNabb also developed the first version of the drainage model as late elaborated by Fradkin et al. (1982). This model idealises the reservoir as an open tank with a free surface, and with pressure-dependent recharge.

This model was used to estimate future pressure drop. Given the stable flow rate, it predicts little change in pressure; a result also obtainable from extrapolating past trends.

Gravity surveys (Allis & Hunt, 1986) were used to determine the amount of recharge and provide major constraints to modelling concepts.

4 HISTORY AFTER 1980 : REDEVELOPMENT PROGRAM

The program of incremental adjustments began to fail in the early 1980's. Larger changes in management are now called for, and reservoir engineering has begun to contribute effectively to decisions.

There are three major pressures on present field management:

1 Existing production is declining, and wells failing. The cause is cold water incursion and falling vapour pressures.
2 An excellent production area remains at Te Mihi, unaffected by cold water, and having generally higher vapour pressures.
3 A commitment has been made to start reinjection.

The response that has evolved is:

1 Abandon attempts to prolong the life of wells in the existing production area.
2 Use a section of the Eastern production area near abandonment for reinjection (thereby accelerating its decline).
3 Develop new production at Te Mihi. This requires drilling and construction of steam lines and, later water lines. The Te Mihi wells will initially be shallow

steam producers, later deepened to normal depths.

The changes in production and injection will cause major changes, locally in reservoir temperature, and field-wide in reservoir pressure.

5 THE PRESENT STATE OF THE BORE FIELD

Wairakei power station's output has been falling significantly in recent years, due to a shortage of steam. (Thain & Stacey 1984). Over much of the field's past history, the field history has been dominated with changes in reservoir liquid pressure. However reservoir liquid pressures are now roughly stable. The continuing fall in output is due to incursion of cold water and falling production temperature. Figure 7 shows the history of field pressure.

As many wells operate close to Maximum Discharging Pressure (MDP) on production, any fall in enthalpy and consequent fall in WHP can be critical. Evidence for the incursion of cooler waters into the borefield comes from a variety of measurements:

(i) downhole temperatures
(ii) production chemistry
(iii) gravity.

For both downhole temperatures and production chemistry, it is the case that changes are sufficiently gradual that they cannot be easily detected over a few years. However over a longer period and using a large number of wells clear trends are detectable, identifying a zone of cold water intrusion from the northeast. Gravity increases in the eastern borefield also require cooler water incursion.

Figure 9 shows the temperature of water entering some representative production wells. There is a clear and continuing fall with time. Chloride contours show much greater detail with fingers of cooler (low silica and chloride) water entering the western borefield. (Brown et al in prep). Isotopic evidence confirms that pattern of groundwater encroachment. The entering cool water is strongly associated with the major faults.

The cold water enters the borefield from above, as a slanting downflow following the path that originally carried upflow to Geyser Valley. The faults provide the passage through the impermeable mudstone. The cold water invasion is getting worse. Several wells have downflows of this water where it enters the well at a shallow feed point and runs down the well.

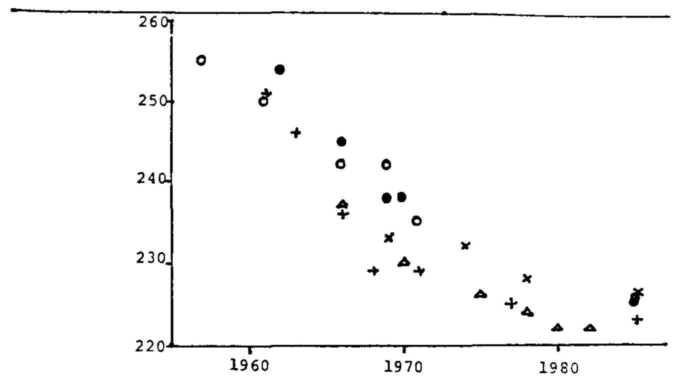


FIGURE 9. Inflow temperatures in five representative wells.

