MODELLING OF THE WAIRAKEI-TAUHARA GEOTHERMAL SYSTEM

M.J. O'SULLIVAN[1], D.P. BULLIVANT[1], W.I. MANNINGTON[1] AND S.E. FOLLOWS[2]

[1]Dept. of Engineering Science, The University of Auckland, Auckland, NZ
[2]DesignPower Genzl, Auckland, NZ

Summary A large complex three dimensional computer model of the Wairakei-Tauhara geothermal system is described and discussed. The model results agree well with natural state data and the response of the system to past production. This model is being used by Contact Energy Limited to assist with field management.

1. INTRODUCTION

The Wairakei - Tauhara geothermal system is located in the centre of the North Island **of** New Zealand in a large geothermally active area called the Taupo Volcanic Zone. Electricity generation at Wairakei commenced in 1953. Originally a plant with a maximum capacity of 192MWe was installed but the supply of steam has never been adequate to reach this figure. The maximum output achieved was approximately 185MWe in 1964. Output subsequently declined and has now stabilised at a steady value of 157MWe (see Fig. **2).** Currently this output is achieved from a total mass take of approximately 130,000 t/d giving a flow of separated steam of 29,000 t/d.

The efficiency of the plant at Wairakei has been improved over the years. This can be seen by comparing the plot **of** total mass flow (Fig. 3) with the plot of yearly average energy produced in Fig. 2

