BOARD OF INQUIRY
TE MIHI GEOTHERMAL POWER STATION PROPOSAL

In the Matter of the Resource Management Act 1991

And

In the matter of resource consent applications by Contact Energy Limited in respect of the Te Mihi Geothermal Power Station Proposal

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BRIEF OF EVIDENCE IN CHIEF OF MICHAEL JOHN O'SULLIVAN

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Introduction

1. My name is Michael John O'Sullivan. I am a professor in the Department of Engineering Science at the University of Auckland.

2. I have the following qualifications and experience relevant to the evidence I shall give:

   - I hold the degrees of BE(Civil), BSc(Mathematics), ME(Applied Mechanics) from the University of Auckland and a PhD from the California Institute of Technology.

   - I teach courses in mathematical modelling, computational methods, fluid dynamics and geothermal reservoir engineering in the School of Engineering.

   - I have been carrying out research on geothermal fluid dynamics and computer modelling of geothermal fields for 30 years. I have published more than 100 scientific papers in journals and conference proceedings, mostly on geothermal modelling. I have been involved in collaborative research projects with research groups at Lawrence Berkeley National Laboratory (California), Stanford University (California), Los Alamos National Laboratory (New Mexico) and the Energy and Geoscience Institute (University of Utah). I am the science leader for a six year research project at the University of Auckland on deep geothermal resources and the environmental effects of geothermal developments ($3.8M funded by the Foundation for Research, Science and Technology).

   - I act as a part-time consultant (through the University company: Uniservices Limited) on computer modeling of geothermal fields with PB Power, Top Energy, Mighty River Power and Contact Energy Limited (Contact).

   - For Contact I have worked on computer models of the Wairakei-Tauhara Geothermal System, Mokai Geothermal Field and Ohaaki Geothermal Field. With PB Power, and their predecessor GENZL, I have developed models of Fushime, Kakkonda (Japan), Kamojang, Dieng, Darajat, Subiyak, Lahendong (Indonesia), Ngawha (New Zealand), East Mesa (USA), Olkaria (Kenya) and Los Humeros (Mexico).

- I have also assisted PB Power with software development projects, namely, the analysis of geothermal wellbore flow (WELLSIM), automated well test analysis (AWTAS) and the modelling of geothermal tracer tests.

3. I confirm that I have read the 'Code of Conduct for Expert Witnesses' contained in the Environment Court Consolidated Practice Note 2006. My evidence has been prepared in compliance with that Code. In particular, unless I state otherwise, this evidence is within my sphere of expertise and I have not omitted to consider material facts known to me that might alter or detract from the opinions I express.

Scope of Evidence

4. My evidence will cover the following matters:

   - A description of the process for modelling geothermal fields;
   - A description of the model of Wairakei-Tauhara, including model calibration, natural state modelling and past history modelling;
   - Modelling results and discussion of two scenarios;
   - A discussion of potential effects on the consented Geotherm project;
   - An outline of ongoing modelling developments.

5. I prepared a detailed report on my modelling study of Wairakei-Tauhara in June 2007 which was included as one of the technical appendices to the "Assessment of Environmental Effects" submitted by Contact Energy Limited with its consent applications for the Te Mihi Power Station Project. Rather than repeat the detailed explanation and analysis contained in my report, I have included the report as an appendix to my evidence for convenience. I will refer to this report as the "AEE Modelling Report". In this evidence, I will therefore seek only to draw out key elements and conclusions from it.

6. The AEE Modelling Report describes the state of the computer model of the Wairakei-Tauhara geothermal system at June 2007. That model is referred to as the "2007 model". I will use this name again in my evidence. Most aspects of the 2007 model are very similar to the 2006 model that I

presented in evidence to the Environment Court in 2006 as part of the appeals related to the continued operation of the Wairakei Power Station.

7. The model is used for future scenario forecasting of two scenarios. They are:

- TM1 - Existing environment baseline
- TM2 - 95,000 tonne per day injection application case

(i) In both cases the total mass production for the Wairakei Power Stations is maintained at the consented maximum (211,000 t/day from 1/7/07-31/12/11, 215,000 t/day from 1/1/12-30/6/13, 245,000 t/day from 1/7/13-31/12/55).

(ii) In both cases a mix of infield and outfield injection as provided for by the available injection consents is used to maintain a pressure target of 56 barA or greater at -400 mRL in TH1 and TH3[1].

(iii) For Scenario TM1 60,000 t/day of separated geothermal water and 35,000 t/day of steam condensate are discharged to the surface at Wairakei[2].

