Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Renewability of the Wairakei-Tauhara Geothermal Resource

Michael O'Sullivan and Warren Mannington

Department of Engineering Science, University of Auckland, Auckland, New Zealand

m.osullivan@auckland.ac.nz

Keywords: Renewability, modeling, Wairakei.

ABSTRACT

The current production of geothermal fluid from the Wairakei-Tauhara system exceeds the natural recharge of heat by a factor of 4.75. Even with this rate of heat abstraction Wairakei-Tauhara is expected to be able continue supplying the present amount of separated steam for at least another 50 years. The present paper considers the recovery of Wairakei-Tauhara after it is shut down, say in 2053. In particular it investigates how long will it take for Wairakei-Tauhara to fully recover to its original state and what changes will occur during the recovery process.

1. INTRODUCTION

The average heat flux through the surface of the continents is 65 mW/m^2 and through the oceanic floor it is 101 mW/m^2 (see Pollack et al., 1993, Stefansson, 2005). Thus the weighted average for the Earth is 87 mW/m^2. In geothermal systems it is higher. In warm water systems the heat flux is 2 – 3 times the world average and the only heat transfer mechanism is conduction. However in vigorous convective geothermal systems such as Wairakei (New Zealand) the heat flux is much larger and is accompanied by a large convective mass flow as well. In its pre-production or natural state the total mass flux at Wairakei was in the range 350 – 550kg/s (Allis, 1981) and the corresponding energy flow was 400 – 620MW$_{th}$. However recently at Wairakei the electrical output has been approximately 170MW$_e$ produced from an average mass take of approximately 135ktonnes/day with a corresponding energy flow of 1900MW$_{th}$. As shown in Fig. 1 the mass take at Wairakei-Tauhara has been relatively constant for almost thirty years but the electrical output has increased slowly as plant modifications have improved the conversion efficiency. Recently a second small power station (approximately 40 MW$_e$) was added at Poihipi Road. More details of the history of Wairakei-Tauhara are given by Clotworthy et al., (1999).

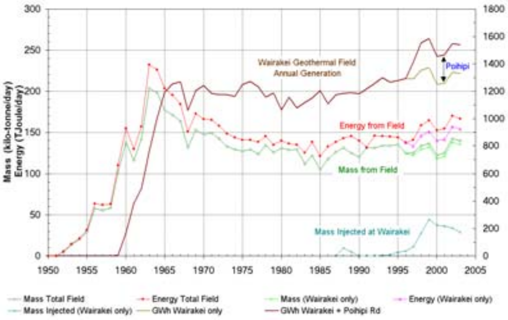


Figure 1: Production History at Wairakei.

For convenience we introduce the term "production ratio" or PR defined by:

$$PR=(\text{produced energy flow})/(\text{natural energy flow}), \quad (1)$$

Using the lowest figure from Allis (1981) this gives a production ratio (PR) for Wairakei of 4.75. Thus heat is currently being removed from the Wairakei-Tauhara system faster than it is being replaced by deep recharge and obviously the present rate of electricity generation cannot be sustained forever. Computer modeling studies show that the present rate of steam production at Wairakei-Tauhara can be sustained for at least fifty years (see O'Sullivan et al. 1998, Mannington et al. 2000, 2004) but the question remains as to what happens after that. The purpose of this paper is to investigate the following two matters:

(i) How long will it take for Wairakei-Tauhara to fully recover to its original state after shut-down at some time in the future?

(ii) What changes will occur during the recovery process?

The first question will be addressed initially by considering a simple lumped parameter model. Then both questions will be investigated with a large, complex, three-dimensional computer model.

2. LUMPED PARAMETER MODEL

In the pre-production or natural state a geothermal system can be represented by the lumped-parameter model shown in Figure 2.

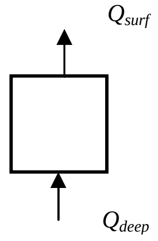


Figure 2: Diagrammatic sketch of the natural state of a geothermal system.

Here the surface outflow of heat Q_{surf} is equal to the deep inflow Q_{deep} , i.e.:

$$Q_{surf} = Q_{deep} \quad (2)$$

During production, energy is extracted at a rate Q_{prod} by the production wells. Some extra convective flow and deep hot recharge Q_{rech} may be stimulated by the production induced pressure decline. Thus the rate Q_{extr} at which heat is being extracted from the system is given by:

$$Q_{extr} = Q_{prod} + Q'_{surf} - Q_{deep} - Q_{rech} \quad (3)$$

Note that in (3) the energy flow from the surface Q'_{surf} is not the same as in the natural state. At Wairakei the surface heat flows decreased in the features supplied by hot water, e.g. Geyser Valley, and increased in some steam-fed features such as Karapiti, but overall heat flows are similar to their pre-production values (Allis, 1981). It is not obvious how much induced recharge is occurring at Wairakei although computer modeling indicates it may be significant (Mannington et al., 2004). If an approximate approach is taken and the surface energy flow and the induced recharge are ignored (or assumed to cancel one another) then (3) becomes:

$$Q_{extr} \approx Q_{prod} - Q_{deep} \approx (PR-1)Q_{deep} \tag{4}$$

Thus the present production regime at Wairakei is mining energy from the water, steam and rock at the top of the large natural convective plume that existed in the pre-production state at a rate of approximately 3.75 times the natural energy supply. Thus as hot water and steam have been produced cold water has flowed laterally and vertically downwards to replace it. This recharge was initially heated by energy in the rock matrix but eventually the cold water has encroached. This has resulted in the cooling off of some of the production wells. (Clotworthy et al., 1999).