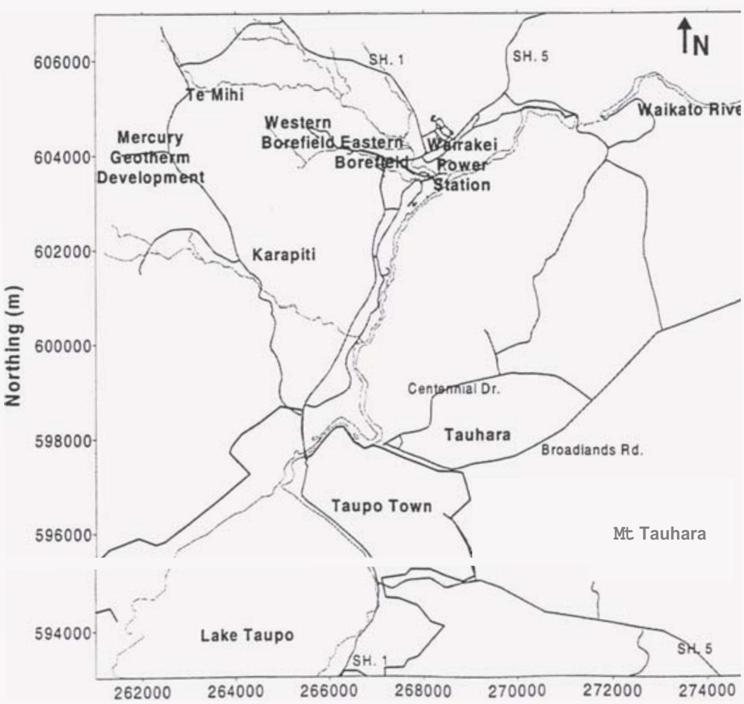

Figure 1 - Map of the Wairakei-Tauhara geothermal system

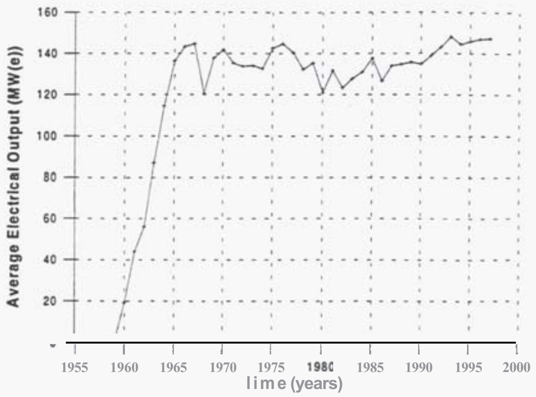

Figure *2* - Yearly Average Electrical Output of Wairakei Power Station

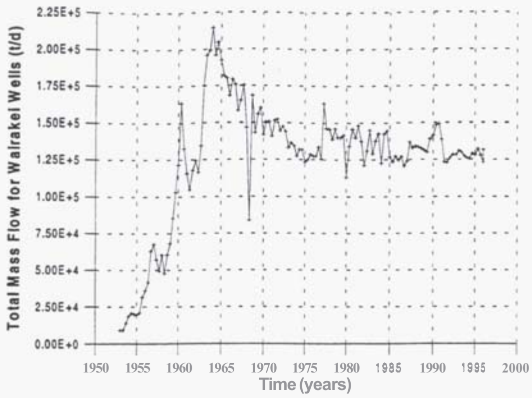

Figure *3* - Total Mass Flow from Wells at Wairakei

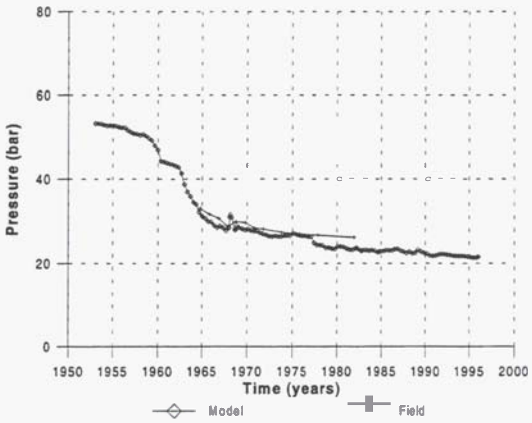

Figure **4.** Pressure history for the Westem Borefield at Wairakei

The main hot upflow for Wairakei is in the western part of the field near Te Mihi. In the natural state this hot flow, at 260°C, was diverted horizontally by the low permeability of the Huka Falls formation located between approximately 250 masl and **330** masl (the surface of the Eastern Borefield varies between ***380*** masl and 420 masl). The capping effect of the Huka Falls formation caused the hot upflow to flow horizontally across the Western Borefield and then to discharge (neutral pH, chloride water) mainly at Geyser Valley in the northwest. There was also some discharge of hot water along the banks of the Waikato River and a small discharge of steam in higher ground at Te Mihi and Karapiti.

Production began in the Eastern Borefield and then spread west into the Western Borefield and Te Mihi. In the natural state almost all of the Wairakei and Tauhara reservoir fluid was hot water but production caused the pressure to drop rapidly (See Fig. **4)** and also caused the formation of a steam zone which expanded rapidly, vertically and horizontally. This process caused the surface features at Geyser Valley to mostly disappear but in some areas, such as Karapiti, the surface heat flows increased (Allis, **1981).**

Most of the deep wells access single phase liquid zones or wet two-phase zones. In the latter case produce a mixture of steam and water with an enthalpy only a small amount above that for liquid water. The average production enthalpy is shown in Fig. **5**. The plots of average enthalpy for the three main production zones at Wairakei are shown as Figs. ***6-8***. The shallow **part** of the steam zone at Te Mihi has **a** high steam content and some wells which access it produce dry steam. This is shown by the high average enthalpy produced from the Te Mihi wells.

As Fig. **4** shows the pressure drop slowed down by 1970. This corresponds to the stage when a quasi-equilibrium state had been established at Wairakei - Tauhara with the induced recharge flow matching production.

Wairakei - Tauhara is characterised by large permeabilities. The pressure drop extended over a large area with pressures in the Western and Eastern borefields varying by less than **2** bar. The pressure decline has spread across to the Tauhara part of the system as shown by the field data in Fig. 9.

Although mass flows have stabilised, temperature declines are continuing as colder recharge fluid moves into the reservoir from the sides and top. Some wells have been "quenched" by this process.

