PROCEEDINGS, Twenty-Ninth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 26-28, 2004
SGP-TR-175

REINJECTION AT WAIRAKEI – TAUHARA: A MODELLING CASE STUDY

W. I. Mannington[1], M. J. O'Sullivan[1], D.P. Bullivant[1] and A. W. Clotworthy[2]

[1]Department of Engineering Science, University of Auckland.
Private Bag 92019,
Auckland, New Zealand
e-mail: warren@mannington.co.nz
[2]Contact Energy Limited,
Private Bag 2001,
Taupo, New Zealand

ABSTRACT

A computer model has been used to investigate various options for disposal of separated water and power station condensate from the Wairakei-Tauhara system. In particular the effects of in-field reinjection are compared with those produced by alternative means of disposal. Our modelling results show that infield reinjection reduces the useful life of the resource and thus compromises its sustainability. This is an important result as the policies and regulations governing geothermal utilisation within the Waikato region of New Zealand, which covers the Wairakei-Tauhara geothermal system, are currently being reconsidered as part of a notified public process.

INTRODUCTION

In the summary of the review article by Stefansson, 1997, it is stated that: "*Both theoretical studies and field experience clearly demonstrate the beneficial effects of reinjection, and reinjection is considered to be an essential part of good field management.*" Several other articles have also discussed the benefits of reinjection. This attitude to reinjection has been adopted by some geothermal regulatory agencies. For example, Section 3.7.2 of the Environment Waikato (New Zealand) Proposed Regional Policy Statement (PRPS) states "*Reinjection of used geothermal fluid, where, practicable, ensures the remaining heat is not lost from the system.*" Section 3.7.2 covers the sustainable management of geothermal resources.

While we agree that reinjection likely forms a part of a geothermal development we believe that the statements about the benefits of reinjection require some qualification. In fact some reinjection strategies may lead to a degradation of the resource.

The obvious question then is what is the best strategy for reinjection in a geothermal field? In our opinion the answer to this key question depends on the type of geothermal field. We will distinguish three general types of system: vapour-dominated (e.g. The Geysers), two-phase, liquid-dominated (e.g. Wairakei) and hot-water (e.g. East Mesa). In deciding upon the best reinjection strategy for each type of system it is important to recognize the dominant depletion mechanisms. For the three cases these are:

(i) Vapour-dominated systems run out of water while heat still remains in the rock matrix. Therefore it is useful to reinject water directly into the borefield (Bodvarsson and Stefansson, 1989; Barker et al., 1995; Cappetti et al., 1995; Pruess, 1995; Goyal, 1999).

(ii) Two-phase, liquid-dominated systems run out of heat rather than mass and the pressure and temperature decline together. Therefore extra water is not required in the reservoir and pressure support from reinjection is not effective. We claim it is best in this case to reinject or dispose of the water far from the production borefield. The main purpose of the present paper is to use a modelling study to support this claim.

(iii) In hot-water systems the failure mechanism is pressure decline, to the point where wells can no longer produce. The ideal reinjection strategy requires the reinjection wells to be close enough to the production wells to provide pressure support but far enough away to prevent premature flooding by cold water. The design of such system depends on details of the structure of the field and the practicalities of well location (Sta. Maria et al., 1995, Tokita et al., 1995).

Previous modelling study (Sigurdsson et al., 1995; Sigurdsson and Stefansson, 1998) considered various reinjection strategies for an idealised reservoir and all three types of initial conditions (i)-(iii). The study concluded that high enthalpy resources benefit from reinjection but the results for two-phase and hot-water reservoirs were not conclusive.

In the present paper we will consider only two-phase, liquid-dominated systems, using the Wairakei –

Tauhara system as a case study. Our aim is to determine what is the best reinjection strategy for a system like Wairakei – Tauhara. In particular we wish to determine where the reinjection wells should be located and if any changes in strategy with time should be made. Because in this study we are concerned with field-wide issues we will classify the location of reinjection only broadly as infield, outfield or none (see Table 1). For this study the existing reinjection area near the Wairakei power station is used as the infield reinjection site. Outfield reinjection is divided between the four sites shown in Figure 1 below.

Table 1. Reinjection locations

Type	Description
Infield	Within known boundaries of the reservoir. Permeable connection to production areas
Outfield	Outside known reservoir boundaries. Weak permeable connection to the reservoir.
None	Surface disposal or reinjection far from the reservoir

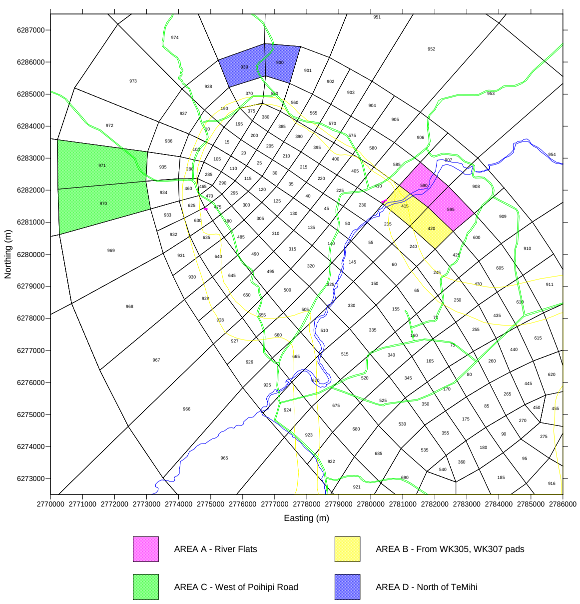

Figure 1- Location of Outfield Reinjection Zones at Wairakei Geothermal Field.