Gravity results also indicate cold water advance. There are areas of gravity increase and decrease. Gravity increase over the western borefield can only be explained by cooling, or by water replacing (Allis & Hunt 1986).

How rapidly production decline will continue if nothing is done is not clear. unpublished reports by Bacon and Grant predict major or steady declines. A better prediction will need an adequate reservoir model, including a good description of the cold water inflow and of well performance.

6 TE MIHI

By contrast to the degraded state of the present production borefield, at Te Mihi the geothermal reservoir has pressures lowered by exploitation but temperatures remain only a few degrees below their original values (except where pressure drop has required cooling by boiling).

As elsewhere in the field, the upper portions of the Wairoa formation contain a steam zone, a vapour-dominated region extending from the base of the overlying Huka Formation to about sea level. At Te Mihi the steam zone has pressures of 20-25 bar. Beneath here liquid water at up to 260°C is found. These temperatures imply far better well performance than from the temperature of 220-230°C available in the existing borefield, although wellheads will be at up to 100 m higher elevation. A region of high pressure extends from Te Mihi and partly into the western borefield. Only in Te Mihi is the zone of high pressure very thick and capable of producing major steam flows.

Given the good production available at Te Mihi, the obvious suggestion is to seek production from here to replace losses in the existing borefield. The exploration wells originally drilled in the 1960's here were production to delineate a new area; they were never used because it was found that they shared a common pressure with the rest of the field, and hence one might as well use the existing borefield, and pressures were then falling so rapidly no additional withdrawal could be tolerated (Bolton, pers. comm.). This argument is no longer valid because of the temperature difference now present. Given that Te Mihi has better production, issues that need to be addressed are:

(i) economic - is it worth drilling at all at Wairakei
(ii) distance from the power station
(iii) interference between Te Mihi and the existing borefield
(iv) longevity of Te Mihi production

and in general the expected response of the reservoir to what would ultimately be a major shift in production in the field.

The reservoir, and the production drilling, needs to be discriminated into steam and liquid. The steam zone at Te Mihi represents an excellent immediate production prospect. WK228, the first well drilled under the new strategy, initially produced 180 t/h steam with a drilled depth of 393 mm. It is the most productive well ever drilled at Wairakei, and leads to the obvious suggestion of drilling as many such wells as the resource will stand. The obvious question then is:

° what is the production capacity of the Te Mihi steam zone?

7 TE MIHI DEVELOPMENT PROGRAM

Some answers are known already, and in consequence some actions can be planned upon now.

The most obvious example is the drilling of steam wells at Te Mihi. The resource is at present over an area of several square kilometres and hence contains sufficient energy to sustain a steam flow of several hundred t/h for several years. The steam is sufficiently valuable that this justifies drilling and construction of steam mains.

When the steam depletes, deepening such steam wells to water also appears viable. As a competent caprock exists at Te Mihi, the reservoir here is protected from overlying colder water.

Assuming therefore that we are committed to an initial program of steam well drilling at Te Mihi, and steam main construction, what is needed is:

(i) what is the expected rundown of the existing borefield - what is the baseline scenario against which we compare alternatives?

(ii) how long will the Te Mihi steam zone last?

(iii) what will be the effects of water production from Te Mihi?

(iv) what will be the effects of reinjection on the existing and Te Mihi borefields?

These questions will be answered by a coordinated program of exploration drilling and scientific work.

8 TE MIHI EXPLORATION DRILLING

Some exploratory drilling is required to define the Te Mihi resource. The most important aspect is its size, and next its temperature. The existing "200 series" wells define only part of Te Mihi, the northern and western extent is really indicated only by resistivity survey.

In particular, the steam zone, which was created by exploitation, need not coincide with the resistivity. The most important parameter is simply its size, and to determine this we need to find its far edge. This requires drilling wells to the north and west, down 100 to 200 m below sea level, to confirm the presence or absence of steam. As a secondary objective the liquid temperature needs to be defined.

9 REINJECTION

Environmental constraints require Wairakei to reduce waste discharge into the Waikato River. Reinjection is the only practical way to achieve this.