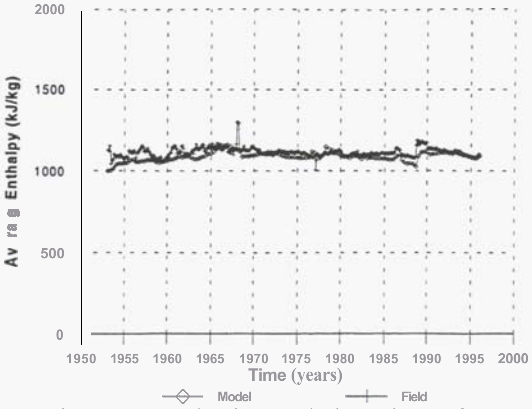

Figure 5 - Production Enthalpy History for Wairakei

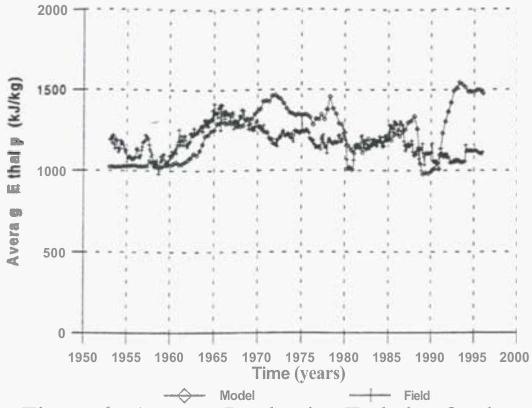

Figure 6 - Average Production Enthalpy for the Eastern Borefield

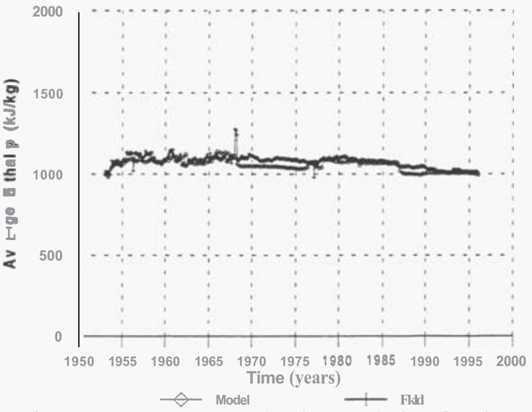

Figure 7 - Average Production Enthalpy for the Western Borefield

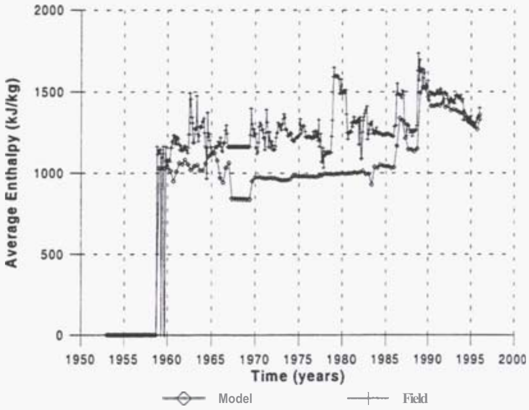

Figure 8 - Average Production Enthalpy for Te Mihi

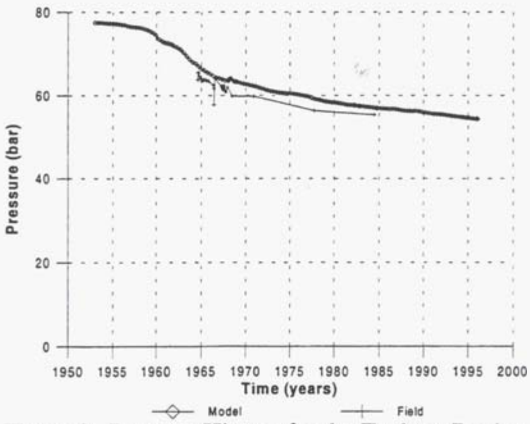

Figure 9. Pressure History for the Tauhara Region

2. DATA

There is a very extensive database for Wairakei. Measurements on individual wells have been made regularly and records of mass flow, production enthalpy, pressures and temperatures are available. Records of changes for chemicals such as chloride are available and various geophysical surveys have been carried out.