In the simulations described below a 100 year period from 1953 to 2053 is considered, but only simple temporal variations in reinjection strategy are allowed (see Table 2 below). Two intervals are used: 50 years representing past history and 50 years of future production. One reinjection strategy is used in each period. Obviously the past strategy for Wairakei –Tauhara cannot be changed but it is interesting to investigate whether or not a better strategy could have been used.

The measure of optimality used for assessing the various reinjection strategies is the amount of useful energy recovered i.e. the amount of separated steam produced. A secondary measure is the average enthalpy. Thus if two scenarios produce the same amount of separated steam then the preferred option is the one with the highest average production enthalpy, and consequently the lowest total mass take.

WAIRAKEI – TAUHARA GEOTHERMAL SYSTEM

The Wairakei power station was the first in the world to generate electricity from a two-phase, liquid-dominated reservoir. It began feeding power to the national grid of New Zealand in 1958. As the effects of geothermal extraction were not well known at the time, extensive scientific studies and monitoring were carried out both before and after production began. There is now 45 years of production history available for the field. Therefore the conceptual model of Wairakei – Tauhara system is well defined.

The Wairakei – Tauhara geothermal system is located to the north of Lake Taupo (Figure 2). The Wairakei field is on the NW side of the Waikato River and the Tauhara field is on the SE side. The hydrological link between the Wairakei and Tauhara fields is demonstrated by the fact that production at Wairakei has caused a change in Tauhara pressures. This means that the model must include both the Wairakei and Tauhara fields in order to get an accurate representation of the system.

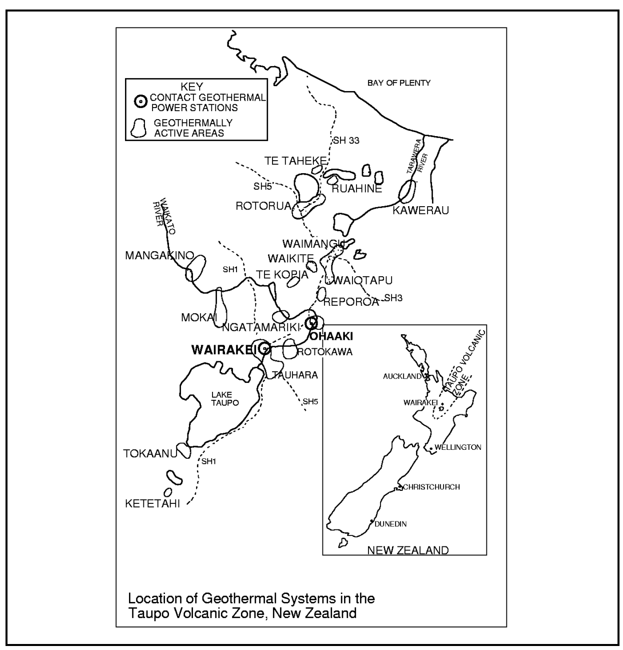

Figure 2- Location of Geothermal Systems in the Taupo Volcanic Zone, New Zealand

RESERVOIR MODEL

The University of Auckland has developed a succession of models of the Wairakei – Tauhara geothermal system (Blakeley and O'Sullivan 1981, 1982, Mannington et. al. 2000, 2004). The model used in this study is referred to as the 2000 Model and is detailed in Mannington. et. al. 2004. The reader is referred to this paper for full details of the model and the calibration process.

The model has 216 columns divided into 32 layers (a total of 5418 blocks). The thickness of the blocks in the top layer is varied to follow the topography of the Wairakei-Tauhara region, with some blocks being removed altogether. The model considers the flow of energy, water, and air within the geothermal system. Figure 3 shows the structure of the 2000 model that is the basis for this study.

