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MODELLING OF THE OHAAKI GEOTHERMAL SYSTEM

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ABSTRACT

The Ohaaki Geothermal field is situated in the Taupo Volcanic Zone of New Zealand. It was the second geothermal field in New Zealand to be developed and is used primarily for electricity generation. Wells were first drilled in the Ohaaki field during the early 1960's. After a period of well testing following drilling, there was a long period of field recovery until steam production for electricity generation started in 1988. A large three-dimensional numerical model of the Ohaaki geothermal field is presented. It is implemented with the geothermal simulator TOUGH2 (Pruess, 1991). The model is used to investigate the natural state, the well testing and recovery period and the recent production period. The model is calibrated by matching natural state temperatures in the wells, pressure data from the well testing and recovery period and enthalpy and pressure data from the recent production period.

INTRODUCTION

The Taupo Volcanic Zone (TVZ) is a 12,000 km^2 zone of predominantly rhyolitic volcanic activity, which extends north-east from Mt Ruapehu to White Island 50 km off the coast (Figure 1). The Ohaaki geothermal system is on the eastern margin of the TVZ. The Waikato River bisects the Ohaaki system, dividing it into the West Bank and East Bank areas (Figure 2).

Drilling commenced at Ohaaki in 1965, with a total of 44 wells drilled between 1966 and 1984. There was an extended period of well testing between 1969 and 1971 followed by injection tests from 1979 to 1981 and then recovery up to 1988, when the Ohaaki Geothermal Power station was commissioned. The maximum capacity of the plant is 116 MW_e.

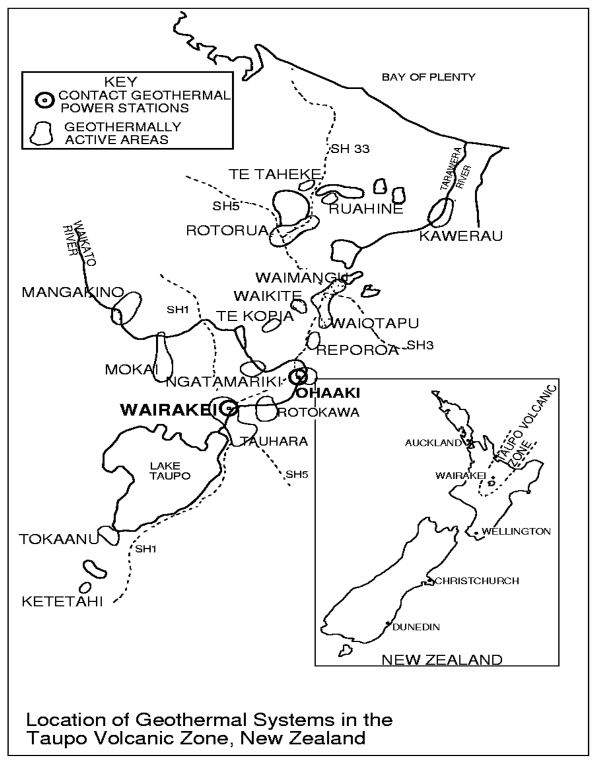

Figure 1. Location of the TVZ and Ohaaki geothermal system.

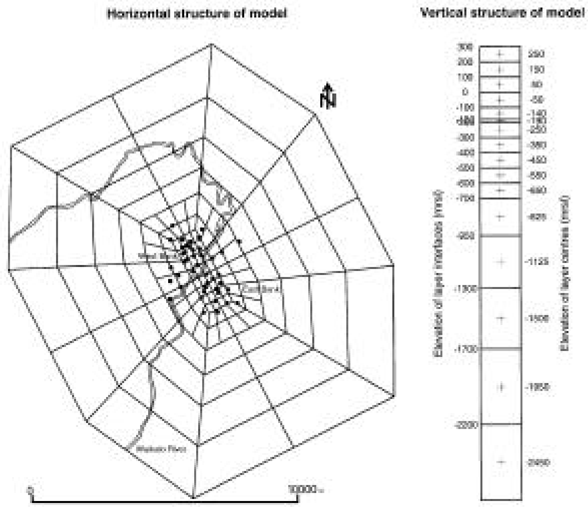

Figure 2. Grid structure of the Ohaaki model. The dots are well locations. The Waikato River divides the field into the West Bank and the East Bank.