Temperature vs depth profiles are available for many wells although the first available data for some wells is considerably after the start of production in 1953. Maps of pre-exploitation surface features are available although the information is qualitative rather than quantitative. Estimates of the total natural through-flow for Wairakei vary but the generally accepted figures are 400kg/s for mass and $450MW_{th}$ for energy (Allis, 1981). For Tauhara the heat flow figure is approximately $100MW_{th}$. Comparison of these figures with the present take of approximately $1650MW_{th}$ shows that Wairakei is being "mined" for heat.

The database for the Tauhara region is not as extensive. Only four deep wells have been drilled and monitored

3. OTHER MODELLING STUDIES

Because of the ready availability of data Wairakei has been used as a test case in several computer modelling studies (Mercer and Faust, 1979; Pritchett et al., 1980) and in discussions of methods for geothermal resource assessment (Donaldson and Grant, 1979). The practical usefulness of these early distributed parameter models was constrained by the limitations of the hardware of the day. Both groups considered essentially 2-D models: a vertical slice was used by Pritchett et al. And a horizontal layer by Mercer and Faust. A few lumped parameter models have also been investigated (Whiting and Ramey, 1969; Fradkin et al., 1981, for example). Some of the lumped parameter models were able to match the observed pressure decline well. It turns out that this task is not difficult to achieve with any simple model with correctly chosen fluid storage and flow parameters. The recent development at Wairakei by Mercury - Geotherm and the various proposals for Tauhara have stimulated several modelling studies. These models were presented in evidence at various resource consent hearings but have not yet been reported in the open literature. All of these studies have considered only a part of the overall Wairakei - Tauhara system

4. MODEL DESIGN AND CALIBRATION

Our computer modelling study of Wairakei - Tauhara has been proceeding for many years (Blakeley and O'Sullivan, 1981, 1982) and our models have grown in complexity, partly as our knowledge of Wairakei - Tauhara has improved, but mainly as software and hardware have improved. Our introduction of conjugate gradient solvers into MULKOM greatly increased the number of blocks we could use in our model of Wairakei - Tauhara and also increased the computational speed (Bullivant et al., 1991). The development of very fast, cheap, workstations has also greatly increased computational speed. We currently run our models of Wairakei-Tauhara on DEC Alpha and Silicon Graphics workstations.

The grid for one of our most recent models of Wairakei-Tauhara is shown in Fig. 10. There are 118 blocks per layer and 14 layers giving a total of 1509 blocks. (including one for the atmosphere). The uppermost layers do not have the full 118 blocks, as blocks above the water table are not included. The design of this grid was based on several criteria:

- The blocks near the Wairakei Borefields are aligned approximately SW-NE along the direction of faults and fractures.
- The adjoining Taupo-Tauhara area is included.
- The boundary of the small blocks in the model corresponds to the resistivity boundary.
- Large "recharge" blocks are included.

