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The Mokai Geothermal Power Plant, New Zealand: Analysis of Performance During First Year of Operation

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ABSTRACT

Construction of the Mokai geothermal power plant, located near Taupo, New Zealand, was begun in February 1998, with commissioning in late September – early October, 1999 and full commercial operation in February 2000. The power plant, which was supplied and constructed by Ormat, has a nominal design capacity of 59.1MWe gross (53.4MWe net).

The measured power plant parameters from the first year of operation indicate that performance has exceeded initial design parameters both in terms of electrical generation and efficiency. The plant has routinely produced over 60MWe gross, with generation peaking at over 63.5MWe gross (59MWe net) during the winter months. Utilisation of the input heat is also approximately 16% more efficient than anticipated, with performance of all components exceeding design specifications.

The plant was shut in late November 2000 for a warranty inspection; the steam turbine required some repairs and was not returned to service until early February 2001. Both the steam and brine OEC units remained in service, however, allowing the power plant to continue generating 29MWe gross. Since the steam turbine returned to service, the power plant has continued to perform well in terms of both generation and efficiency.

Introduction

The Mokai geothermal field is located in the North Island of New Zealand within the Taupo Volcanic Zone (TVZ), approximately 30kms north-west of Lake Taupo (Figure 1). The field was initially overlooked as a potential commercial geothermal resource due to the relatively low level of surface thermal activity when compared to other fields in the TVZ. In late 1976, a deep penetrating roving dipole resistivity survey was conducted across the TVZ (Bibby *et al.*, 1981) and the results indicated the presence of a large potential geothermal resource in the area of the Mokai springs.

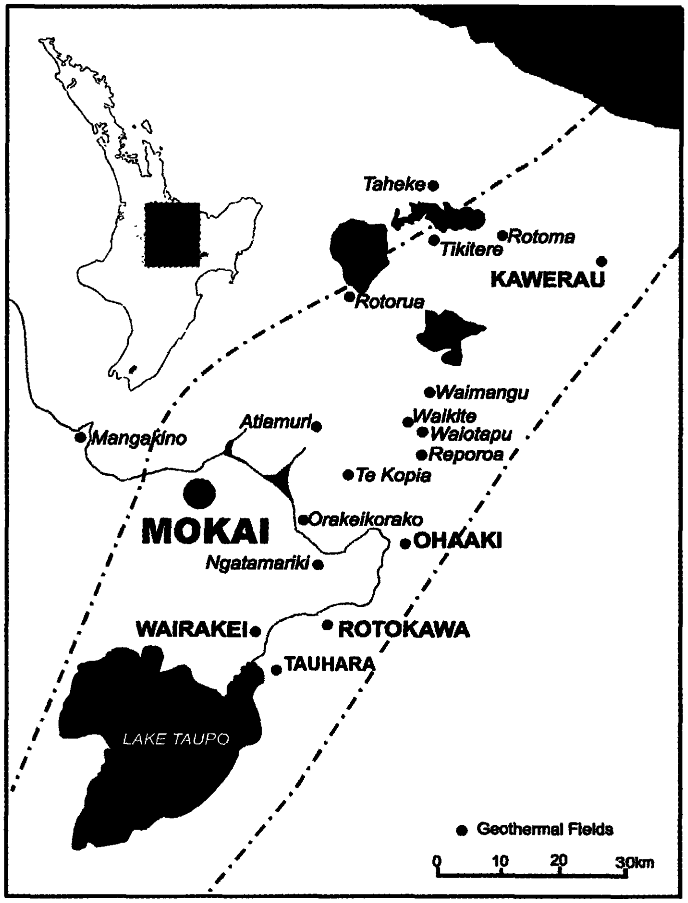

Figure 1. Project Location.