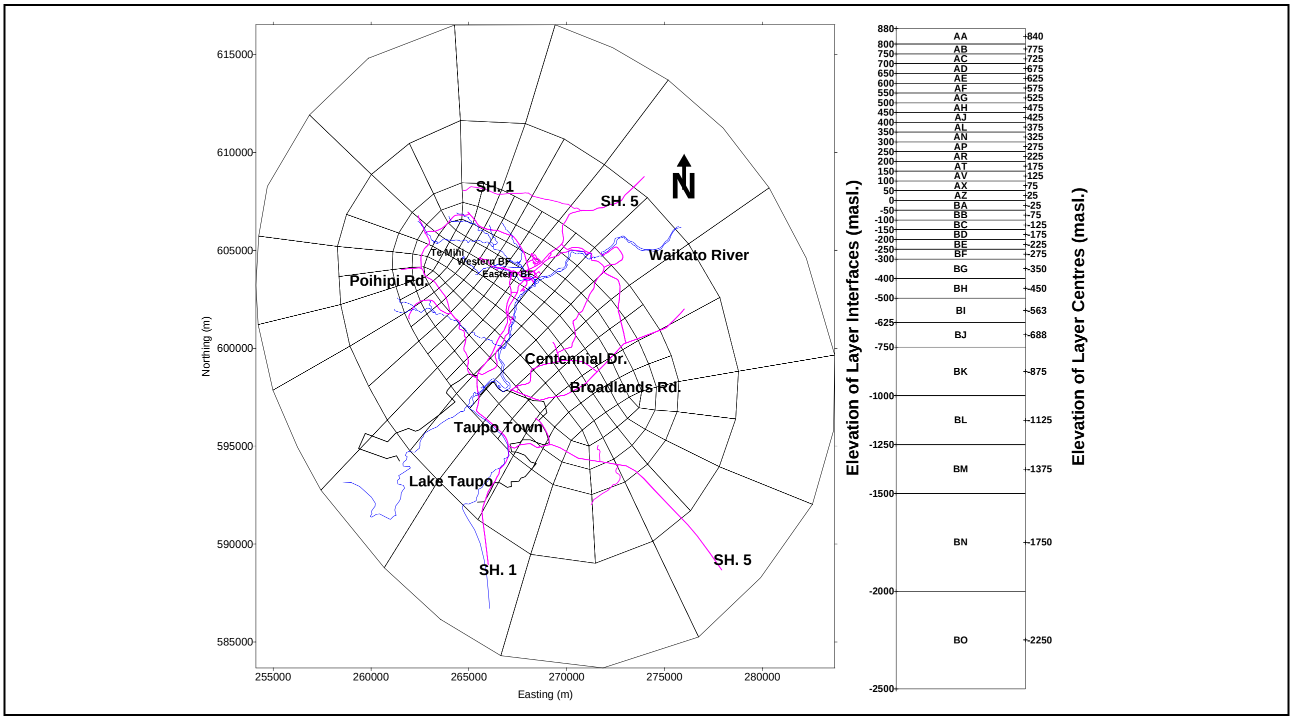

Figure 3– Model Grid Structure

MODEL SCENARIOS

Over the last 45 years of production at Wairakei only a small amount of the separated geothermal water has been reinjected. Most of the reinjection has occurred over the last 10 years.

The observed effects of this strategy include:

(i) The creation of a large two-phase zone with high vapour saturation in some locations (steam zones) and high enthalpy wells.

(ii) An increase in steam heated surface features (Karapiti).

(iii) The large drop in reservoir pressures have induced an increase in the deep recharge to the field.

With the scenarios listed below in Table 2 we are interested in investigating where it is best to reinject at Wairakei-Tauhara and whether or not it is best to maintain the present policy for 100 years or to change it now.

In all the scenarios a target figure of 32,000t/d for separated steam flow is used. Production wells are modelled as wells on deliverability and make-up wells are added when required to maintain the steam flow to Wairakei station. The scenarios are run for 100 years from 1953 to investigate the long-term effects of the different field management decisions. In all cases we assume Wairakei power station is the only station on the system with production initially coming from the Eastern and Western borefields. Production moves northwest into Te Mihi as new production is required.

Table 2 – Model Scenarios.

Scenario	1953-2003 Reinjection	2003-2053 Reinjection
A	Infield	Infield
B	none	none
C	30% Infield	30% Infield
D	Outfield	Outfield
E	none	Infield
F	none	Outfield

RESULTS AND DISCUSSION

Mass and steam flows

The mass flows for the Wairakei power station is shown in Figures 4 and 5, and the total steam flows are shown in Figures 6 and 7.

The scenarios that limit infield re-injection (B, C, D and F) are able to maintain the flow of separated steam flow for close to 100 years. Of these, Scenario F with no reinjection followed by outfield reinjection, maintains the flow for the longest time. The scenarios with a high level of infield reinjection (A and E) cannot maintain the steam flow for the full 100 years and when output starts to decline it does so rapidly.

As shown in Figures 4 and 5 the scenarios with a high level of infield reinjection (A and E) require a large production of mass to maintain the separated steam flow. This is also demonstrated in the average production enthalpy plots that are shown in Figures 8 and 9. The highest production enthalpy is achieved with Scenario B (no reinjection), but the enthalpy for Scenario F is not much lower.

Figure 7 shows that of the three options available for the future, outfield reinjection (Scenario F) produces the longest period of full production.