(iv) For Scenario TM2 there is no discharge of either condensate or separated geothermal water to the surface except for the evaporation from the Poihipi Road Power Station cooling tower. TM2 considers a case where all the steam condensate is injected as would be the case if a dry cooling system was employed in the Te Mihi power station generation process and no evaporation occurred to the atmosphere. The amount of injection modelled is therefore the maximum that could be contemplated.

Summary of Conclusions

8. The conclusions from the scenario forecasts are:

- Both scenarios achieve the required 56 barA minimum pressure at Tauhara (TH1 and TH3) at the -400 mRL level. For both scenarios, the pressure at the -400 mRL level slowly increases by about 6 to 8 bar above the minimum target pressure by the end of the 50 year modelled period. The difference between the scenarios is that the additional

[1] This is the initial pressure target specified in the Wairakei General Conditions which is required to be achieved after a four year transition

infield injection in TM2 causes the pressure rise to occur more quickly over the interval from 2012 to 2035.

- Scenario TM1 requires more make-up wells but produces higher enthalpy fluid[3].
- The effect of increased infield injection under the application scenario (TM2) is to reduce the production enthalpies at Wairakei.
- For Scenario TM2 a smaller amount of infield injection could be used to maintain pressure at Tauhara while not degrading production enthalpies at Wairakei so much. In the AEE modelling report, I drew attention to the fact that suitable sites for increased outfield injection would have to be found to enable such a reduction to occur. The same comment would apply to other discharge options such as condensate spray irrigation. I understand that any reduction in infield injection and indeed the larger question of the appropriate mix of discharge methods would have to meet the objectives for the Discharge Strategy specified in the General Conditions of the Wairakei consents.
- Geotherm obtain a small beneficial effect (for its consented power station project) in that infield injection supports Geotherm's production for a little longer[4]. The overall production level is about 5000 tonnes per day greater at 2026 with the additional infield injection.
- Neither scenario significantly affects the shallow temperatures near the Crown Road area at Tauhara.

The Modelling Process

9. In a geothermal system like Wairakei-Tauhara there is a large scale convective system driven by magmatic heat flow, with hot water rising in two plumes – one at Wairakei and another at Tauhara (possibly a third at Rotokawa is also linked at depth). The shape of this convective system is determined by the sub-surface geological structure. The aim of computer modelling is to reproduce, with a reservoir simulator, the pressures, temperatures, heat flows and mass flows that occur in the Wairakei-Tauhara System.

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2 This is the case at present.
3 Enthalpy is a measure of energy content, so this is an important parameter for production purposes.
4 As I discuss later in my evidence, this is relative as the outlook for the Geotherm project is poor under all scenarios.

10. Modelling is conducted in four phases: conceptual modelling, natural state, production history matching, future scenarios.

11. ***Conceptual Model.*** Before a reservoir simulator can be used and a good model developed, there must be a good understanding of the important aspects of the structure and important physical processes of the geothermal system. In the conceptual modelling process all available data is brought together and used to develop this understanding. Data comes from a number of sources, including well tests, reservoir monitoring, geology, geophysics and geochemistry. In the case of Wairakei - Tauhara, the conceptual model is well developed. There is over 50 years of monitoring and measurements within the field, and there are many wells. However there is still some uncertainty about the detailed structure of some areas of the field which have not been so extensively explored.

12. The computer model is developed from the conceptual model. This involves designing a grid structure that covers the region of interest and assigning suitable numerical values to the parameters in each block or element in the model. Adjustments are made to the parameters as the model is refined through the calibration process.

13. Boundary conditions on the top, bottom and sides of the model are also included, in particular the location and magnitude of deep inflows.

14. ***Natural state.*** This involves running a model to simulate the development of the geothermal system over geological time. The results of this simulation can then be compared with pre-production measurements within the field. The quantities examined include the reservoir temperatures, location of surface outflows, and liquid saturations. The model results and the measured data are compared, the model parameters are adjusted and the simulation is repeated. The calibration process generally involves varying the permeability structure of the model by a small amount to obtain a better match. The location and magnitude of deep inflows may also need to be adjusted. Usually many iterations of this process are required to obtain a satisfactory match to the field data. This process may highlight inconsistencies in the conceptual model that need to be re-examined.

15. Detailed results for the natural state model are presented in Section 4 of the AEE Modelling Report. They show that a good match to the pre-development temperatures has been achieved.