Schumberger resistivity surveys were conducted in 1977/1978 and six exploration wells (MK-1 to 6) were drilled between 1981 and 1983 by the New Zealand government agencies (DSIR and MWD) responsible for geothermal exploration and development at the time; locations are shown in Figure 2. The wells were drilled to depths ranging from 606m (MK-1) to 2,602m (MK-5); MK-1 was completed with 6-5/8-inch production casing, MK-2, 3 and 4 with 8-5/8-inch production casing and MK-5 and 6 with 9-5/8-inch production casing. Well MK-5 was considered to be one of the most productive wells in the world at the time it was drilled; the estimated maximum output was 690 t/h at a wellhead pressure of 11.5 barg (Watkins, 1985), corresponding to a capacity of approximately 25MWe. Wells MK-2, 3 and 6 were also productive but with significantly lower outputs than MK-5.

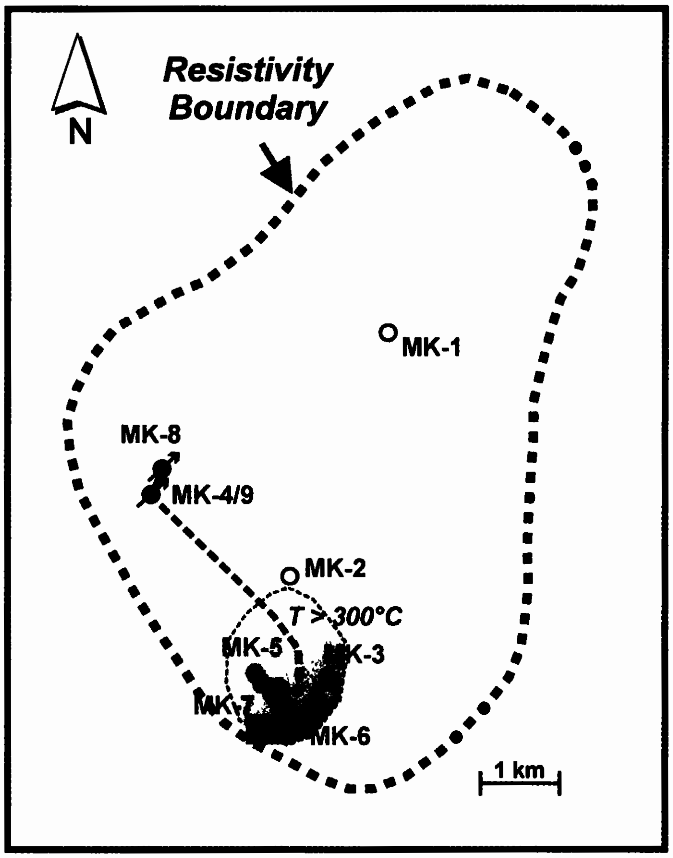

Figure 2. Well Locations, Mokai Geothermal Field.

The interpreted boundary of the Mokai geothermal field, based on the surface geophysical surveys, and the area where downhole temperatures of greater than 300°C were encountered are also shown in Figure 2. It was also found that the geothermal resource has slightly artesian pressure conditions.

With the success of the exploration programme, development of the geothermal resource for commercial power generation was promoted by various government agencies. However, the Tuaropaki Trust, which owns and administers land overlying the resource for the benefit of seven local Maori hapu (sub-tribes), decided to proceed with development on their own behalf. They applied for and obtained the required Resource Consents to develop the resource in 1994 and purchased the Crown's interests in the existing wells in 1996. The Tuaropaki Power Company Ltd (TPC), a wholly owned subsidiary of the Trust, was formed to carry out the development and a turnkey agreement was signed with the Ormat Group of Companies to supply and construct the power plant and related facilities while financing was arranged through Westpac Banking Corporation.

Construction of the surface facilities, including the fluid collection system, power plant and 20km of 110kV transmission line began in February 1998, with the plant commissioned in late September – early October 1999 and full commercial operation starting in February 2000. An additional production well (MK-7, with 13-3/8-inch production casing) and two shallow (<550m) injection wells (MK-8 and 9) were also completed and the current configuration of the production system is shown schematically in Figures 2 and 3. The power plant is currently supplied from four production wells (MK-3, 5, 6 and 7) through a centralised separator station containing two separators and a brine accumulator.