This type of production strategy is not unique to Wairakei. Most developed geothermal fields are exploited at a rate faster than the energy is replaced by the pre-production flow (see for example: Williamson et al., 2001). Because of this fact the concept of sustainability or renewability of geothermal systems is complicated.

Clearly they cannot be produced at a rate corresponding to the installed capacity of their power plants on a continuous basis, forever. Thus in this sense they are not sustainable. However if after a time the power plants are shut down the natural energy flow will slowly replenish the geothermal system and it will again be available for production. Therefore when operated on a periodic basis, with production followed by recovery, geothermal systems are renewable and indefinitely sustainable. Again using the simple, lumped-parameter energy balance above the rate of energy recovery Q_{reco} will be given by:

$$Q_{reco} = -Q''_{surf} + Q_{deep} + Q_{rech} \tag{5}$$

If we assume that the surface flow Q''_{surf} and the induced recharge Q_{rech} are small and can be ignored then:

$$Q_{reco} \approx Q_{deep} \tag{6}$$

By equating the total heat extracted to the total heat recovered it follows that:

$$Q_{reco}T_{reco} \approx Q_{extr}T_{extr} \tag{7}$$

Here T_{reco} is the recovery time and T_{extr} is the duration of past production.

Then (4), (6) and (7) together give

$$T_{reco} \approx (PR-1)T_{extr} \tag{8}$$

Thus the ratio duration of the recovery duration to the duration of the production should be approximately one less than the ratio of production energy flow to natural energy through-flow (the PR defined in (1) above). The detailed recovery process will depend on the state of the reservoir and will require three-dimensional modeling for accurate assessment, but (8) should give a reasonable approximate estimate.

3. PREVIOUS INVESTIGATIONS

Several other authors have recognized the requirement for a production/recovery cycle in the long-term exploitation of geothermal systems. The most quantitative study of the topic was carried out by Pritchett (1998) in a computer modeling study of a generic geothermal reservoir. His model had a high permeability upflow leading into a reservoir zone with horizontal and vertical permeability both 10md. The maximum permeability of 10md used in the model is lower than that at Wairakei and many other fields but nevertheless the predicted post-abandonment behaviour is of general interest. In Pritchett's reservoir the natural state flows are 100 kg/s and 133MW$_{th}$ (330^{o}C water). The reservoir was produced for 50 years at an average rate of 60MW$_{e}$. This corresponds to 166.7kg/s of separated steam (5.5bars well head pressure). Pritchett does not provide the average fluid enthalpy but if we use a typical value from Wairakei of 1150kJ/kg then the total mass flow is 708kg/s and the energy flow is 814MW$_{th}$. This gives a PR value of 6.1.

After production ceased at 50 years Pritchett ran his model for a further 1000 years and calculated a 90% energy recovery at this time. He also gave figures at other times, for example 57.9% energy recovery at 250 years. Thus the approximate estimate obtained using (8) of a recovery time of 305 years is reasonable.

Pritchett concludes that *"Accordingly, it seems reasonable to conclude that geothermal systems which have been thermally depleted in this way will not recover after abandonment on time-scales comparable to life times of typical electrical power development projects. They will, however, recover on time-scales typical of lifetimes of civilizations"*.

We agree with this statement but observe that as in our discussion above that the recovery period can be obtained approximately by using (8).

Rybach et al. (2000), Megel and Rybach (2000) and Rybach (2003) also considered the question of the time-scale of the renewability of geothermal resources. They used a modeling study to show that for a doublet system operated cyclically in production-recovery modes that a 10-year cycle produced more energy then 20 year or 40 year cycles over a 160-year period. They also used modeling to investigate the thermal recovery of a warm water system following the cessation of the operation of a down-hole heat exchanger operation. They deduced that *"the recuperation period equals nearly time operation period"*. They also stated the general conclusion that *"….geothermal resources can be considered renewable on time-scales of technological/societal systems and do not need geological times as fossil fuel reserves do…"*

Stefansson (2000) discussed the renewability issue in qualitative terms and stated a similar conclusion *"… that the natural recharge of energy to most natural geothermal systems takes place on a similar time-scale as the exploitation of these resources…"*.

4. WAIRAKEI-TAUHARA

The Wairakei-Tauhara system has been under production for almost 50 years (Clotworthy et al., 1999). As discussed above the production ratio for Wairakei is 4.75 (i.e. (produced energy flow)/(natural energy flow)=4.75), and therefore the current operation at Wairakei is not sustainable on a continuing basis.