16. ***Production history matching***. The next stage of calibration seeks to match the simulation of the past behaviour of the geothermal system to the production history. In this process the past production rates for the wells are assigned to the relevant blocks in the model (based on information about the locations of the feed-zones) and a simulation of the production period is carried out. The pressures and temperatures in the model at the start of production are taken from the natural state model.

17. The model results for pressure changes are then compared to field data and adjustments made to permeabilities and porosities if necessary. Also a comparison of model production enthalpies with field data is made. Enthalpy is a measure of the heat content of the water/steam mixture produced from the wells.

18. Detailed results for the history matching simulation are given in Section 5 of the AEE Modelling Report. A very good match to the production enthalpy for most wells has been achieved and there is also a good match to most of the pressure decline data.

19. ***Future scenarios***. Once a satisfactory match to the available data is obtained, the model can be used to simulate the behaviour of the geothermal system to future production or injection. Various scenarios can be developed and tested.

20. The initial values of pressure and temperature for the future scenario simulations are taken from the final values in the production history simulation. In the future scenario simulations the wells are operated in "deliverability" mode. In this mode the flow rate depends on the feed block pressure and as the block pressure declines the flow rate declines. When the block pressure drops below a pre-set cut-off pressure the well ceases to flow. Also wells cease operation when the enthalpy drops to below 860 kJ/kg. In both respects, this matches the way wells are operated in the field.

21. A number of features have been added to the simulator to assist with the scenario modelling. Make up wells are automatically added when either the total mass flow or the total steam flow from a set of wells falls below a pre-set target. Injection can be made proportional to the total separated water flow or the total condensate flow.

22. It is quite difficult to gain a good understanding of the main features of the two scenarios modelled by reading the AEE Modelling Report, because the descriptions of them are necessarily detailed. Therefore I will provide a brief overview here. I have attached some of the figures from the AEE Modelling Report as exhibits to assist with this process.

23. Exhibit MJO 1 shows the outfield injection areas used in my modelling study. Areas A and B are near the Waikato River, straddling and just east of the resistivity boundary shown on the exhibit (quite close to Aratiatia). Area C is at the far northwest of the model, west of Te Mihi.

24. Exhibit MJO 2 shows the infield injection areas (most of which are used only for Scenario TM2). Area 5 is the injection area adjacent to the Waikato River. Area 2 is near Karapiti and area 1 is adjacent and just south of there. Area 3 is in the north-east of Tauhara while Area 4 is a small zone in the middle of Tauhara. Area X is near the Wairakei power station and area Y is in the north-west of Wairakei, just east of Te Mihi.

25. Exhibit MJO 3 shows on one page both Figs. 4.17 and 4.18 from the AEE Modelling Report. Fig. 4.17 shows a large proportion (approximately 40%) of the total fluid disposal is to the surface for Scenario TM1. Approximately 50% is injected infield in Area 5. The remaining 10% is mostly injected outfield in Areas A and B with a small amount going outfield to Area C.

26. For Scenario TM2, to accommodate the 95,000t/d additional infield injection, outfield injection is increased with approximately 1/3 going to Area C and 2/3 going to Areas A and B. While the total of infield injection is increased from that for TM1 the amount going to Area 5 is decreased. Approximately 60% of the infield injection goes to Area 5 and the remaining 40% is spread around the other areas.

27. In both scenarios the total mass production for the Wairakei Power Stations is maintained at the consented maximum (211,000 t/day from 1/7/07-31/12/11, 215,000 t/day from 1/1/12-30/6/13, 245,000 t/day from 1/7/13-31/12/55).

28. The main conclusions from the scenario simulations were presented above in Paragraph 8. More details are given in Sections 7 and 10 of the AEE Modelling Report.

Geotherm

29. In both scenarios I allowed for a possible take by Geotherm of 70,000t/day. The result of an initial take by Geotherm at this level, however, is that reservoir pressures in this part of the field drop quickly. This is because the Geotherm wells are located at the very edge of the Wairakei field in a zone of low or medium permeability. Because the wells are operating on a deliverability basis within the model, the effect of the rapid drop in reservoir pressures is that the target mass flow is not achieved. The addition of make-up wells would not help because pressures in the whole of the Geotherm area are low. For Scenario TM1 the mass flow very quickly drops to about 8,000t/day and then steadily declines further to less than 2,000t/day by 2020.

30. For Scenario TM2 the larger infield injection rate helps to maintain production by Geotherm but only at a low rate of less than 8,000t/day up to 2028 and then at a rate of 5,000t/day or less.