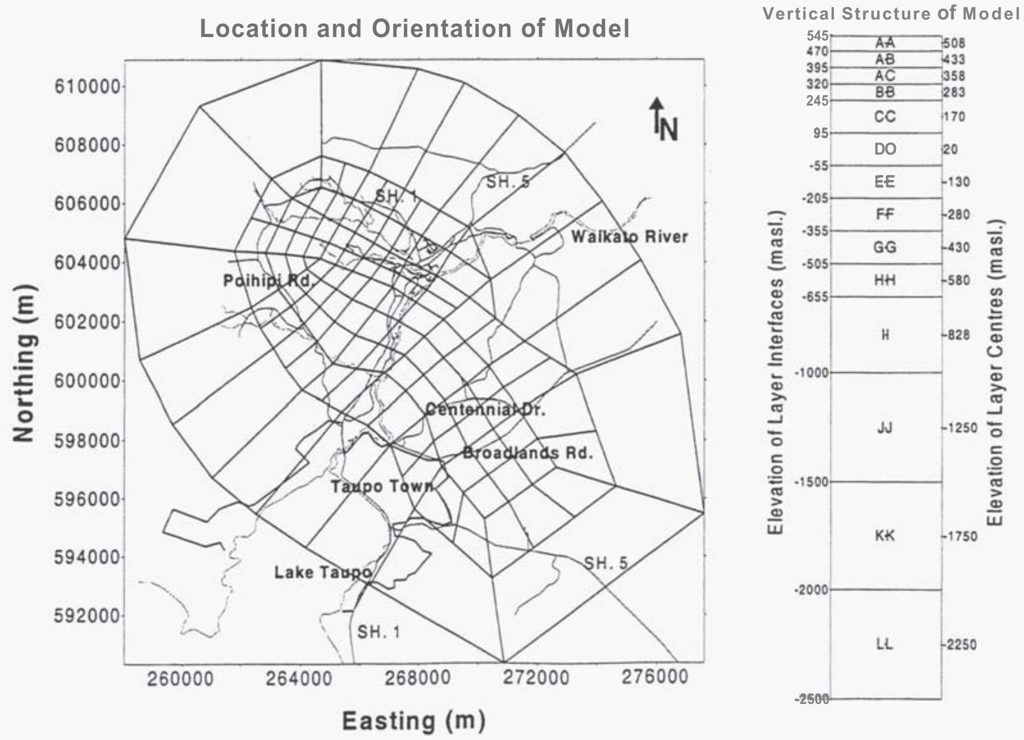

Figure 10. Grid layout for the Wairakei-Tauhara model

It is assumed that the model is sufficiently large, so that all recharge at the outer lateral boundaries of the model is negligible and they are treated as closed. At the surface of the model, corresponding to the water table, the temperature and pressure are fixed at atmospheric values. At the base hot water at 260°C is injected over part of the model and a low background heat flow is applied over the rest. During production runs some extra hot inflow at the base is allowed by adding recharge proportional to the pressure drop.

The model is calibrated in two stages, firstly by matching the natural state behaviour and secondly by matching the historical performance (O'Sullivan, 1985). For natural state matching the permeability structure and deep inflows (location and magnitude) are adjusted and the model results are compared with measured temperature profiles and surface outflows (location and magnitude). Some typical results for the calibrated natural state model are shown in Figs. 11.and 12.

For matching of past production history, further adjustments are made to the permeability structure and also porosities are adjusted. Model results are then compared with measured pressure declines, enthalpy transients and temperature changes. Typical model results are compared with field data in Figs. 4 -9.

This calibration process required many iterations at each stage (natural state and past history) and between the two stages. Most of the calibration process was carried out by "hand", that is, with one or more of the authors deciding which parameters should be adjusted. Recently we have experimented with computerised calibration (Finsterle et al., 1997) with some success.

The model of Wairakei - Tauhara described here is working well in terms of its match to natural state and historical data. It has reached the state where it produces good results for some data which were not included in the original calibration. For example well-by-well enthalpy data were not included in the calibration process; only the average enthalpies for the Western or Eastern Borefields were used. However the calibrated model gives a good match to the well performance for both its deep (liquid) and shallow (steam) wells in Te Mihi. Typical results are shown in Figs. 13 and 14.

Our model of Wairakei - Tauhara was used as a test for the chemical transport version of TOUGH2 developed at IRL (White, 1995). A good match between model results and field data was obtained for chloride concentrations at Wairakei (Kissling et al., 1996).

