THE RECHARGE TO THE WAIRAKEI RESERVOIR

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ABSTRACT

A heat balance on the changes at Wairakei due to exploitation gives a rough estimate of the enthalpy of the recharge entering the productive reservoir as 1000 kJ/kg. As this fluid will have already gained some heat by passage through peripheral rocks, it is indicated that some of the recharge induced by exploitation is of surface groundwater.

Temperatures in the steam zone and in liquid beneath it, and the pattern of upflow and downflow in wells, indicate that recharge of deep hot water continues to occur in the northwestern (Te Mihi) sector of the field, and flowsdue west into the borefield. Colder water is invading the western borefield along the Kaiapo and Wairakei Faults.

Ultimately production will decline and fail in the present borefield, as cold water enters more pervasively. A productive resource will remain at Te Mihi, which could be used to feed either the present station or a new plant at Te Mihi. Reinjection plans Should reflect the future as well as the present pattern of withdrawal. In particular there should be no reinjection at Te Mihi, e.g. WK219 or 221.

INTRODUCTION

Wairakei is a high-temperature liquid-dominated reservoir. In its natural state it had a base temperature of 260-265°C, and two-phase conditions occurred in the upper few hundred metres of the reservoir. Under exploitation, the two-phase zone expanded and a steam zone formed. This steam zone now extends down to a little below sea level. For a review of the initial and exploited state, and illustrations of the pressure and temperature distribution in the reservoir, see the companion paper in the Tour Guide (Grant, 1982).

A TWO-ZONE MODEL

The most successful modelling of Wairakei has been the very simple lumped-parameter model beginning with the inappropriate sealed box model of Whiting (1966) and its development into an open reservoir model by Bolton (1968) and McNabb (1975), ending with the statistically refined analysis of

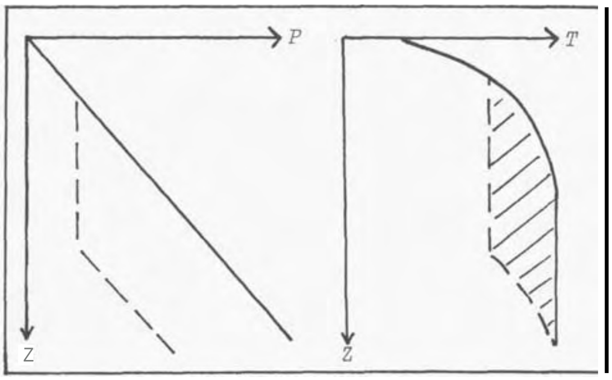

Figure 1. Conceptual model of fluid profile, in initial (solid line) and exploited state (dashed line).

Fradkin et al. (1982). This model has dealt with a single observable describing the changes in Wairakei: the deep liquid pressure, and uses only the history of mass discharge while ignoring its enthalpy. The model is basically an unconfined aquifer, a box of water subject to recharge and discharge with a zone at constant pressure above the liquid. The constant pressure zone could be interpreted either as a steam zone or as the atmosphere. This model describes only a mass balance upon the reservoir, while an energy balance is ignored by assumption.

The logical next development of this model is a two-zone model that describes the changes in the vertical fluid profile. This is sketched in Figure 1. It is assumed that the reservoir is initially in hydrostatic equilibrium, and contains water which is at boiling point down to the depth where the 260°C base temperature is attained. Under exploitation, a steam zone develops between two zones of liquid. The effect of the steam zone is to displace downwards the temperature profile in the liquid beneath. This assumption of vertical equilibrium (Mercer and Faust, 1979) ignores the steam content of the liquid-dominated zone, and the non-static gradients present in both zones. It is also assumed that the saturation of the steam zone is constant, at a little above residual. This is because it is assumed that there is sufficient downflow of water through

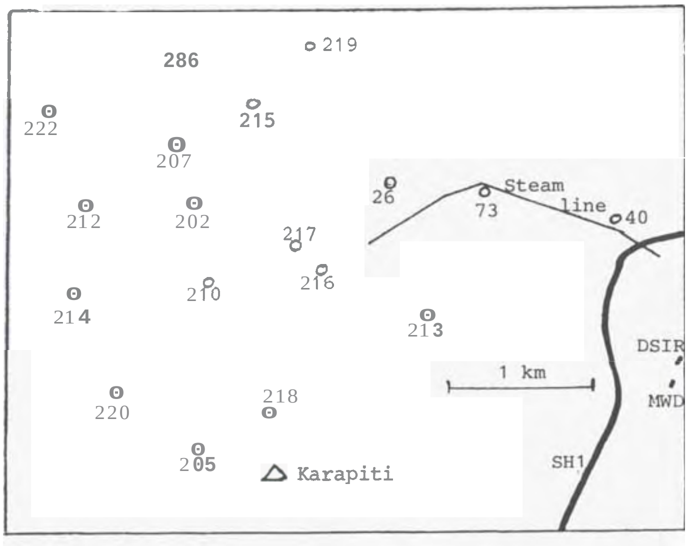

Figure 2. Field Map

the steam zone to keep it wetted. Support for this assumption comes from the fact that no superheated zone has ever developed.