31. The outputs of a modelling study I undertook for the purposes of evidence I prepared in relation to Geotherm's consent applications using my 2006 model[5] provide an indication of the effects of varying the parameters from those modelled in this latest study in relation to injection strategies. For two scenarios, one with full infield injection (Scenario 12) and one with a small amount of infield injection (Scenario 11), my 2006 model showed production by Geotherm decreasing rapidly. For Scenario 12 full infield injection maintained production at around 10,000t/day up to 2014 and then it declined rapidly to zero. In other words, a greater level of infield injection was of marginal short term benefit, but hastened the decline of production in the medium term.

32. All of the scenarios I have considered show the Geotherm wells declining rapidly in production rate, being unable to sustain a rate of even 10,000t/day. Some scenarios (such as TM2) provide a marginal benefit for Geotherm, others (such as the full injection Scenario 12) provide a marginal short term benefit for Geotherm, but medium to long term detriment. I would not expect variations in the scenarios from those which I have modelled to alter that picture. In summary, therefore, the outlook for the Geotherm project is poor whatever production and injection scenario

[5] The appeals on Geotherm's consent applications were settled prior to hearing and so the evidence I prepared was never called.

Contact adopts. Any differences will at most be of marginal benefit or detriment to Geotherm, and will not overcome the fundamental difficulties with that project.

33. I have read the submission of Geotherm Group Limited (In Receivership) which suggests (on page 3) that my modelling assumed the use of a conventional steam turbine and that the results would be different if alternatives were considered- a binary plant is given as the example. It is incorrect that my modelling assumed use of any particular type of surface plant. I focused on mass flow and assumed 100% reinjection (which Geotherm's consents require). Changing from a steam turbine plant to a binary plant will not alter my conclusion that the reservoir cannot deliver much mass for Geotherm in anything other than a very short term and that the reinjection options chosen by Contact will only have a marginal effect on that position."

Ongoing Modelling Developments

34. Our computer model of Wairakei-Tauhara is a work in progress. We are continuing to work to improve its accuracy. Thus changes were made to the model between 2006 when I presented evidence to the Environment Court and the 2007 version utilised in the AEE Modelling Report. The main changes resulted from new data that became available from wells recently drilled at Te Mihi (WK243, WK245 and WK247). Some model recalibration was required to match the new data (details are in Section 1 of the AEE Modelling Report).

35. Further changes to the model have been made during 2007 and 2008. The first stage of this process occurred when data from two new wells drilled in the north-east sector of the Tauhara Field became available (TH 11 and TH12) and demonstrated that that sector of the Field was both productive and hotter than previously predicted. Some recalibration was required to fit the model to the new data.

36. The second stage of our 2007/2008 model improvement was carried out in response to a peer review of our model conducted for Contact by Dr John Pritchett and Dr Sabodh Garg from Science Applications International Corporation (SAIC). Their work identified that the long-term predictions from our model may be too strongly dependent on the recharge boundary conditions specified at the base of our model. Two actions were suggested:

- Check the chloride content in the production (to determine whether or not the balance between deep recharge of more saline water and shallow recharge of fresh water is correct in the model).
- Deepen the model.

We have recently followed both of these suggestions.

37. ***Chloride***. We ran our model allowing for a mixture of water and sodium chloride and found that our model results matched the chloride data well.

38. ***Deeper model***. Our 2006 and 2007 models included a volume down to 2.5km below sea level giving a model thickness of approximately 3km. We have now added an extra 1km depth to our model giving a total depth of approximately 4km.

39. With each modification we have made to our model since mid-2007 we have re-checked the natural state, the history match and the future scenarios TM1 and TM2. The results we have obtained are so similar to those given in the AEE Modelling Report that I have not included them with my evidence.

40. In the future, my intention is to make the model even deeper so that it includes the whole of the convective system of Wairakei-Tauhara within the model and thus deep recharge boundary conditions will no longer be necessary.

41. As well as reservoir modelling, my research group is working on modelling subsidence in Wairakei-Tauhara. We use the changes in pressure and temperatures predicted by our TOUGH2 reservoir simulator as input into a rock mechanics simulator called ABACUS. This process is mathematically complex because the elements used in the ABACUS subsidence calculation are more refined than the coarser elements in our TOUGH2 reservoir simulations and careful interpolation of pressure changes is required.

42. We have achieved promising results for our 3D simulations of the development of the Wairakei subsidence bowl and we are working to have a 3D model of subsidence for the balance of the Wairakei-Tauhara system.

M.J. O'Sullivan