Initial investigations focussed on peripheral reinjection and a trial reinjection well was drilled as WK301. It lies on the resistivity boundary near the power station. Unfortunately it was one of the few wells drilled at Wairakei that did not find good permeability.

Accepting that failure, it is necessary to move into the field to be sure of good permeability. Tracer tests have repeatedly shown rapid movement of tracer over long distances, arguing very strongly that injection wells need to be well separated from procedures. I suggest that a reasonable design is to have injection wells spread over the southern boundary, from the eastern borefield to WK226.

If this is accepted, about one-third of the area lies near the existing eastern borefield. If these wells are now dying, it is an obvious suggestion to use them instead. A reinjection trial is therefore proposed for an initial test of injection 500 t/h into the eastern borefield. This will accelerate the decline of adjacent wells but their expected lifetime is short anyway.

11 ISSUES

A considerable number of issues need to be described or quantified. They can be roughly grouped under four headings:

(i) Existing trends - what is the baseline against which to evaluate the effects of changes in field management? This essentially requires a good model of the field. The primary contribution is from chemistry and reservoir engineering.

(ii) Te Mihi development - what is the capacity to supply steam, how long will the steam wells last (how many of them?) before they need to be deepened to liquid?

This requires adequate physical definition of the Te Mihi resource by exploratory drilling, well testing, interference testing, geology, geophysics and chemistry; followed by some modelling.

(iii) Eastern injection - what are the effects on existing producers, will thermal decline or pressure increase dominate?

This requires adequate physical and chemical monitoring of the injection, tracer testing and gravity surveys, again followed by modelling.

(iv) Field wide interactions. Injection will raise the liquid pressure. Substituting Te Mihi steam production for liquid borefield production also reduces the withdrawal of liquid. Both will affect reservoir liquid pressure. The addition of 3 "200 series" wells in 1983 added to net total steam flow only half the added capacity, due to the interference effects on existing wells. A rise in liquid pressure will improve well performance but has other long term effects. This is at present substantial hot recharge and raising pressure may reduce this. This will be addressed as part of the modelling required elsewhere.

11 RESERVOIR ENGINEERING CONTRIBUTION

Major changes in field management plans have occurred in the last three years, equivalent to a redevelopment plan for the next ten years. Reservoir engineering studies played a major part, for perhaps the first time in Wairakei's history.

The original decision not to exploit Te Mihi was based on reservoir engineering - the fact that pressures were the same as the borefield. The decision to progressively substitute Te Mihi production was based on two lines of argument:

- initially, economic calculations (Thain) of the cost of additional steam supplies available by connecting existing 200 series wells.
- arguments by reservoir engineers (Bixley, Grant) that long-term production could be maintained only from Te Mihi : and the suggestion of drilling initially shallow wells to exploit the steam zone. Such wells can later be deepened to water producers.

A major reservoir engineering and simulation effort is underway based on both simple models and simulations. Starting injection, and substituting steam for liquid producers will produce major rises in liquid pressure, and falls in temperature. All these effects need to be quantified. In practical terms the major decisions to be made are:

- How much can the Te Mihi steam zone supply before being flooded out?
- Where can injection safely proceed?

12 EXPLORATION RESULTS SO FAR

So far five production wells and three exploration wells have been drilled at Te Mihi since 1985. The first production well, WK228, was drilled in 1985 and was spectacularly successful. An initial flow of 180 t/h of steam made it the best well ever drilled at Wairakei - 35 years after there exploration began.

WK229 was drilled in 1986 to test steam production near the existing borefield. No steam permeability was found and it is a normal Wairakei liquid producer.

WK230-232 are exploration wells drilled to 600 m in 1986-87. WK230 found steam but little permeability, and a temperature reversal. WK231 found low temperatures. WK232 found steam, high permeability and temperature, and produces 50 t/h.

Production wells WK233 and 234 each produce an initial flow of about 270 t/h of dry steam. WK235 did not find permeability and was drilled on to 1400 m.

An additional steam line is under construction.

ACKNOWLEDGEMENTS

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