During the production history of Wairakei a number of interesting phases have occurred. Early on (late 1950's, early 1960's) the pressures in the borefield declined rapidly (see Fig. 4). By 1970 the pressures stabilized as a quasi-equilibrium state had been established with the combination of induced recharge (cold from the sides and above and hot from the sides and below) and induced boiling matching production. The boiling induced by the pressure decline has resulted in the development of a large boiling zone. As the boiling has progressed heat has been extracted from the rock matrix and the pressure has continued to slowly decline and the reservoir temperatures have declined. Thus the mass change effects happened on a shorter time scale than the energy changes.

The purpose of the present paper is to investigate the behavior of Wairakei-Tauhara system after it is shut down at some time in the future. From our analysis above it is anticipated that it will take 3-4 times as long to recover as the total production period but it is interesting to find out exactly what form the recovery will take. From experiences during the past production and the expected difference in time-scales for mass and thermal effects, it is expected that the pressure recovery will be much faster than the temperature recovery.

5. COMPUTER MODELLING

The authors have developed a computer model of Wairakei-Tauhara (O'Sullivan et al 1998, Mannington et al. 2000, 2004) on behalf of Contact Energy Limited (the field operators). Because of the extensive database for Wairakei-Tauhara and the relative long production history it has been possible to develop a well-calibrated model. For the present study a scenario is considered where Wairakei-Tauhara is continued in production for a further 50 years and then shut down for 500 years. This gives a total of 100 years of production followed by 500 years of recovery.

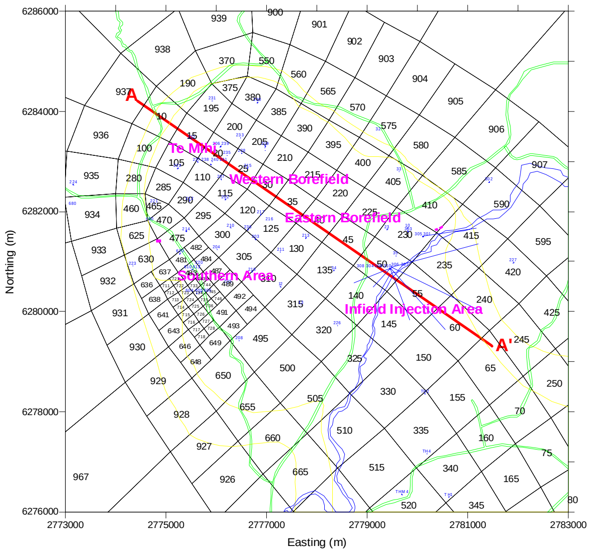


Figure 3: Plan view of the model structure.

A plan view of part of the model structure is shown in Fig. 3. The main production areas are labeled: Eastern Borefield, Western Borefield and Te Mihi.

6. RESULTS

In Fig. 4 the pressures in the Western and Eastern Borefields are plotted for 1953-2353. There is very little change between 2353 and 2553 and therefore those results are not shown in Fig. 4 or later plots. The rapid decline in pressure after production began in 1953 is clear and there is also a rapid recovery after field shut-down in 2053. Most of the current production is from the Western Borefield and Te Mihi, but after shut-down the pressure recovery is very rapid in both the Western and Eastern Borefields. This is a consequence of the high permeabilities in the Wairakei-Tauhara system.

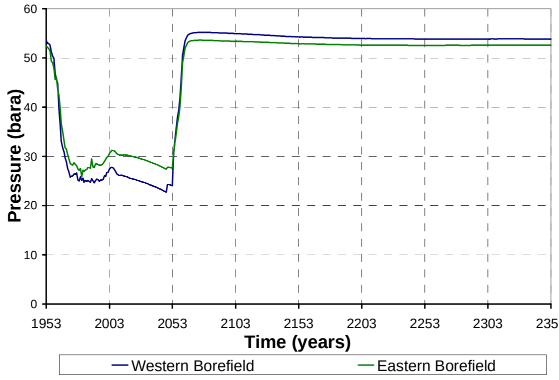


Figure 4: Pressure Recovery

The corresponding plot of temperature versus time is given in Fig. 5. It shows the slower decline followed by the expected slower recovery. The recovery is slower in the Eastern Borefield, which is further away from the deep recharge.

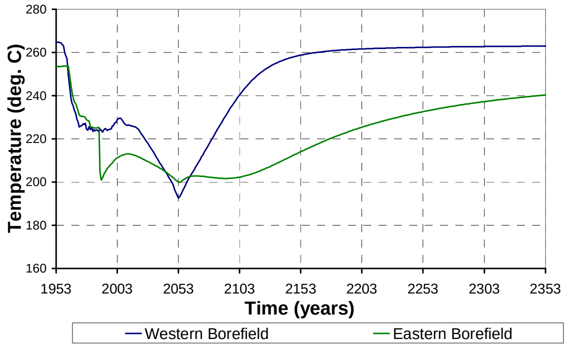
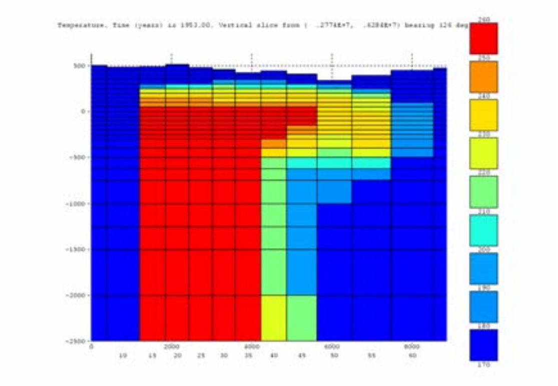