OHAAKI GEOTHERMAL SYSTEM

The natural heat flow of the Ohaaki system is thought to have been approximately 100 MW (Allis, 1980), but this figure may not be accurate as discharge into the Waikato River was not well quantified prior to production. The resistivity boundary at ~ 500 m is NNW-SSE trending, and all the surface activity is within this area. The most significant feature is the Ohaaki Pool, which discharges boiling neutral chloride water at approximately 10 l/s, and precipitates silica sinter around the perimeter of the pool.

The basement greywacke at Ohaaki is down-faulted to the north-west. Two major basement scarps have been drilled, but little permeability has been found in the basement. However, higher temperatures associated with sections of the faults indicate the existence of limited permeable pathways for upflow of geothermal fluid (Wood, 1996). The rocks overlying the basement are a sequence of volcaniclastic sediments, interspersed with predominantly rhyolitic and dacitic volcanic domes and flows.

Permeability in the volcanic rocks is highly variable, and is related to internal fracturing or to the contacts with bounding formations. The Ohaaki Rhyolite which outcrops in the south-west of the field is the main conduit for cold surface water inflows to the reservoir (Bromley *et al*, 1993).

Similarly, permeability in the volcaniclastic rocks also varies widely within the formations. The shallow Huka formation generally acts as an impermeable cap on the field, but still has local permeable zones. The Waiora formation below this is regarded as an aquifer, but there is no apparent pattern in the permeability distribution. Low permeability siltstone, and volcanic flows, separate the Waiora Formation from the Rautawiri Breccia, which is also considered to be an aquifer rock, particularly at its upper and lower contacts. Below this lie impermeable ignimbrites, minor lava flows, sediments, and the basement.

The conceptual model of Ohaaki presented by Grant (1995) (Figure 3) is that of diffuse hot upflow through the eastern (higher) basement, which then flows laterally through the overlying volcanics to discharge on the West Bank. The deep temperature reversals shown in some wells, for instance, BR9 and BR48, indicate that there is some inflow of groundwater in the west. Permeability on the East Bank is limited laterally and vertically. The Ohaaki system is open to surface groundwater, particularly through the near-surface, high permeability Ohaaki rhyolite in the west.

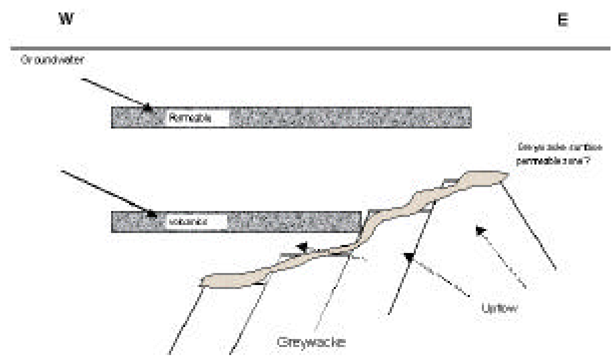

Figure 3. Conceptual model of the Ohaaki system, from Grant (1995).

Effects of mass withdrawal rapidly became apparent during the early well testing period. Reservoir pressures dropped rapidly and discharge ceased from the Ohaaki Pool. In 1988, almost two years after some discharge recommenced, the base of the Ohaaki Pool was sealed to prevent down-flows during production (Clotworthy *et al*, 1995).

Subsidence indicated pressure decline in the basal Huka formation in the late 1960's. Despite a recovery in reservoir pressure, there was no rebound of the subsidence, and it has continued during the production period (Allis *et al*, 1997).

Pressures at the base of the Huka Formation reflect the drawdown in the underlying Ohaaki rhyolite. Water levels in monitoring wells in the Ohaaki rhyolite have declined up to 10 m, and it is thought that the cold down-flows in the Ohaaki rhyolite have production wells since 1988.

DATA

Many measurements of downhole temperatures have been made. These were summarised by Lee Joe and O'Sullivan (1985). More recently Grant (1996) has provided interpretations of the natural state reservoir temperatures for most of the Ohaaki wells.