Let P be the pressure at a standard depth in the deep liquid, and P_0 its initial value. Let ϕ be the porosity, assumed uniform, and S_0 the residual saturation. The mass loss from the reservoir is simply the mass loss from the steam zone, which occupies the reservoir area A and has thickness $Z = (P_0 - P)/\rho_w g$. Then conservation of mass gives:

$$-\phi S_0 A \frac{dZ}{dt} = W_r - W$$

where W is the mass discharge and W_r the recharge. This is the same form of equation as used in the simpler model, so that previous fitting of the mass discharge and pressure history remains unchanged. Energy loss from the reservoir is given by the shaded area in Figure 1b, plus a correction for heat carried by mass loss of the steam zone:

$$-A \frac{d}{dt}\{(T_b - T')\langle\rho C\rangle Z + Z\phi(1-S_0)\rho_w h_w(T')\} = h_r W_r - hW$$

where $T_b = 260^0$ is the base temperature, T' the steam zone temperature, and $\langle\rho C\rangle = \rho_f C_f + \phi\rho_w C_w$ is the heat capacity per unit volume of wetted rock. Temperature, and hence pressure, changes in the steam zone are controlled by the energy balance on the reservoir. By contrast the deep liquid pressure is controlled by the mass balance.

This energy balance is an idealisation. A more accurate heat balance would use not the assumed temperature profile, but an actual horizontal average across the reservoir. Regions of lower temperature do occur: there is a temperature inversion beneath the borefield, and lower temperatures were present near surface over much of the field. Also not included are temperature changes in peripheral regions of the field where there are no wells.

CHANGES IN THE STEAM ZONE

After full scale production began in 1958, pressures began to fall and boiling in the reservoir increased. The fluid did not segregate into well-defined steam and liquid-dominated zones until 1962. Figure 2 shows a plan of the field, and Figures 3a-c show, over the same area, pressures in the steam zone. Areal averages, which are no more accurate than ±1 bar, are given in Table 1.

Year	P'	$T' = T_s(P')$
1962	24.5	223
1972	20.5	214
1982	17.0	205

Table 1. Average Steam Tone T & P

Significant detail appears on the figures. The area occupied by the steam zone is not constant. As temperatures fall, the steam zone expands into regions formerly too cold to contain steam. The highest pressures are always at Te Mihi. Lower pressures at Karapiti reflect the presence of lower temperatures in the initial state of the field. Lower pressures in the borefield reflect the discharge of steam by shallow-feeding wells and the loss of steam condensed by entering groundwater. Steam pressures at Te Mihi are also sustained by continued deep upflow, which boils and supplies steam.

Using $\langle\rho C\rangle = 2.5$ MJ/m^{3}K, $\phi(1 - S_0) = 0.10$, $A = 11$ km^2, gives the heat loss 1962-72 as 3.5×10^{17} J, and 1972-82 as 10^{17} J. Natural and artificial discharge 1962-72 was 8.7×10^{17} J, so that there was 5.2×10^{17} J of heat recharge. Gravity (Hunt, 1977) indicates recharge of 4.8×10^{11} kg, so that the recharge enthalpy was 1080 kJ/kg, or 250^0 water. The smaller heat loss 1972-82 indicates a similar recharge enthalpy, as the discharge enthalpy was then lower.

Part of the recharge is of course at 260^0+. The natural upflow of 400 kg/s will have continued to enter the reservoir. This is about one-quarter of the discharge. The remaining recharge has been stimulated by exploitation, in particular by the pressure drop in the reservoir.

Some of the recharge stimulated by exploitation will be of colder water. The steam zone temperature changes take account only of the recharge enthalpy at the point where it contacts the steam zone. Water flowing inwards laterally will gain heat from the peripheral rock, and the resultant cooling of this peripheral rock has not been counted in the heat balance.

A further heat transfer unaccounted for is the heat taken from the steam zone when it expands into rock that was not initially at boiling temperatures. Steam is condensed to heat the rock and hence lost from the steam zone.