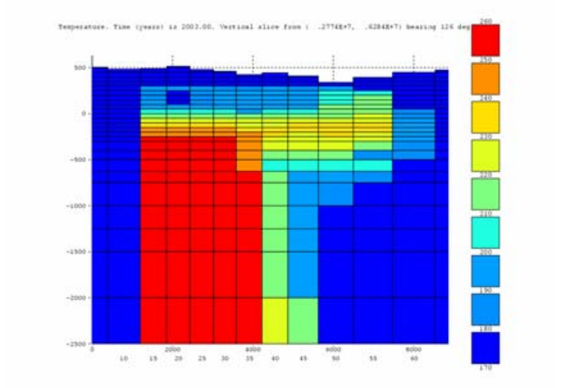
Figure 5: Temperature Recovery

Temperatures on a vertical slice through part of the Wairakei model are shown in Fig. 6. The location of the slice in the model is indicated by the line AA' shown in Fig. 3, running from block 937 to block 65. Fig. 6(a) shows the pre-exploitation situation in 1953. The upflow of hot water under the Te Mihi Borefield (blocks 15, 20 and 25) and the Western Borefield (blocks 30 and 35) is clear. Similarly the outflow through the Eastern Borefield (blocks 40 and 45) to Geyser Valley is clear. The temperatures for 2003 shown in Fig. 6(b) show effects of the gradual "mining" of heat during the production phase. The temperatures in the Eastern Borefield area have declined significantly between Fig. 6(a) and Fig. 6(b). This effect is confirmed by field data. Similarly the temperatures in the Western Borefield and Te Mihi have declined. Fig. 6(c) shows further mining of heat from the top of the upflow plume that will occur by 2053.

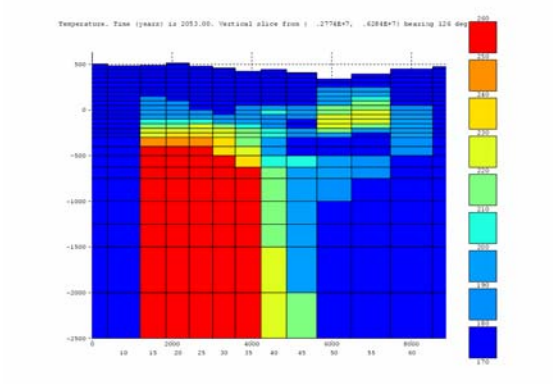
After shut-down the slow recovery begins. By 2153 (see Fig. 6(d) the hot plume has started to rise in the Western Borefield and Te Mihi. This process has proceeded further by 2253 (see Fig. 6(e)) and by then some recovery in the Eastern Borefield has occurred. By 2353 the system has almost recovered to its pre-production state (compare Fig. 6(a) and Fig. 6(f)).