The extended period of well testing from 1966 to 1972 provided drawdown and recovery pressure data for 12 West Bank and 4 East Bank wells.

Pressure data are also available from various monitoring wells. Many of the earlier monitoring wells were very shallow (30-40 m), but there are some which were drilled to 140 – 450 m. More monitoring wells have been drilled since production began. Some of the earlier exploration wells are also used to monitor deep reservoir pressures.

Unfortunately a continuous record of production data from individual wells at Ohaaki is not available. However mass and enthalpy production data is available from the Separator Plants (SPs). There are five SPs at Ohaaki, each of which is supplied by between 2 to 9 wells. Each SP provides the combined mass flow and production enthalpy for that group of wells. Individual wells are also output tested, and the operating well head pressure recorded regularly, enabling a proportion of the SP mass flow to be assigned to individual wells.

The well output tests also provide production enthalpy for individual wells. This information is used in model calibration.

The procedure of using occasional output test data to assign the SP flows to individual wells and thus obtain continuous records of well-by-well production rates and enthalpy is not entirely satisfactory. The fraction of the SP totals calculated for each well varied from one output test to the next. Possibly modelling of above ground separation processes (Pritchett, 1995) would be an advantage in this case.

OTHER MODELLING STUDIES

The first model of Ohaaki was a simple quasi-analytical lumped parameter model constructed by Grant (1977). Later a sequence of numerical models were set up by O'Sullivan and co-workers (Zyvoloski and O'Sullivan, 1978; Zyvoloski and O'Sullivan, 1980; Blakeley *et al.*, 1983; O'Sullivan *et al*, 1985.). As computer hardware and software improved these models increased in complexity and evolved into the model discussed below.

MODEL DESIGN AND CALIBRATION

The Ohaaki reservoir model is designed to incorporate the entire recharge and discharge zones of the system. The block structure is shown in Figure 2. There are 128 blocks per layer, and 16 layers (2048 blocks in total), extending to a depth of 2450 m below sea level. The land surface at Ohaaki is approximately 300 meters above sea level. The rectangle of blocks at the centre of the model corresponds to the area inside the resistivity boundary, and are referred to as the 'reservoir blocks'. The two rings surrounding the reservoir blocks contain most of the reinjection and 'marginal', or unproductive, wells. The large blocks beyond the marginal blocks are the recharge blocks.

The top surface of the model is fixed at the water table. Data on the level of the water table was obtained from the early shallow monitoring wells.

The boundary pressure and temperature at the surface of the model are fixed at atmospheric values, and allow a flow of heat and mass across the model surface. The lateral boundaries of the model are closed. The reservoir blocks at the base of the model have hot water injected at 300°C. The mass fraction of CO_2 in the injected water is 0.06 (O'Sullivan *et al.*, 1985). The marginal blocks have an input of heat but no mass corresponding to a conductive heat flow. A low background heat flow is applied to the remainder of the base of the model.

Mass withdrawal and injection during production is shown in Figure 4.

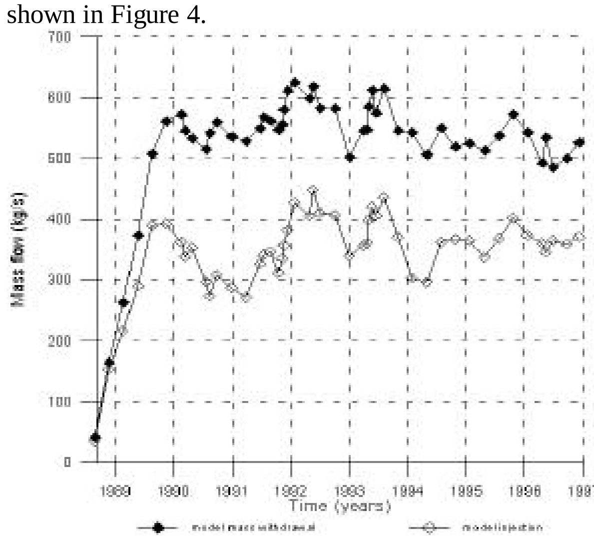

Figure 4. Mass withdrawal and injection for the Ohaaki model.