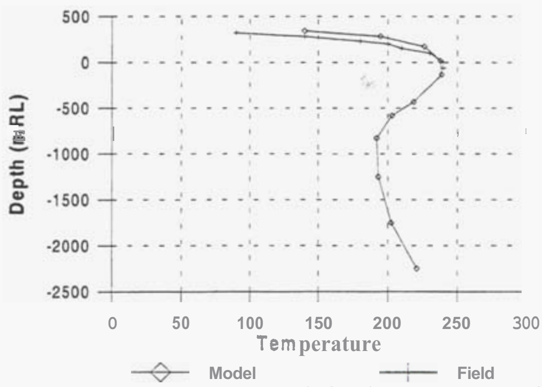

Figure 11 - Temperature vs Depth for the Eastern Borefield

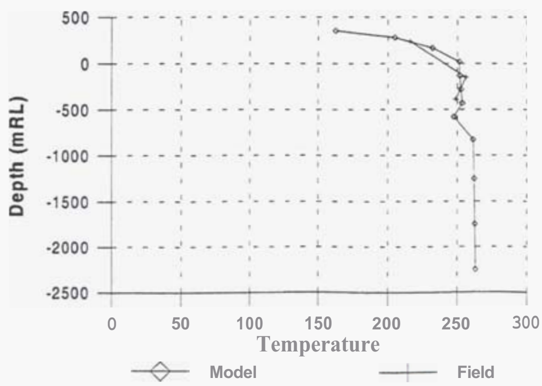

Figure 12. Temperature vs Depth in the Western Borefield

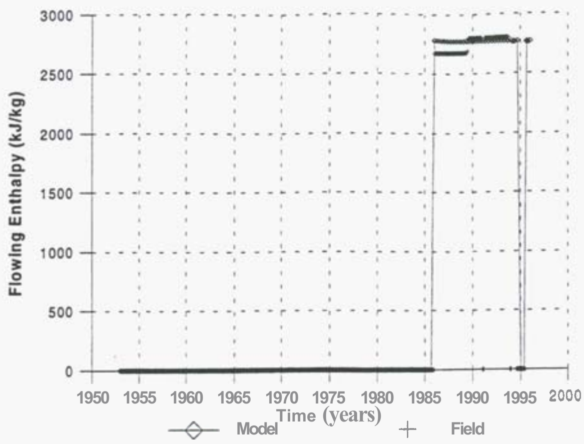

Figure 13 - Flowing Enthalpy for a Shallow Te Mihi Well

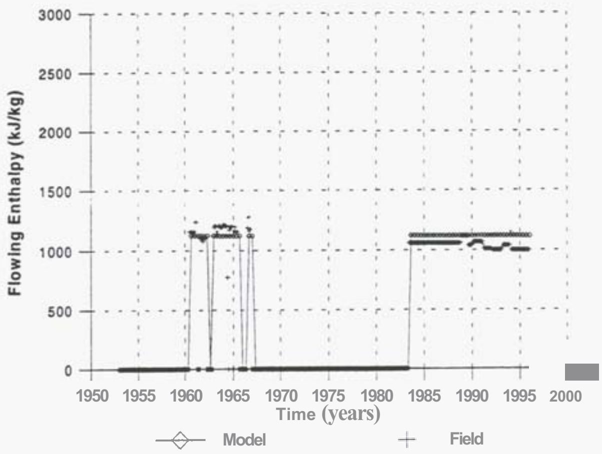

Figure 14 - Flowing Enthalpy for a Deep Te Mihi Well

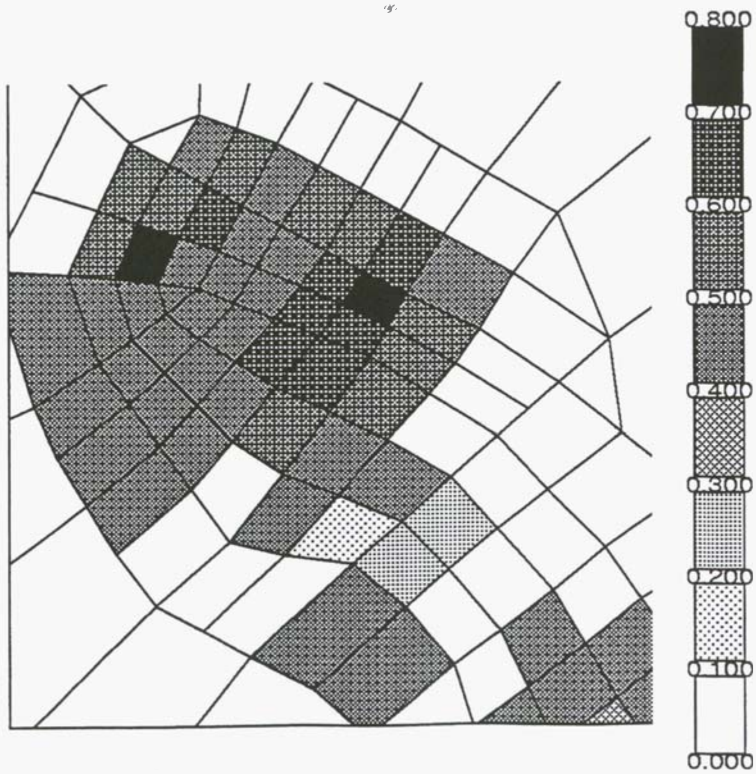

Figure 15 - Shallow Steam Zone at Wairakei for layer CC (170 masl.).