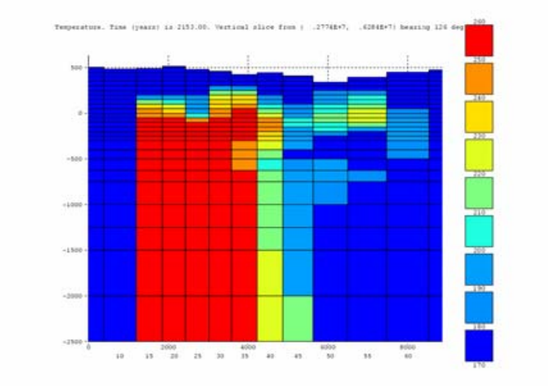
(a) 1953



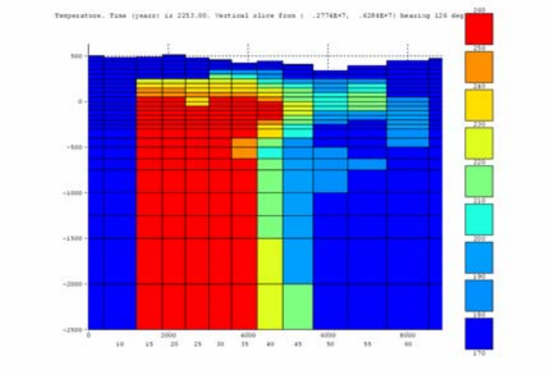
(b) 2003



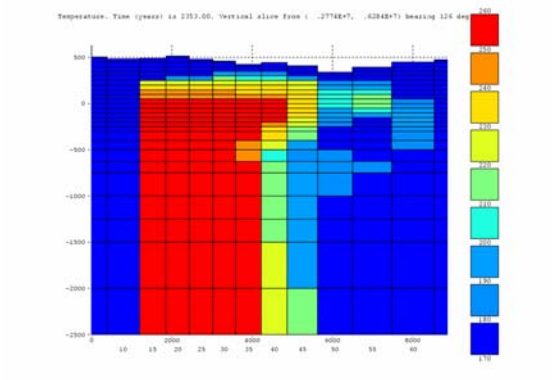
(c) 2053



(d) 2153



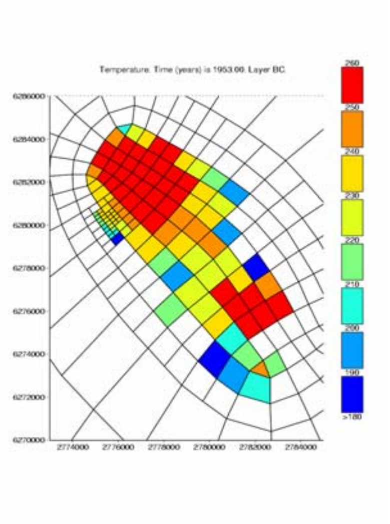
(e) 2253



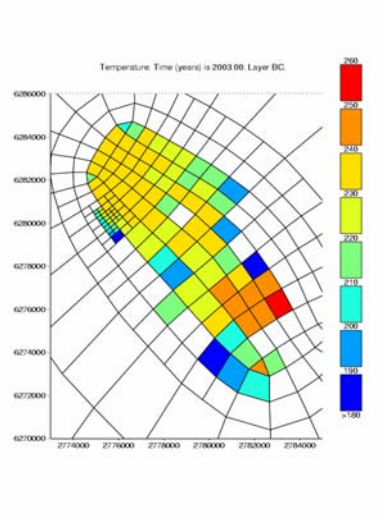
(f) 2353

Figure 6: Temperatures on a vertical slice through the Wairakei model

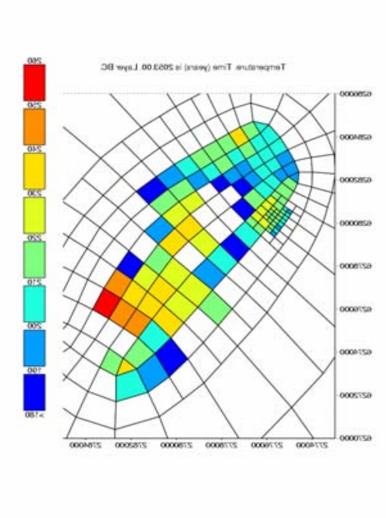
An alternative view of the temperatures is given in Fig. 7 where temperatures are shown on model layer BC which corresponds to the deep liquid production zone. They also show the decrease in temperatures on this layer from 1953 to 2003 and then to 2053. The recovery proceeds slowly from 2053 through 2153 and 2253 and is nearly complete by 2353. In these plots the blocks with temperatures less than 180 $^\circ C$ are not shaded.