Figures 6 and 7 show that for the scenarios considered here, the policy of no reinjection for the previous 50 years is optimal. While outfield reinjection for 100 years (Scenario D) gives a better result than no reinjection for 100 years (Scenario B), overall Scenario F is better. As the separated steam flows for Scenarios B, D and F are similar a secondary measure of optimality, production enthalpy, should also be considered. The enthalpy under Scenario B (Figure 8) is the highest, hence requires the least amount of mass to be drawn from the system. Thus it is difficult to choose between Scenarios B, D and F. The environmental and economic aspects of each scenario have to be considered in order to make a decision.

Some infield reinjection can be tolerated without degradation of the resource. For example Scenario C (30% infield reinjection) gives results which are similar to those for Scenario B and are not much worse than those for Scenario F.

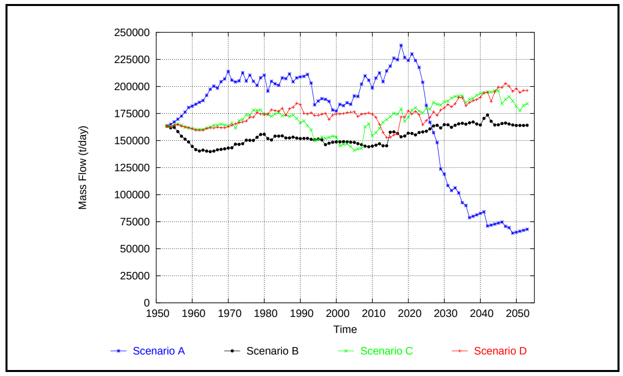

Figure 4 : Mass Flows

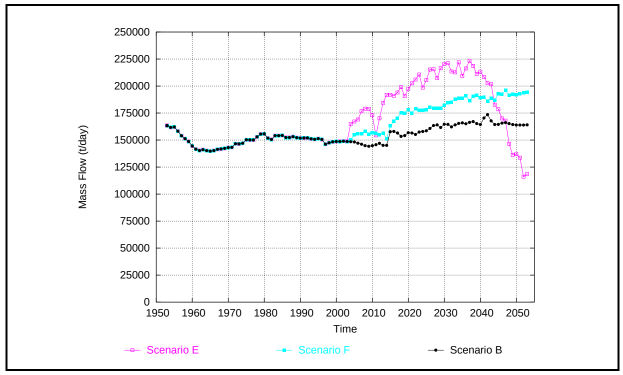

Figure 5 : Mass Flows

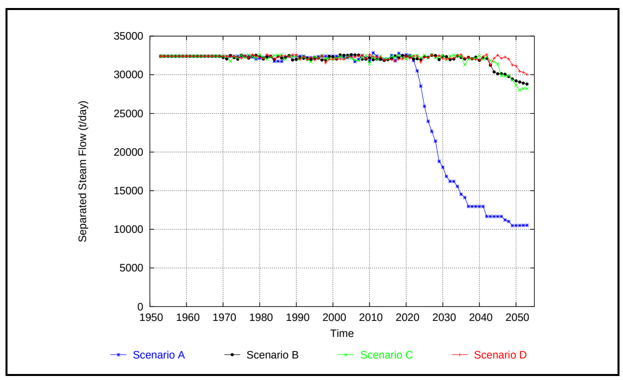

Figure 6 : Separated Steam Flows

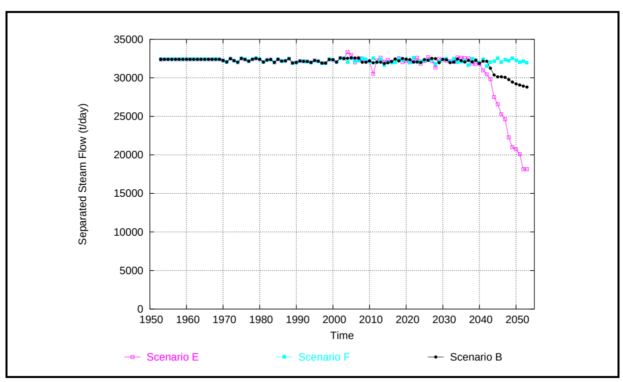

Figure 7 : Separated Steam Flows

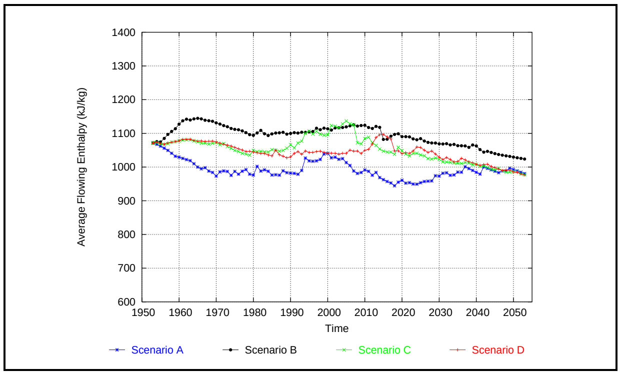

Figure 8 : Average flowing enthalpies

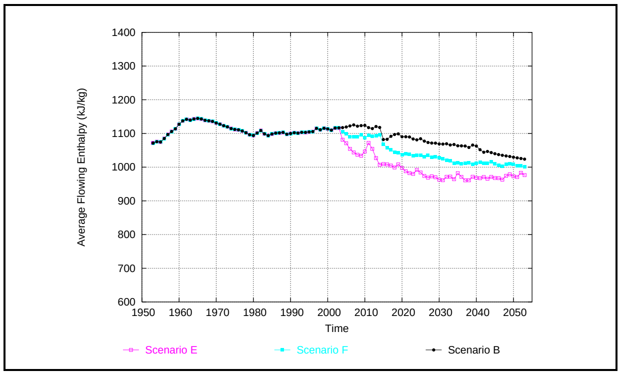

Figure 9 : Average flowing enthalpies

Energy Balance

As another measure of field performance we looked at the amount of stored energy in the Wairakei resource and how it changes with time under the different production scenarios. These data are presented in Figure 10. The energy values are relative to liquid saturated rock at 180°C.

Somewhat anomalously, for Scenario B, C and D at early times the stored energy decreases much faster than under Scenario A. This is because under Scenarios B, C and D the pressures decline quickly and a two-phase zone develops which causes an increase in steam heated surface features and hence there is an increase in heat flow to the surface which is lost to the system.