The power plant has a nominal design capacity of 59.1MWe gross (53.4MWe net) and includes an Ormat GCCU (31MWe GE back pressure turbine/generator and 4 x 4.6MWe OEC's) and 2 x 4.9MWe OEC's for extracting additional energy from the separated brine. Air coolers are used to provide the cooling requirements for the binary units. Further information on the power plant has been presented in Legmann (2000) and Legmann and Citrin (2001).

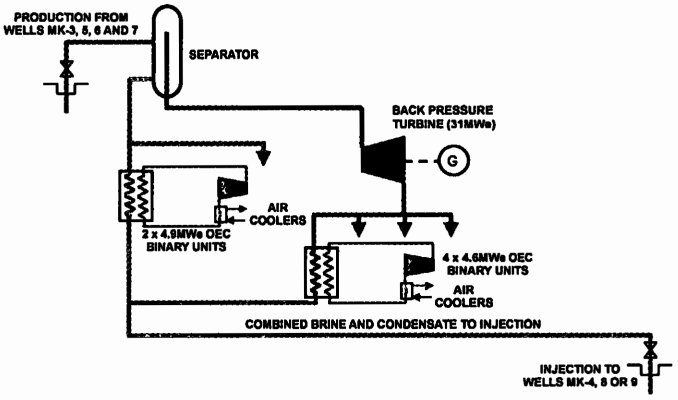

Figure 3. Schematic showing Major Plant Components.

The steam is separated at 18.6 bara and piped to the back pressure turbine, which has a design inlet pressure of 17.6 bara. The exhaust steam from the back pressure turbine then enters the four steam OEC units at just above atmospheric pressure and is condensed to produce additional power. The separated brine passes through two brine OEC units, where heat is extracted to produce power and the temperature reduced from 207°C to 152°C. The heat-depleted brine is then recombined with the steam condensate and disposed of by injection into wells MK-4, 8 and/or 9. These wells are located approximately 4km from the power plant and approximately 40m higher in elevation. Injection booster pumps were included in the initial design but due to the high permeability encountered in the shallow injection wells, the pumps have not been required and have recently been taken out of service and stored. Without the need to use these pumps, the anticipated parasitic load on the power plant has also been reduced, thereby increasing the net power available.

Mighty River Power (MRP), which was previously part of the Electricity Corporation of New Zealand (ECNZ), operates the power plant and steamfield under a long term O&M contract with TPC. MRP also provided some additional financing for the project and purchases the majority of the produced electricity under a 25-year Hedge Contract. The produced electricity is then on-sold to the wholesale spot market.

Production Parameters

The Mokai power plant began commercial operation in February 2000 and was operated until November 2000 when it was shut for a scheduled warranty inspection. During commissioning and early operation, leaks were found in the vapourisers of the steam OEC units, apparently caused by pitting corrosion, which required the affected tubes to be plugged. Once the plant was running continuously, however, the only outages that occurred were from 25 May to 10 June when one of the steam OEC's (OEC-11) was out of service due to a pentane fire and a scheduled outage from 18 to 23 June.

During the November shutdown, inspection of the steam turbine revealed damage to the internals as a result of both corrosion and erosion and the shutdown was extended so repairs could be undertaken. The reasons why the damage occurred are still under investigation.

Both the steam and brine OEC units remained in service during the shutdown, which allowed the power plant to continue producing approximately 29MWe gross. The steam turbine was returned to service in early February 2001.

Production data from May through to August were obtained from screen dumps of the Main SCADA system display, which provides "snapshots" of information on various well and plant parameters. The screen printouts were not taken on a regular basis and the density of data over this period is therefore not uniform. There are also no data from March and April while the data from February are restricted to only two periods; 9 and 10 February, collected during the Reliability Run, and on 17 February, during the Performance Test.