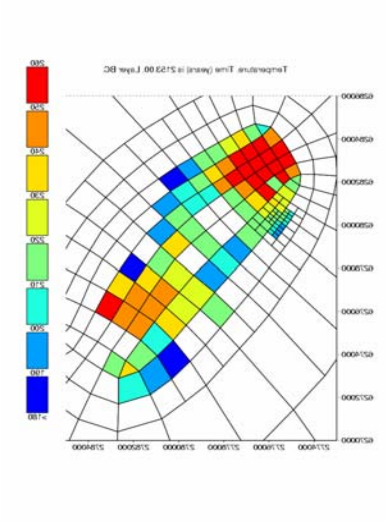
(a) 1953



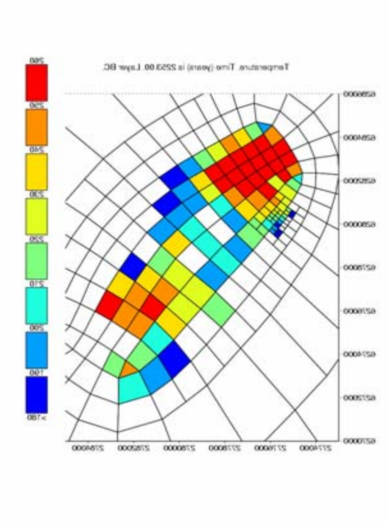
(b) 2003



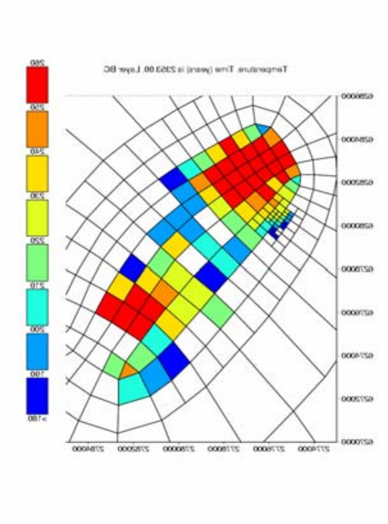
(c) 2053



(d) 2153



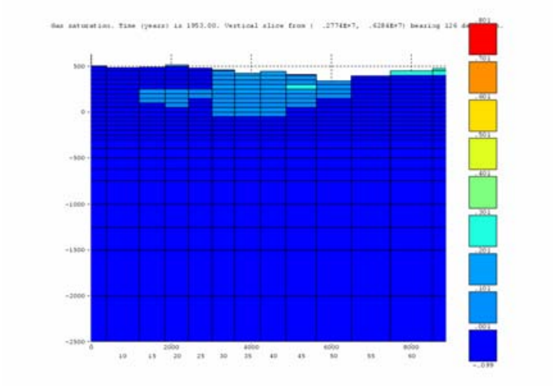
(e) 2253



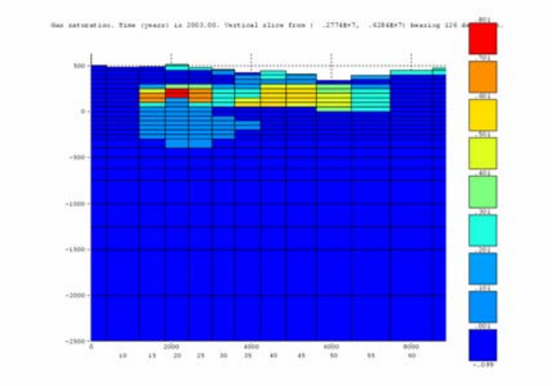
(f) 2353

Figure 7: Temperatures on the BC layer (deep liquid production zone) in the Wairakei model

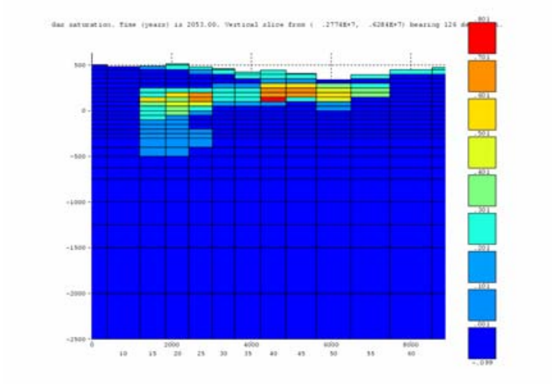
Plots of vapour saturation on the vertical slice are given in Fig. 8. As shown in Fig. 8(a) there was only a low level of boiling in the pre-production state in 1953, but there was a large expansion of the boiling zone during production up to 2003 (see Fig. 8(b). The slow cooling of the system between 2003 and 2053 causes the boiling zone to contract slightly (see Fig. 8(c)), even though pressures continue to fall slowly. The pressure build-up after shut-down causes the rapid collapse of the steam zone. By 2153 there is very little boiling at all (see Fig. 8(d)). However a slow return of a low level of shallow boiling occurs by 2253 and 2353 (see Fig. 8(e) and Fig. 8(f)).