Withdrawal in the early years of production is approximately 550 kg/s, falling to around 500 kg/s by

1996. Injection has been more variable, but is slightly above 350 kg/s in 1995-96.

The size of blocks in the model allows most wells to be assigned to their own column (all the wells are vertical except the most recent 3 deep wells drilled in the early 1990's). The wells do not all feed from the same depth, and many of the wells have more than one feed zone. The approach to multiple feed wells has been to assign a fixed proportion of the mass flow from the well to each depth. In reality the proportion of the total mass flow from each feed is likely to vary with time.

The correct allocation of production to the various feed zones in a multi-feed well has been one of the difficult aspects of calibrating the Ohaaki model. In order to model the change in behaviour of each feed zone two options were tried. The first was to change the proportions of flows from the feed zones, over part or all of the production period. The second was to model the flows from each feed using a pressure-dependent deliverability option. The first option was preferred because of the difficulty in calibrating the 'productivity index' for each feed zone in each multi-feed well.

In the calibration process only a few parameters were changed in each new run. Thus calibration required many, time consuming, iterations to achieve a good match of model output to measured field data.

The first stage of model calibration involves matching the natural state behaviour of the system. The natural state temperature profiles in the wells are used to calibrate the location and magnitude of the deep inflows, and the permeability structure.

The second stage of calibration involves matching the past production history. This included the prolonged well testing and recovery period between 1966 and 1988 as well as the more recent data. The behaviour of Ohaaki during mass withdrawal and injection was simulated, and the model parameters of permeability and porosity were adjusted until there was good agreement between model results and measured values for pressure response and discharge enthalpy.

Examples of the model pressures, discharge enthalpy, and CO_2 mass fraction in well discharge are shown, with field data, in Figures 10 to 16.

DISCUSSION

The east-bank model temperatures show a similar profile for all model blocks, and where a full measured profile exists, are a good match to field data. (Figure 5). The natural state temperature results for some west-bank wells are shown in Figure 6. Some of these wells have one or more shallow temperature reversals which are not matched in the model. It would require the use of a finer vertical grid to match these temperature profiles.

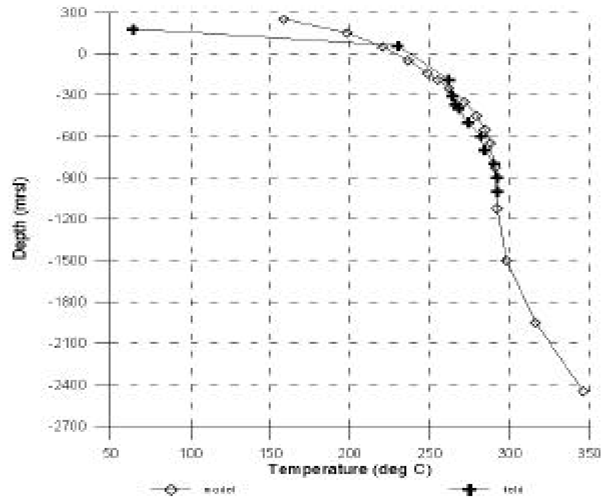

Figure 5. Temperature profile, East Bank well.

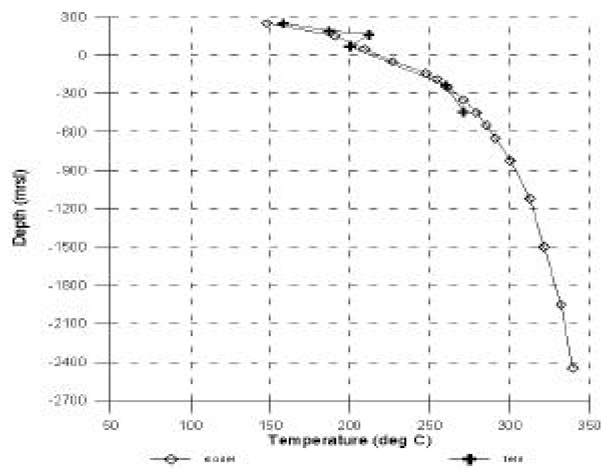

Figure 6. Temperature profile, West Bank well.