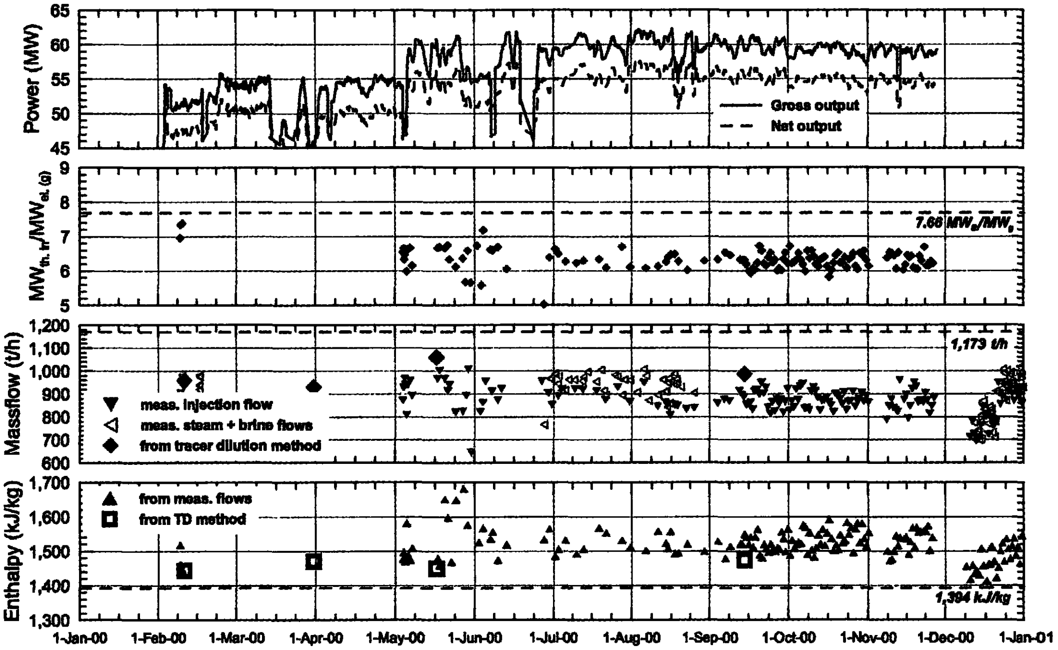

Figure 4. Overall Power Plant Production Parameters.

Since September 2000, it has been possible to download data directly from the control system to an EXCEL workbook. The data are now being sampled every four hours, with the information downloaded every month for plotting and analysis.

The data are used to follow the long term trends in field and power plant performance and to determine how the overall power plant, the GCCU and the brine OEC's are performing compared with initial specified design conditions. The effect of ambient temperature on power plant operation has also been analysed as this can have a significant impact on the air coolers used to condense the binary fluid. The operating efficiency, based on gross electrical power output, of the GCCU has also been compared with the performance of condensing turbine units recently installed in other geothermal fields.

In addition to the measured power plant data, the steam and water flows from the wells are also measured periodically using SKM's tracer dilution (TD) method (Lovelock and Stowell, 2000) and the results are compared with the measured data in the appropriate plots.

Overall Plant Performance

Input and output parameters associated with the overall performance of the Mokai power plant are shown in Figure 4, including gross and net power output, specific heat rate, total flow from the wells and total field enthalpy. The power plant design was based on a total flow of 1,173 t/h at an enthalpy of 1,394 kJ/kg, to give a steam flow to the GCCU of 313 t/h and a brine flow of 860 t/h at the design separator pressure of 18.6 bara. This corresponds to a specific heat rate of 7.66MWth input per gross MWe generated.

The measured data shown in Figure 4 indicate that the actual production enthalpy has been between 1,500 and 1,550 kJ/kg, which is higher than the design value. The higher enthalpy results in a higher steam fraction after separation and the total flow required to provide the design steam flow is therefore reduced, which also reduces the brine flow available for the brine OEC units. It would be anticipated that the overall output from the power plant would therefore be lower than design if the steam flow was the controlling factor. In practise, the measured data indicate that the design gross and net generation capacities have been exceeded with a total flow rate of between 900 to 1,000 t/h, which is approximately 20% lower than the design value.