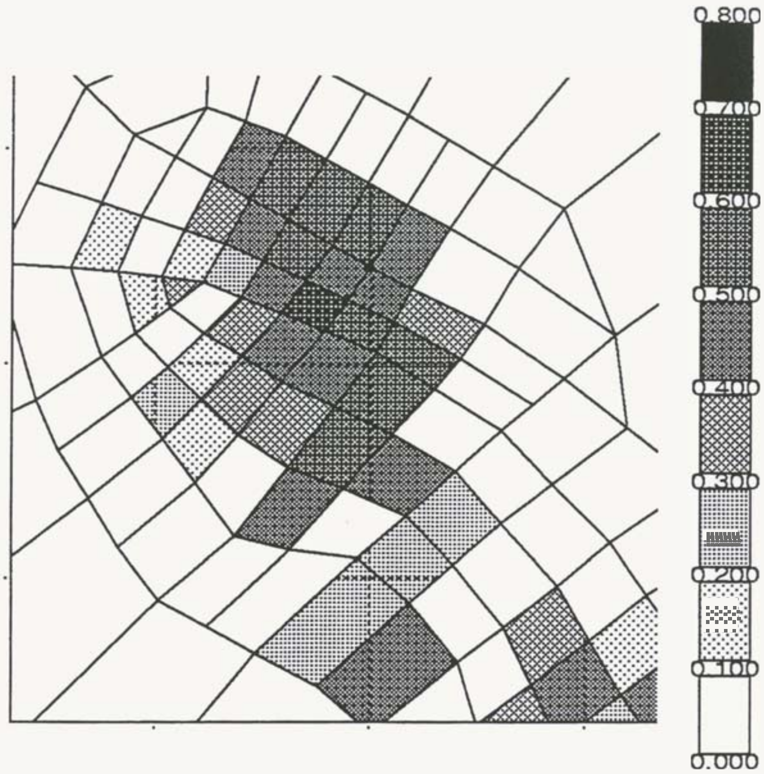

Figure 16 - Shallow Steam Zone at Wairakei for layer **DD** (20 masl.).

The model reproduces the important large scale features of the behavior of the Wairakei - Tauhara system. For example the development of an extensive shallow steam zone occurs in the model as it does in the real system. Plots of vapour saturation in 1996 for layer CC (centred at elevation of 170 masl.) and layer **DD** (centred at elevation of **20** masl.) are shown is Figs. 15 and 16.

A few aspects of the model need improvement, for example the average enthalpy for the Eastern Borefield between the period of 1970 to 1980 is too high in the model. We are currently reviewing feed zone data and may adjust feed zone depths. Similarly the average enthalpy from the model for Te Mihi is too low between 1965 and 1985. Not all wells show a match between model and field results as good as the ones shown in Figs. 13 and 14. Further calibration of this part of the model is being undertaken with the aid of ITOUGH2 (the inverse modelling version of TOUGH2, Finsterle, 1993). However it may be impossible to improve the model greatly without further grid refinement (thinner layers and more blocks per layer).

Some of the model temperatures in the zone between Wairakei and Tauhara are too high. This aspect of the model is not particularly important in terms of the model performance but it is being reviewed.

The interaction between the deep reservoir and shallow near surface zone is an important matter in the Wairakei - Tauhara system. The model described here uses a relatively coarse vertical discretisation and does not include the unsaturated zone above the water table at all. We are currently investigating models with a larger number of blocks and "air-water" models which include both the unsaturated and saturated zones.