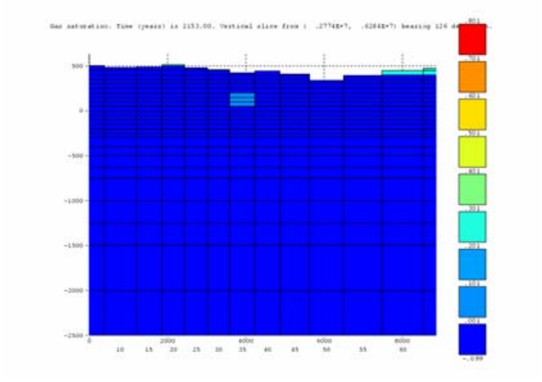
(a) 1953



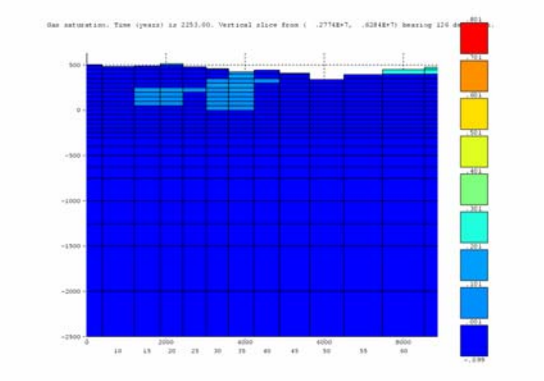
(b) 2003



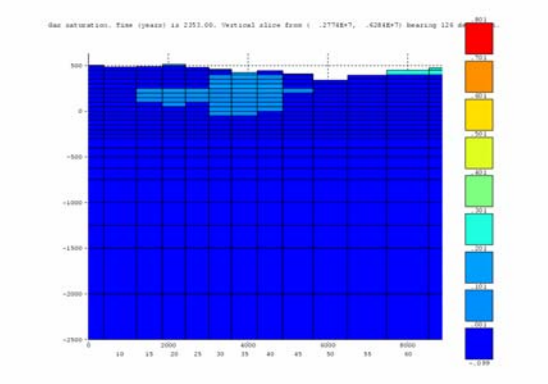
(c) 2053



(d) 2153



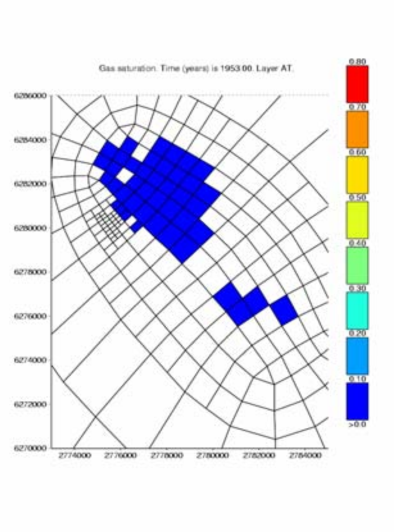
(e) 2253



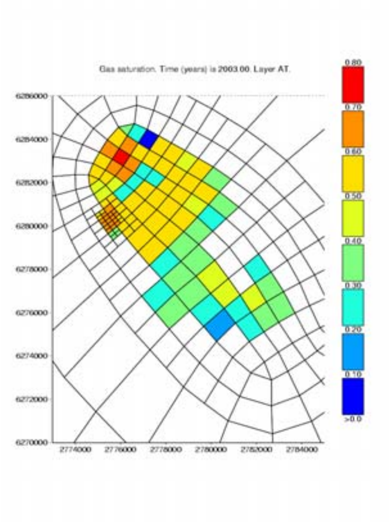
(f) 2353

Figure 8: Vapour Saturations on a vertical slice through the Wairakei model

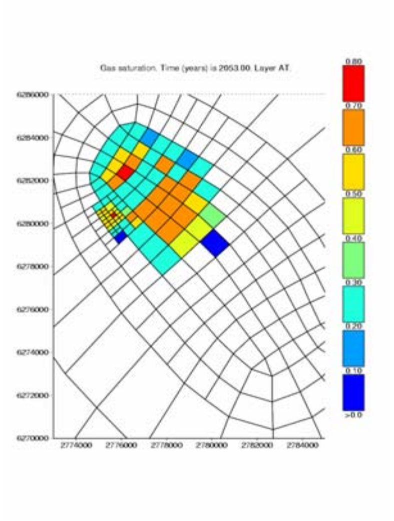
The vapour saturations are also shown in Fig. 9 for layer AT in the model. This corresponds to the elevation of the feed zones of wells that tap the shallow steam zone. These plots show the same pattern as in Fig. 8. The steam zone expands up to 2003, and then slowly contracts until shut-down in 2053. It then disappears almost completely and very slowly recovers to its pre-exploitation state. In Fig. 9 all-liquid zones are not shaded.



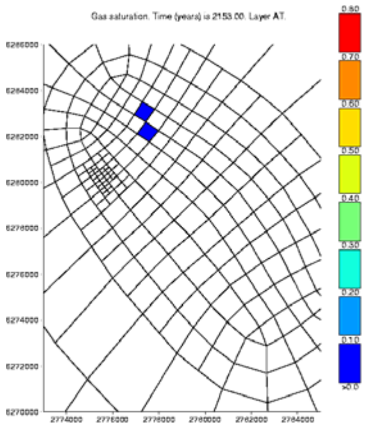
(a) 1953



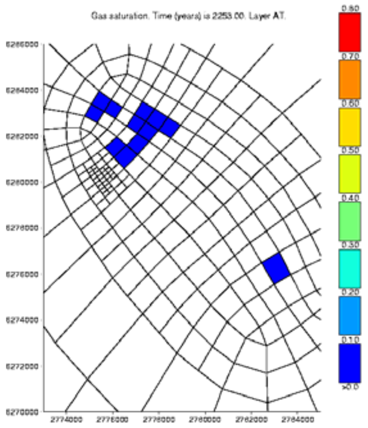
(b) 2003



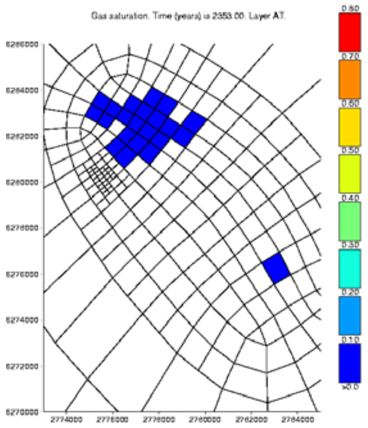
(c) 2053



(d) 2153



(e) 2253



(f) 2353

Figure 9: Vapour saturations on the AT layer (shallow steam zone) in the Wairakei model

The disappearance of the steam zone is also shown by the plots of vapour saturation vs time, for two typical steam zone blocks, given in Fig. 10. In these blocks the boiling ceases very soon after the field shut-down in 2053. A very small amount of boiling gradually develops after 2203 as the system returns to its 1953 state. As shown in Fig 9(a) blocks AT 20 and AT35 are just boiling in the natural state.

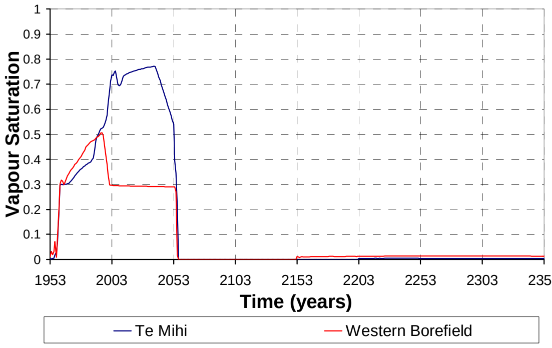


Figure 10: Vapour saturations vs Time for Te Mihi Steam Zone (block AT 20) and Western Borefield (Block AT 35)

The surface mass and heat flows at Geyser Valley are shown in Fig. 11. These plots show the rapid decline of activity at Geyser Valley resulting from production (as was observed) and the rapid return of surface flows after field shut-down. However as shown in Fig. 11 the surface flows at Geyser Valley after 2053 will be cool to begin with and it will take a long time for the original thermal activity to redevelop.