To remove the influence of enthalpy, the specific heat rate has also been calculated and plotted; this parameter has an average value of 6.4 MWth per MWe, which is approximately 16% less than the design value of 7.66MWth per MWe.

GCCU Performance

The GCCU, which includes the steam turbine (STG) and four steam OEC units, has an overall gross rated capacity of 49MWe but this has generally been exceeded during the first year of operation (Figure 5). This performance is also being achieved with a measured steam flow of 295 to 300t/h, which is approximately 4% lower than the design flow requirement of 313t/h. The measured steam flow required per gross MWe produced varies from 5.5 to 6 t/MWe.h, compared with the design value of 6.35 t/MWe.h (Figure 5). The measured value has only exceeded the design value when OEC-11 was out of service. With all units running, the GCCU is able to produce up to 4 to 5MWe more than design and with a higher efficiency, even though some of the vapouriser tubes were plugged during commissioning due to leaks associated with pitting corrosion.

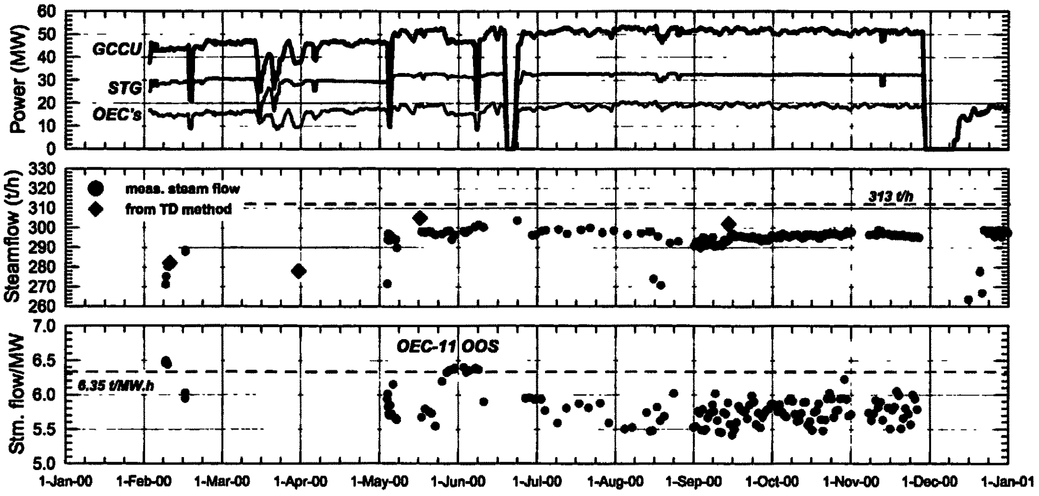

Figure 5. GCCU Production Parameters.

Ambient Temperature

The measured output from the GCCU and the steam flow per gross MWe are plotted as functions of ambient temperature in Figures 6 and 7.

It is apparent that ambient temperature has a significant effect on generation, with output decreasing from 54.5MWe at 0°C (winter night) to approximately 48MWe at 25°C (summer day) for a steam flow of 300 t/h. It is also apparent that the GCCU is producing more power and is also more efficient under all conditions than was anticipated based on the Design Correction Curves; the Design conditions were approached only while OEC-11 was out of service.