5. DISCUSSION

Our computer model of Wairakei - Tauhara is working well and is being used by Contact Energy Limited to assist with field management and planning; for example to study the impact of major reinjection and to investigate the interaction between Wairakei and Tauhara. (Contact Energy Limited was previously part of the Electricity Corporation of New Zealand (ECNZ) which in turn was set up by corporatising the New Zealand Electricity Department (NZED)). Support of our work by Contact Energy Limited is gratefully acknowledged.

Apart from the authors several others have contributed significantly to the development of our computer model of the Wairakei - Tauhara system. In particular Paul Bixley and Brian Carey from Contact Energy Limited and Rick Allis and Peter Wood from the Institute of Geological and Nuclear Sciences have frequently offered very useful advice.

We have found MULKOM/TOUGH2 to be a very effective tool for geothermal reservoir modelling, both for Wairakei - Tauhara and several other fields. The flexible block structure is very useful and apart from introducing fast solvers (which are now available with the standard version of TOUGH2) we have had to modify MULKOM/TOUGH2 very little. We have introduced extra options for the operation of wells to allow the actual field procedures to be closely modelled.

Perhaps the most important feature we have added to MULKOM/TOUGH2 is the tightly coupled graphical interface MULGRAPH (O'Sullivan and Bullivant, **1995).** This enables **us** to graphically edit the geometry and permeability structure of our model and to very quickly view the results and compare them with field data.

6. REFERENCES

Allis, R.G., **1981,** "Changes in heat flow associated with exploitation of Wairakei Geothermal Field, New Zealand", *N.Z. Journal of Geology and Geophysics,*__24__, **1-19.**

Blakeley, M.R. and OSullivan, **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.**

Bullivant, **D.P.** ,O'Sullivan, M.J. and Zyvoloski, G.A., **1991,** "Enhancements of the **MULKOM** geothermal simulator", **Proc. 13th** New Zealand Geothermal Workshop, University of Auckland, **175-182.**

Donaldson, I.G. and Grant, M.A., **1979,** "An estimate of the resource potential of New Zealand geothermal fields for power generation", ***Geothennics,*__7__, 243-252.**

Finsterle, **S, 1993,** "ITOUGH2 User's Guide Version **2.2",** Lawerence Berkeley Laboratory, University of California.

Finsterle, **S.,** Pruess, K., Bullivant, D.P. and OSullivan, M.J., **1997,** "Application of inverse modeling to geothermal reservoir simulation", Proc. 22nd Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, 8 p.

Fradkin, L.,Ju., Sorey, M.J. and McNabb, **A., 1981,** "On identification and validation of some geothermal models **",*Water Resources Research,*__17__, 929-936.**

Kissling, W.M., Brown, K.L., O'Sullivan, **M.J.,** White, S.P. and Bullivant, D.P., **1996,** "Modelling chloride and **C02** chemistry in the Wairakei geothermal reservoir", ***Geothermics,*** **__25__(3), 285-305.**

Mercer, J.W. and Faust, C.R., **1979,** "Geothermal reservoir simulation: **3,** application of liquid- and vapour-dominated hydrothermal modelling techniques to Wairakei, New Zealand", ***Water Resources Research,*** **__15__, 653-671.**

OSullivan, **M.J., 1985,** "Geothermal reservoir simulation", ***J. Energy Research,*** **__9__, 319-332.**

OSullivan, **M.J.** and Bullivant, D.P., **1995, "A** graphical interface for the TOUGH family of flow simulators', Proc. TOUGH Workshop **'95,** Berkeley, California, **90-95.**

Pritchett, J.W., Rice, L.F. and Garg, **S.K. ,1980,** "Reservoir simulation studies: Wairakei geothermal field, New Zealand, Final Report", Geothermal Reservoir Engineering Management **Program** report **GREW-11,** Lawrence Berkeley Laboratory.

White, **S.P., 1995,** "Multi-phase nonisothermal transport of systems of reacting chemicals", ***Water Resources Research,*** **__31__, 1761-1772.**

Whiting, R.L. and Ramey, H.J. Jr., **1969,** "Application of material and energy balances to geothermal steam production", **Journal** of Petroleum Technology, **21,893-900.**