The temperature profiles in the marginal wells are not well matched, for instance, the temperatures in the southern marginal wells are too high. Calibration is continuing on these aspects of the model.

The model pressures during the drawdown-recovery period are a good match for some wells (Figure 7), but others show a greater drawdown, and then greater recovery than the measured data. This can be seen in Figure 8, which shows the more extreme response to the early well tests predicted by the model for one of the West Bank wells.

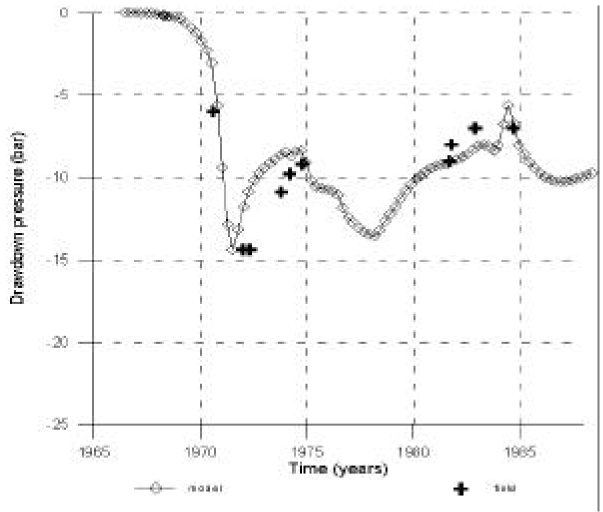

Figure 7. West Bank well, drawdown pressure.

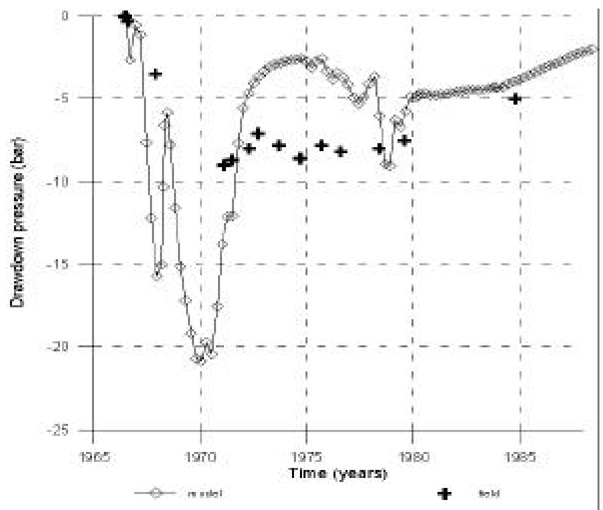

Figure 8. West Bank well, drawdown-recovery response showing the modelled recovery as greater than the measured data.

Production pressures in the deeper West Bank reservoir predicted by the model follow the same trend as the field data, but are around 4-5 bar lower (Figure 9). Some of the early pressure transients and the later production pressure match require some improvement. Currently ITOUGH2 (Finsterle, 1993), the inverse modelling code for the TOUGH2 simulator, is being used to assist with model calibration and it is hoped an improved match to the pressure data will be obtained.

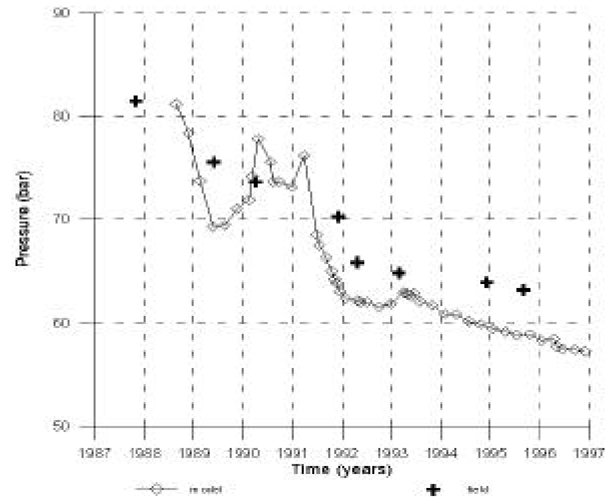

Figure 9. Deep reservoir production pressures, West Bank.