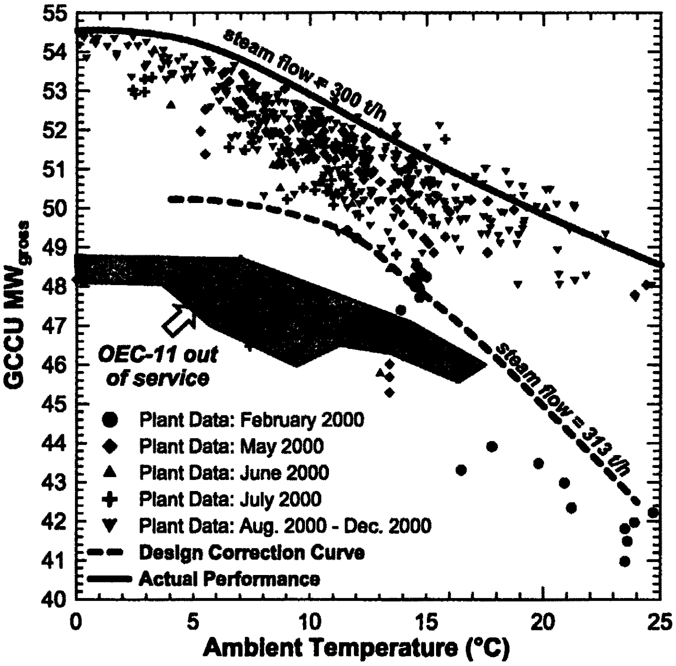

Figure 6. Impact of Temperature on GCCU Output.

Brine OEC Performance

The two brine OEC units have a combined nominal capacity of 9.9MWe gross although the actual output has generally been between 8 and 9MWe (Figure 8). This is due to a lack of brine flow, which has generally been below 700 t/hr, compared with the design requirement of 860 t/h. As mentioned above, the reduced brine flow is caused by the average field enthalpy being higher than the design value of 1,394 kJ/kg (Figure 1).

Although the brine flow has been lower than design, the brine flow requirement per gross MWe produced (Figure 8) has averaged 75 t/MWe.h, compared with the design value of 87 t/MWe.h. Hence, the brine OEC's are approximately 14% more efficient than design.

Ambient Temperature

The overall measured output from the brine OEC's is plotted as a function of ambient temperature in Figure 9. There is significant scatter in the data, which makes it difficult to deter-

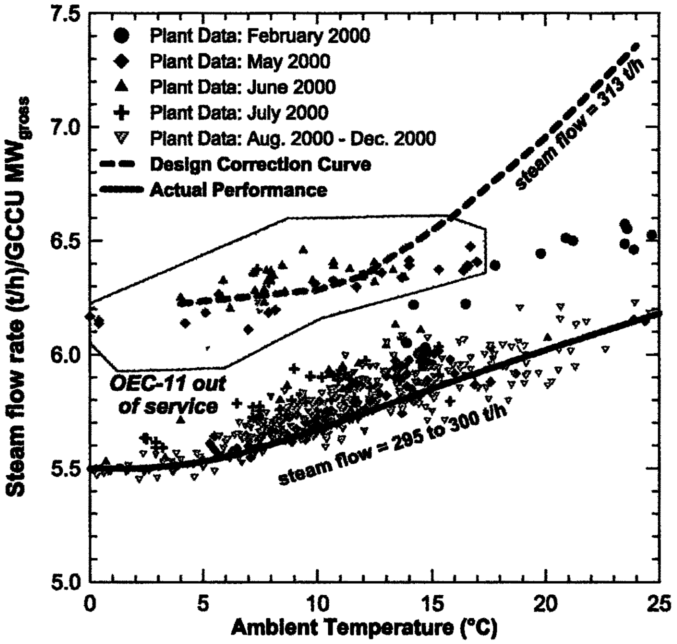

Figure 7. Impact of Temperature on Heat Rate.