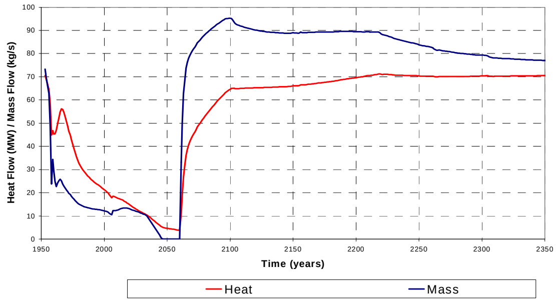


Figure 11: Heat and Mass Flows at Geyser Valley

Although production at Wairakei caused the thermal activity at Geyser Valley to decrease it caused an increase in the steam heated features at Karapiti. The heat flux at Karapiti is shown in Fig. 12. This plot shows that the thermal activity at Karapiti will continue to slowly decline until 2053 when it will have almost disappeared. After field shut-down some small activity will re-establish but the heat to mass ratio will be less than during the production period.

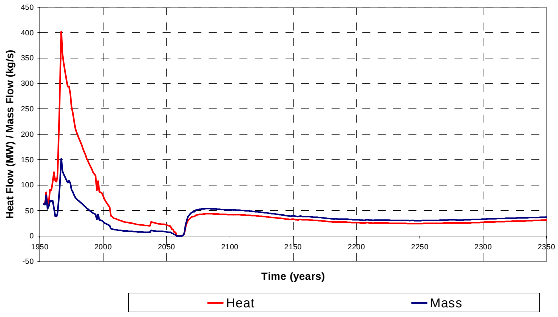


Figure 12: Heat and Mass Flows at Karapiti

7. CONCLUSIONS

These investigations show that if steam production, and therefore electricity generation, is continued at Wairakei-Tauhara until 2053 and then shut down the field will recover to almost its pre-production state in 300 years. This is three times the total period of production. The factor of three agrees well with the value of 3.75 obtained from our approximate formula (8).

Thus Wairakei is indefinitely sustainable on a cycle of 100 years of production (at 170MW$_e$) followed by 300 years of recovery. It is an interesting question (beyond the scope of this paper) to consider whether or not this strategy is optimal or indeed what the criteria for optimality should be.

REFERENCES

Allis, R.G., Changes in Heat Flow Associated with Exploitation of Wairakei Geothermal Field, New Zealand, *New Zealand Journal of Geology and Geophysics*, **24** (1981), 1-19.

Clotworthy, A.W., Carey, B.S. and Allis, R.G., Forty Years Sustained Production from the Wairakei-Tauhara System, *GRC Transactions*, **23**, (1999), 535-540.

Mannington, W.I., O'Sullivan, M.J. and Bullivant, D.P.: An air/water model of the Wairakei-Tauhara geothermal system. *Proceedings of the World Geothermal Congress*, Kyushu-Tohoku, Japan, (2000), 2713-2718.

Mannington, W.I., O'Sullivan, M.J. and Bullivant, D.P.: Computer Modelling of the Warakei-Tauhara Geothermal System, in press in *Geothermics*, 2004.

Megel, T. and Rybach, L., Production Capacity and Sustainability of Geothermal Doublets, *Proceedings of the World Geothermal Congress*, Kyushu-Tohoku, Japan, (2000), 849-854.

O'Sullivan, M.J., Bullivant, D.P., Follows, S.E. and Mannington, W.I.: 1998, Modelling of the Wairakei – Tauhara Geothermal System, Proceedings, TOUGH Workshop '98, Berkeley,California (1998).

Pollack, H.N., Hurter, S.J. and Johnson, J.R., Heat flow from the earth’s interior: Analysis of the global data set. *Reviews of Geophysics*, **31**, (1993), 267-280.

Pritchett, J.W., Modeling Post-Abandonment Electrical Capacity Recovery for a Two-Phase Geothermal Reservoir, *GRC Transactions*, **22**, (1998), 521-527.

Rybach, L., Megel, T. and Eugster, W.J., At What Time Scale are Geothermal Resources Renewable?, *Proceedings of the World Geothermal Congress*, Kyushu-Tohoku, Japan, (2000), 867-872.

Rybach, L., Geothermal Energy: Sustainability and the Environment, *Geothermics*, **32**, (2003), 463-470.

Stefansson, V., The Renewability of Geothermal Energy, *Proceedings of the World Geothermal Congress*, Kyushu-Tohoku, Japan, (2000), 883-888.

Stefansson, V., World Geothermal Assessment, To be published: *Proceedings of the World Geothermal Congress*, Antalya, Turkey, (2005).

Williamson, K.H., Gunderson, R.P., Hamblin, G.M., Gallup, D.L. and Kitz, K., Geothermal Power Technology, *Proc.IEEE*, **89**(12), (2001), 1783-1792..