TEMPERATURES OUTSIDE THE STEAM ZONE

Some peripheral wells do give the appearance of cooling, e.g. WK47; although WK10 (Grant, 1979) is an example where this appearance is deceptive. Figure 4a shows temperatures at RL-200 m in 1981. Figure 4b is an enlarged plan of the western borefield. Saturated conditions correspond to about 235°C.

There were severe problems with data interpretation for Figures 4 and 5, which are discussed in the Appendix.

Strikingly apparent is a colder area in the western borefield, associated with the Kaiapo and Wairakei Faults- As temperatures here were once above 250°C, this indicates cold water entry. Highest temperatures (and pressures) are found at Te Mihi. The lower temperatures toward Karapiti have apparently always been present.

A further indication of the fluid flow in the reservoir is shown in Figure 5. Wells were divided into those showing upflow and those showing downflow in the water column in the well. Downflow is found in the eastern borefield, and along the faults in the western borefield. Upflow is apparent along an east-west line extending from wells WK212 and 221 in the western borefield.

No intrusion is apparent in the eastern borefield, although there is known to be some surface water entry (from the enthalpy of wells WK4/1, 4/2, 40). Although the intrusion markedly affects some wells, it is not a significant part of the reservoir heat balance. Assuming 10°C cooling over 1 km² of reservoir, and over a thickness of 300 m, there is a heat loss of 10^{16} J, small compared to the heat loss from the steam zone. A more accurate quantitative assessment of the extent of cold water entry could probably be made from chemical data, as for example in Grant and O'Sullivan (1982).

CONCLUSIONS

In the natural state of Wairakei there was an upflow in the northwest of the field (Te Mihi) from which fluid flowed laterally to the area of the present borefield and to Geyser Valley. Under exploitation, pressures have fallen and temperatures with them. Upflow has continued at Te Mihi, while cold surface water has entered the borefield.

With continued exploitation, the effects of cold inflow will increase, and there will be a steady loss of productive wells. Even when this is so extensive that most wells cease to produce, there will remain at Te Mihi a productive resource - a permeable area of about 4 km² with wells that compare very favourably in performance with those in many fields. Long-term exploitation of Wairakei