The match between the model results and measured data for separator plant enthalpy (see Figs. 10 and 11) and gas contents (see Figs. 12, 13 and 14) is good. However the enthalpy results from the model for some of the individual wells, particularly on the East Bank, could be improved. The East Bank wells are two-phase, and the enthalpy varies substantially throughout the production period. Some wells show an initial high enthalpy discharge and a decline thereafter (Figure 15), while other wells have an initially low enthalpy which increases during the production period, as shown in Figure 16.

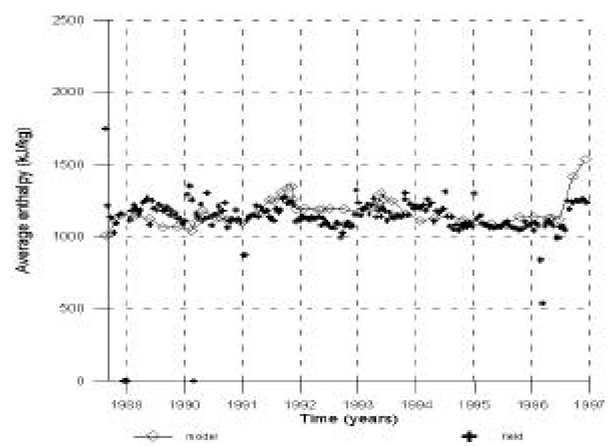

Figure 10. West Bank, SP enthalpy.

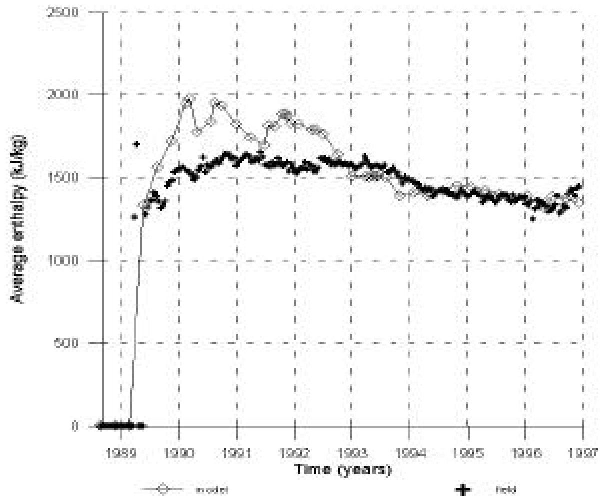

Figure 11. East Bank. SP enthalpy.

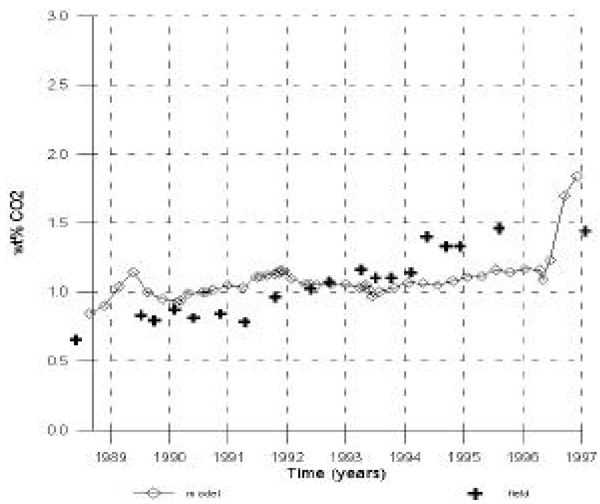

Figure 12. West Bank. Gas discharge trends.

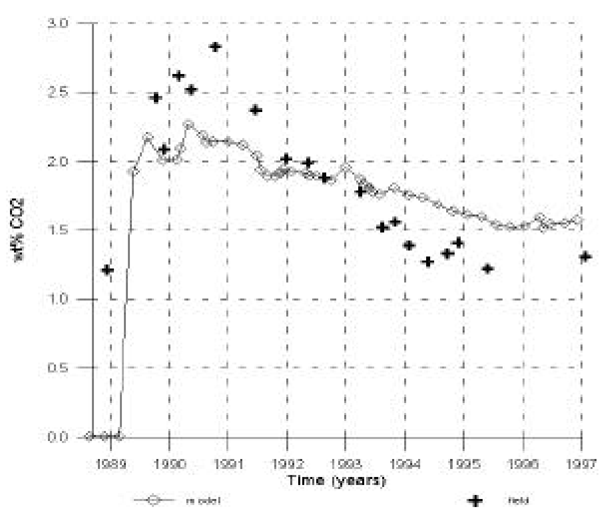

Figure 13. East Bank. Gas discharge trends.