For Scenarios B, C and D there is virtually no decline in the energy content from 1985 through to 2010, although production continued throughout this time. The reason for this is as reservoir pressures decline this induces additional hot recharge from depth (Figure 11). For this period the system was in a quasi-steady state where the inflow of energy into the system matched the outflows from production and surface discharge. Under Scenario A the pressures are maintained by infield reinjection and suppress the hot recharge from depth (Figure 11). Also for Scenario A the reinjected water is at less than 180°C and therefore decreases the stored heat. The competing effects of surface losses, hot deep recharge and 80°C reinjected water mean that initially Scenario A performs well but eventually is inferior.

The energy content under Scenario F (not shown) follows a curve very similar to that for Scenario B. Under Scenario E (not shown) the energy content increase slightly above that for Scenario B from 2003 until 2035 and then declines more rapidly. The increase in energy content is due to reinjection just outside the borefield pushing warmer water inwards. The increase in reservoir pressure causes recharge from depth to decrease hence the energy content under Scenario E eventually declines faster than under Scenario B

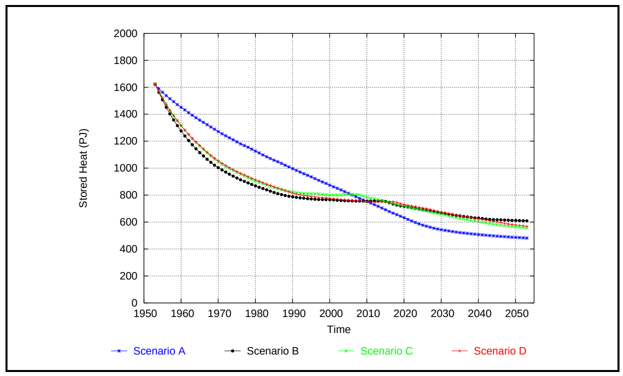

Figure 10 : Stored Energy in the Wairakei Area

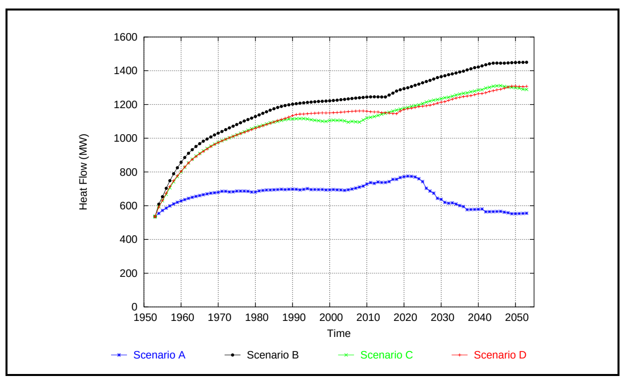

Figure 11 : Recharge of heat from depth in the Wairakei Area

Surface Features

Geothermal surface features have a high intrinsic value and over the history of Wairakei a number of surface features have ceased to flow. Hence we wanted to investigate the effect of different reinjection strategies on the natural surface features. Before development most of Wairakei and Tauhara's surface manifestations were liquid-fed. One of the major thermal areas was Geyser Valley, which is just to the north of the Eastern Borefield at Wairakei. Flow of geothermal water to the surface declined rapidly once production commenced (Bromley. et. al. 2000).

Figures 12 and 13 show the surface heat and mass flows respectively for the Geyser valley area. It is interesting to note that a large amount of infield reinjection would not have prevented the decline in Geyser valley. In fact the decline is faster due to the cooling caused by injection. Under Scenario A from 1980 onwards the surface mass flow slowly returns to pre-development levels, but the heat flow (hence the temperature of the discharge) is significantly less than pre-development levels.