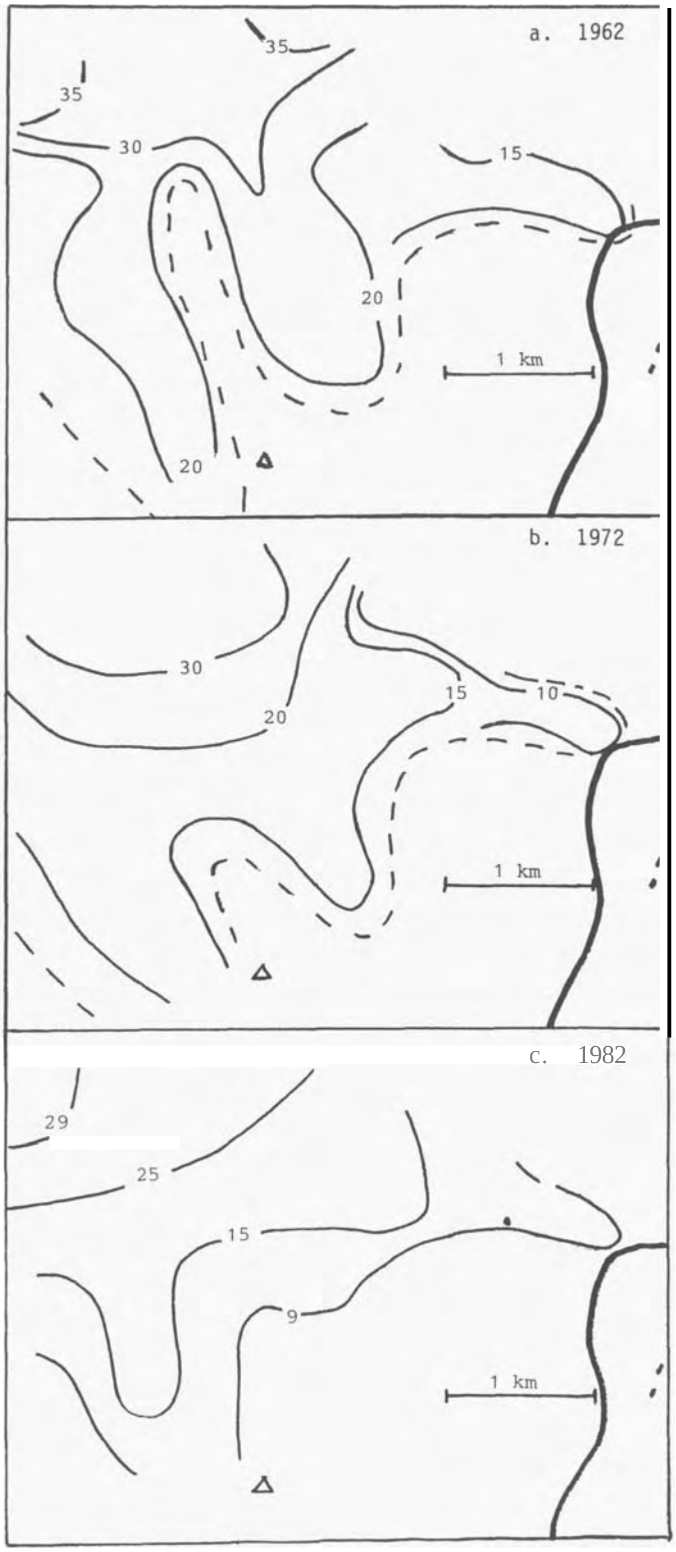

Figure 3. Steam Zone Pressures in Bars. Dashed line indicates boundary of Steam Zone.

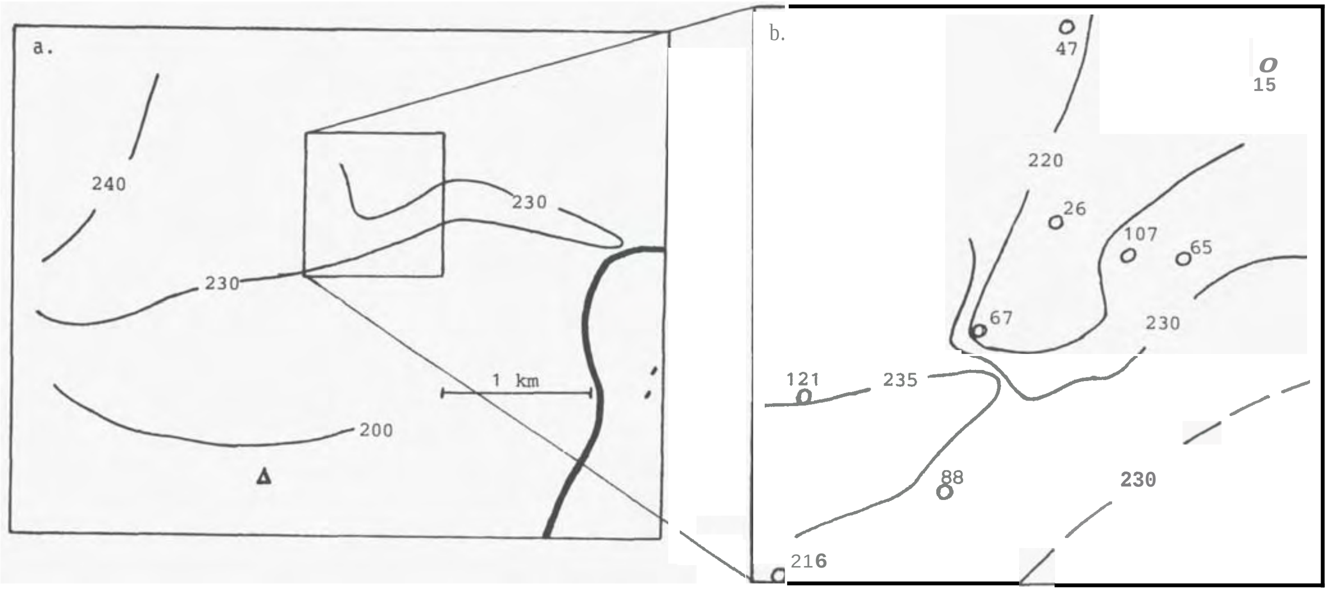

Figure 4. Isotherms at RL-200 m
a. Field;
b. 1 km square inset covering western production area.

will depend upon the development of Te Mihi, to supply steam either to the existing station or to a replacement built nearby.

A long-term exploitation strategy for Wairakei will probably also include reinjection, perhaps of the existing waste and certainly of the waste from any new development. The extensive permeable area at Wairakei means that suitable injection sites are much easier to find than at, say, Broadlands. The observed pattern of tracer returns and of cold water entry shows a marked preference for flow along the SW-NE trending faults. Given that there should be no rapid returns to the existing borefield or to the Mihi, a very suitable injection area is available at Karapiti. In the long term, as the existing borefield is quenched, some wells there might be used as injectors, on the assumption that little production remains in the area anyway. Under no circumstances should wells at Te Mihi (e.g. WK219 or 221) be used as injectors.