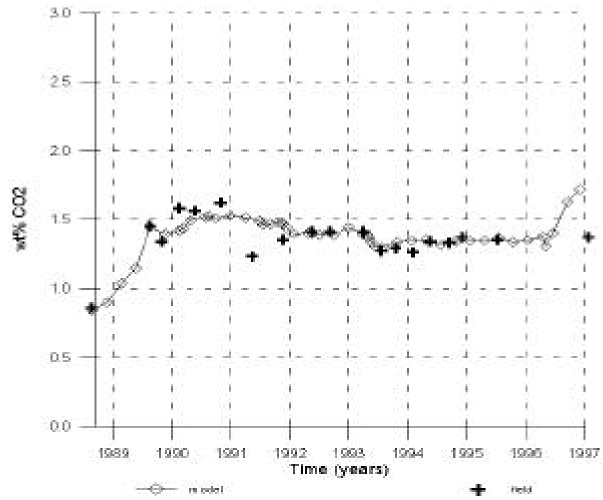

Figure 14. Gas discharge trends for all wells.

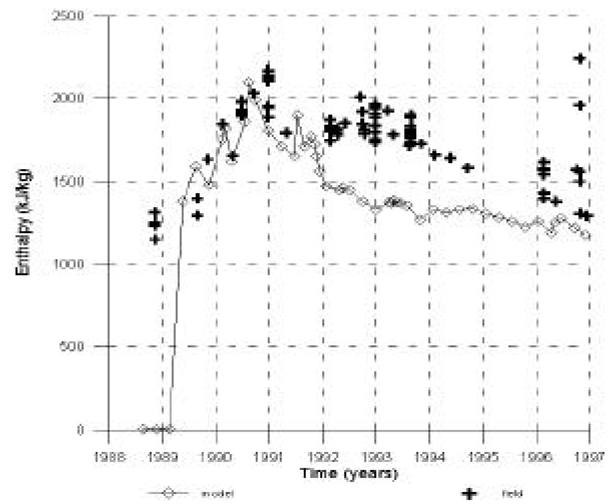

Figure 15. East Bank well enthalpy. Decline of a shallow feed, high enthalpy well.

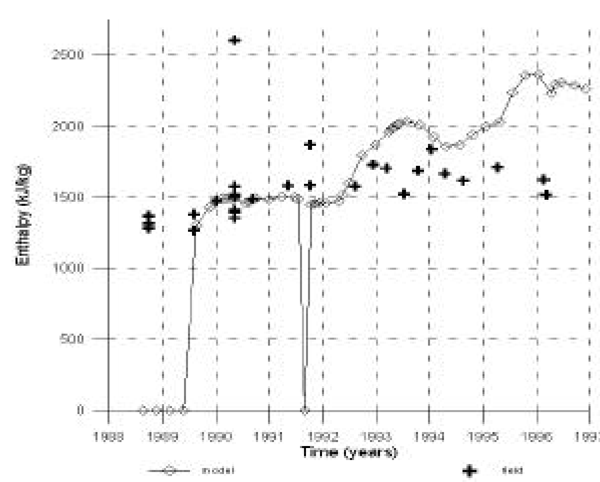

Figure 16. East Bank well. Increasing enthalpy during production from a deep feed well.

The computer model of Ohaaki is working well. It has been used to generate simulations of a number of possible future scenarios for Ohaaki which are being used by Contact Energy Limited to assist with field management and planning.

Acknowledgements

Alan Clotworthy and Brian Carey from Contact Energy Limited have contributed significantly to the development of the computer model of Ohaaki. Dr Malcolm Grant, and Dr David Bullivant, have also frequently offered very useful advice.

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