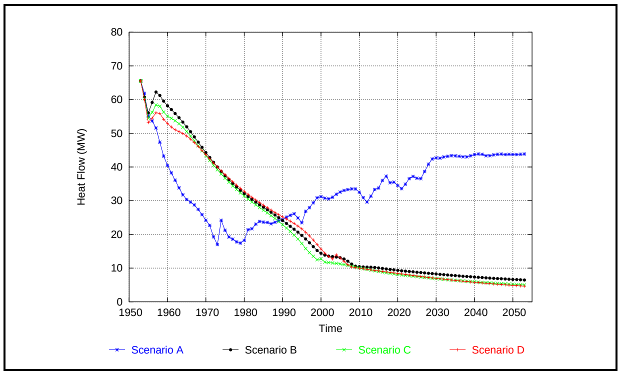

Figure 12 : Surface heat flow for Geyser Valley.

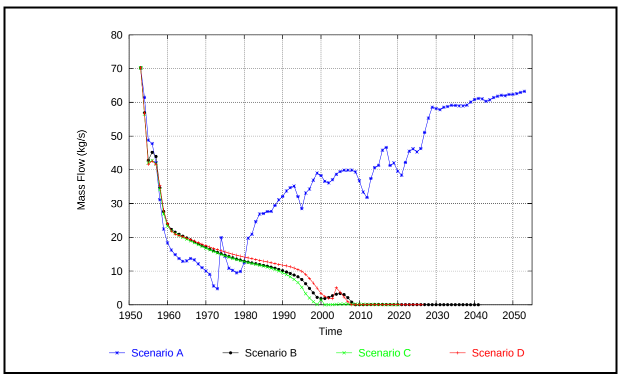

Figure 13 : Surface mass flow for Geyser Valley.

The Karapiti (Craters of the Moon) thermal area is an interesting aspect of the Wairakei field. Pre-development there was only about 40 MW_{th} of surface heat flow. As a result of the pressure decrease caused by production a large steam zone formed and caused an increase in surface activity at Karapiti. The surface heat flow increased to a peak of about 450MW_{th} in the 1960's and is now around 200 MW_{th}. (Bromley. et. al. 2000). Karapiti is now a popular tourist attraction.

Figures 14 and 15 show the surface heat and mass flows respectively for the Karapiti area. Scenarios B, C and D behave in a similar way and demonstrate the large increase in surface heat flow caused by the creation of the two-phase zone. Whereas with Scenario A, infield reinjection means that the pressures do not decrease and a steam zone does not form. Hence there would not have been a large increase in surface activity at Karapiti under this scenario.

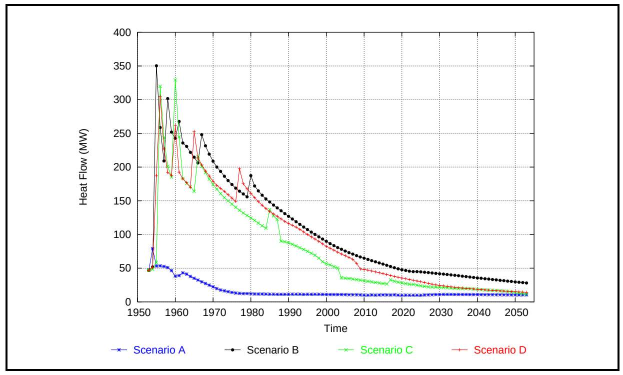

Figure 14 : Surface heat flow for the Karapiti area

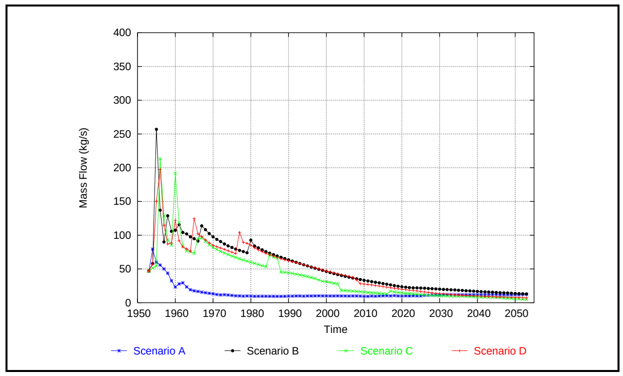

Figure 15 : Surface mass flow for the Karapiti area

Steam Zones

At present there is two steam zones that are used for steam extraction at Wairakei. One is the low-pressure southern steam zone, which extents to the south west of the production borefields. The other is the high-pressure Te Mihi steam zone. Most of the wells tapping these zones produce dry steam. Steam wells are more efficient as there is no separated water to be disposed off.

Figure 16 shows the vapour saturations on layer AT in 2003 for Scenario A. The steam zone is almost non-existent under this scenario. Figure 17 shows the same plot for Scenario B. A large steam zone is present. The effect of infield reinjection is to:

a) slow the decline of pressures, and
b) cool the reservoir fluid.

Hence with a higher pressure and a lower temperature, boiling is less likely to occur.