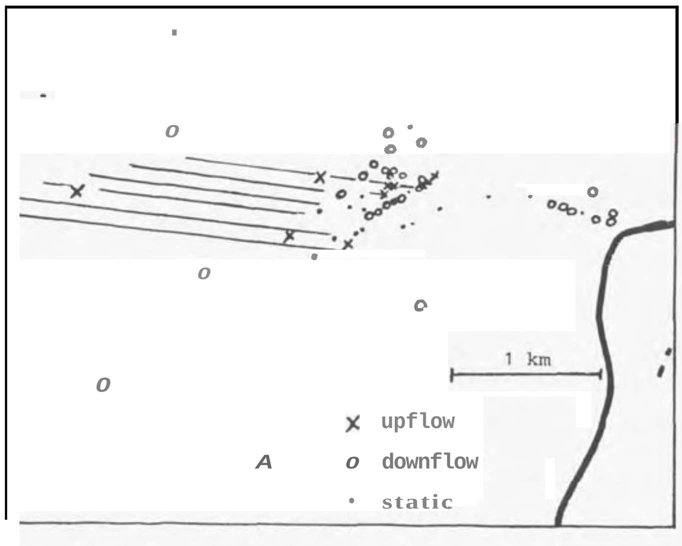

Figure 5. Indications of upflow or downflow in wells. Area of upflow is shaded.

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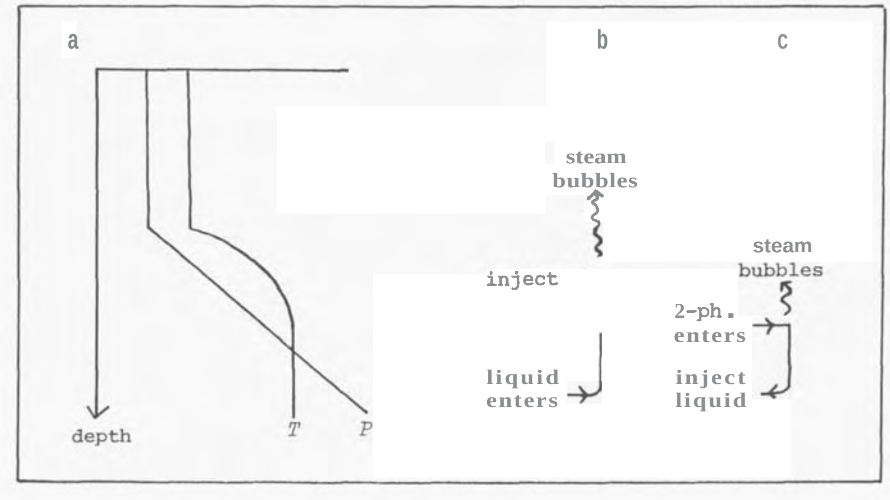

Figure 6. Isothermal/boiling-point profile and two possible interpretations.

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APPENDIX

Both in the determination of reservoir temperatures, and in the direction of flow in a well, there are severe problems with many Wairakei production wells. The difficulties in determining reservoir temperature mean that Figure 4b shows an exaggeratedly smooth profile of cold water entering. Only extreme temperatures, high and low, can be safely identified, and these show the indicated pattern. It is possible that wells with intermediate temperatures may reflect reservoir temperatures truly between the extremes. There could, for example, be spots at 225o within the 220o contour.

The direction of flow within a well poses a more subtle problem. Figure 6a shows a frequently encountered temperature and pressure profile - the water column in the well shows an isothermal/boiling-point profile. The normal interpretation is that this reflects an upflow in the well, as is shown in Figure 6b. As the isothermal section in recent measurements is usually considerably colder than original temperatures, this interpretation implies some cooling by cold water entry, as well as upflow in the well. An alternative interpretation is possible, shown in Figure 6c. Two-phase fluid enters the well, and there is a downflow of water in the well. It is often not possible to decide between the two alternatives. A discharging profile is usually conclusive. WK30 is an example. Discharging temperatures show the same temperature in the bottom section of the well, confirming a liquid water feed, cooling by cold water entry, and upflow in the shut well. WK61 (Grant, 1979) is an example where other measurements show higher temperatures at bottom, indicating the second interpretation and downflow in the well.