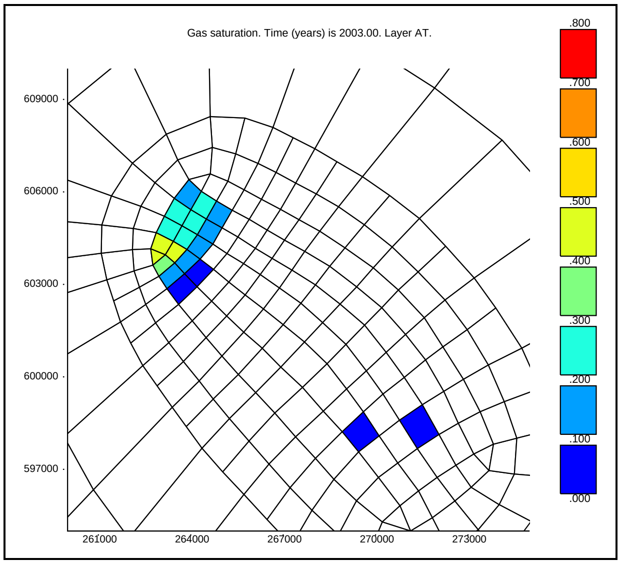

Figure 16 : Vapour Saturation on Layer AT (+175masl) for Scenario A in 2003.

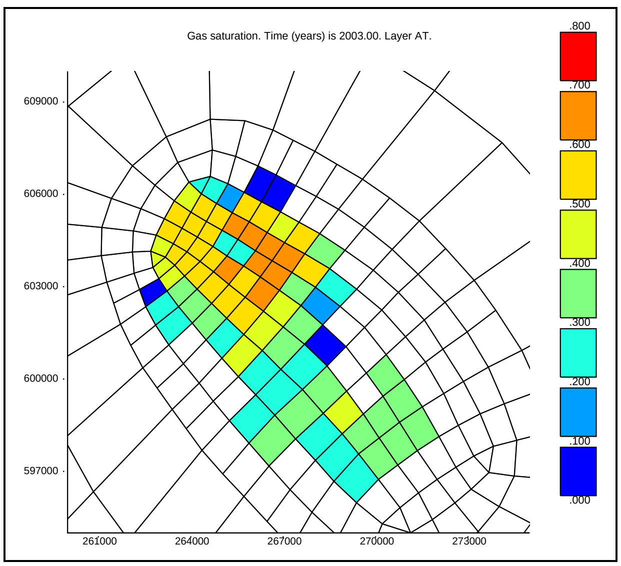

Figure 17 : Vapour Saturation on Layer AT (+175masl) for Scenario B in 2003.

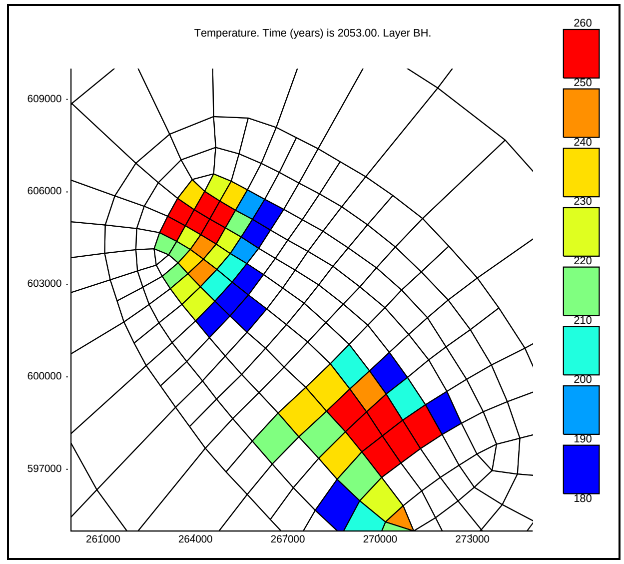

Figure 18 : Temperature on Layer BH (-450 masl) for Scenario A in 2053.

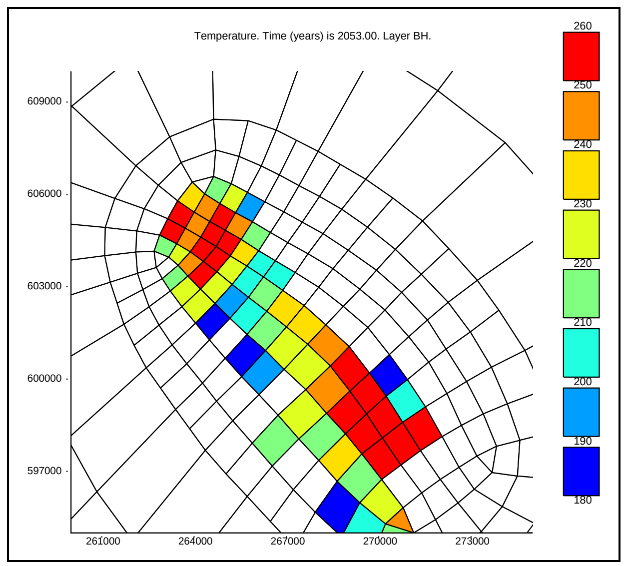

Figure 19 : Temperature on Layer BH (-450 masl) for Scenario B in 2053.

State of the Resource

In order to investigate the state of the resource after 100 years of production, we looked at the temperatures on a deep layer within the model at 2053.

The results for scenarios A and B are presented in Figures 18 and 19 respectively. Although we have extracted more useful energy under Scenario B (Figure 6), Scenario B shows generally higher temperatures over a larger area on this layer than Scenario A.

CONCLUSIONS AND RECOMMENDATIONS

This study focused on the Wairakei – Tauhara geothermal system, however the principles are generally applicable to other high temperature liquid dominated geothermal resources.

Disposal of separated water away from the geothermal resource for at least the early period of development (Scenarios B or F) is the preferred option, provided there is an environmentally acceptable and economic means of doing this. Otherwise outfield reinjection near the field (Scenario D), low levels of infield reinjection (Scenario C) or possibly combinations of these two are the next best options. High levels of infield reinjection (Scenarios A or E) are not desirable.

Infield reinjection may be seen as a cheap method of disposal of separated water, but the total cost of infield reinjection should include the cost of lost future production potential, the cost of drilling the additional wells required to maintain output as field enthalpy declines and the reduced long term productivity of the field.

Our modelling study has shown that for two-phase liquid dominated geothermal fields, such as Wairakei-Tauhara, it is best to keep reinjected fluid as far away from production zones as possible.

ACKNOWLEDGEMENTS

Apart from the authors several others have contributed significantly to the development of our computer model of the Wairakei - Tauhara system. In particular Chris Bromley (IGNS), Peter Wood (ex IGNS) and Rick Allis (Utah Geological Survey) have offered useful advice.

REFERENCES

Barker, B.J., Koenig, B.A. and Stark, M.A., 1995, “Water injection management for resource maximization: observations from 25 years at The Geysers, California”, Proc. of World Geothermal Congress 1995, Florence, Italy, 1959-1964.

Blakeley, M.R. and O'Sullivan, M.J., 1981, "Simple models of the Wairakei reservoir", Proc. 3rd New Zealand Geothermal Workshop, University of Auckland, 131-136.

Blakeley, M.R. and O'Sullivan, M.J., 1982, "Modelling production and recharge at Wairakei", Proc. 4th New Zealand Geothermal Workshop, University of Auckland, 23-31.
Run
Bromley, C. J., Hunt, T. M., Sherburn, S., Wood, C. P., 2000, “Wairakei Geothermal Resource: Geo-scientific information”, Institute of Geological and Nuclear Sciences Limited, Client Report 2000/5 to Contact Energy Limited.

Cappetti, G., Parisi, L.,Ridolfi, A. and Stefani, G., 1995, “Fifteen years of reinjection in the Larderello-Valle Secolo area: analysis of the production data”, Proc. of World Geothermal Congress 1995, Florence, Italy, 1997-2000.

Environment Waikato (NZ), 2003, “Waikato Regional Policy Statement. Proposed Change No. 1: Geothermal Section”, Document number 845143, 23 August 2003, http://www.ew.govt.nz/policyandplans/rpsintro/.

Goyal, K.P., 1999, “Injection related cooling in Unit 13 area of the Southeast Geysers, California, USA”, Geothermics, **28**, 3-19.

Mannington, W.I., O’Sullivan, M.J. and Bullivant, D.P., 2000, “An Air-Water Model of the Wairakei-Tauhara Geothermal System”, Proc. of World Geothermal Congress 2000, Kyushu - Tohoku, Japan, 2713-2718.

Mannington, W.I., O’Sullivan, M.J., Bullivant, D.P., and Clotworthy, A.W., 2004, “Computer Modelling of the Wairakei - Tauhara Geothermal System”, accepted for publication, Geothermics.

Pruess, K., 1995, “Numerical simulation of water injection into vapor-dominated reservoirs”, Proc. of World Geothermal Congress 1995, Florence, Italy, 1673-1679.

Sigurdsson, O., Arason, P. and Stefansson, V., 1995, “Reinjection strategy for geothermal systems”, Proc. of World Geothermal Congress 1995, Florence, Italy, 1967-1971.

Sigurdsson, O. and Stefansson, V., 1998, “Use of TOUGH2 in studying reinjection strategies”, Proc. TOUGH Workshop ’98, Berkeley, California, 7-12.

Sta. Maria, R.B., Villadolid-Abrigo, M.F., Sussman, D. and Mogem, P.G., 1995, “Development strategy for the Bulalo geothermal field, Philippines”, Proc. of World Geothermal Congress 1995, Florence, Italy, 1803-1805.

Stefansson, V., 1997, “Geothermal Reinjection Experience”, Geothermics, **26**(1), 99-139.

Tokita, H., Yahara, T. and Kitakoga, I., 1995, “Cooling effect and fluid flow behavior due to reinjected hot water in the Hatchobaru geothermal field, Japan”, Proc. of World Geothermal Congress 1995, Florence, Italy, 1869-1874.