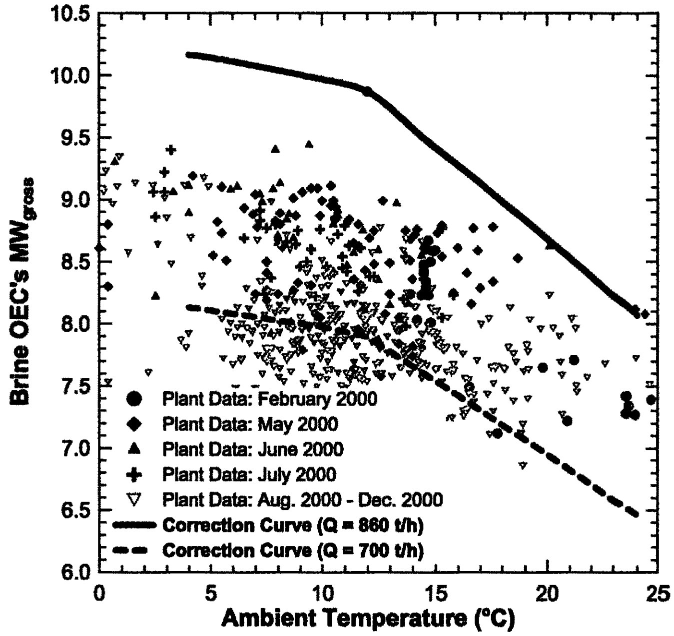

Figure 9. Effect of Temperature on Brine OEC Performance.

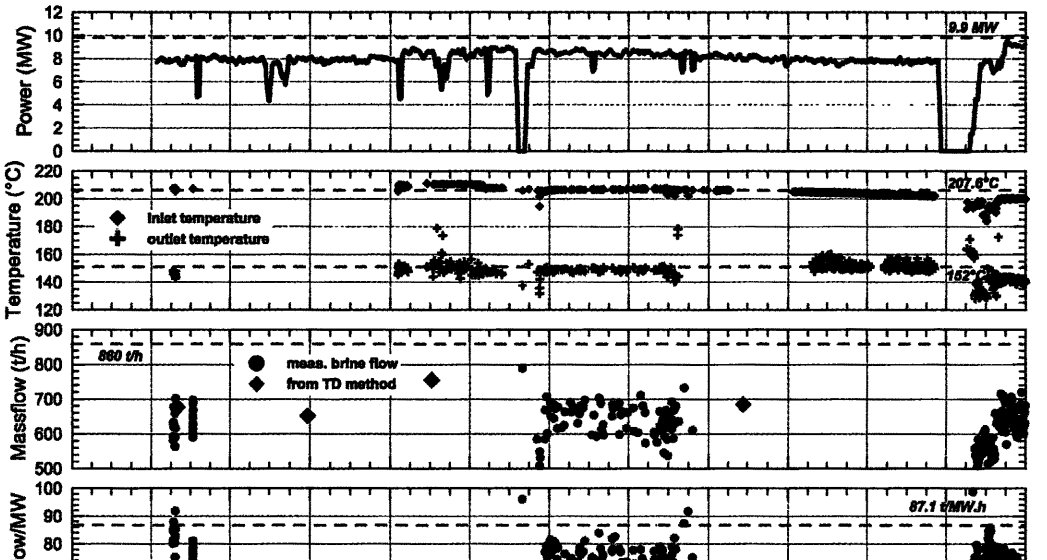

Figure 8. Brine OEC Production Parameters.

mine if there is any correlation with ambient temperature. It is apparent, however, that the brine OEC's are operating at higher efficiency than design under all conditions. To illustrate this, correction curves for the full design flow of 860t/h and a reduced flow of 700t/h are included in Figure 9. The curves indicate that reducing the flow to 700 t/h should result in a reduction in power output of approximately 20%. The majority of the measured data plot between the two design curves, even though the brine flow has generally been between 600 and 700t/h.

Accuracy of Flow Measurements

The observations and conclusions reached from the above analysis are directly affected by the accuracy of the collected power plant data, with particular emphasis on the measured flow data. There are a number of flow meters installed that provide data on steam flow to the GCCU, brine flow from each of the brine OEC units and injection flow. The injection flowmeter should also provide a very good estimate of the total flow as it measures the combined flow of both the separated brine and steam condensate, with the only losses being the non-condensable gases (NCG) from the steam OEC units. The NCG concentration in the steam varies for the production wells from 0.4 to 1.1 wt-%, indicating that the NCG flow should be less than 4 t/h.

Measured Flow Rate Data

The total flow has been determined by two methods; adding the individual steam and brine flow measurements and by assuming that the measured injection flow provides a good estimate of the total flow.

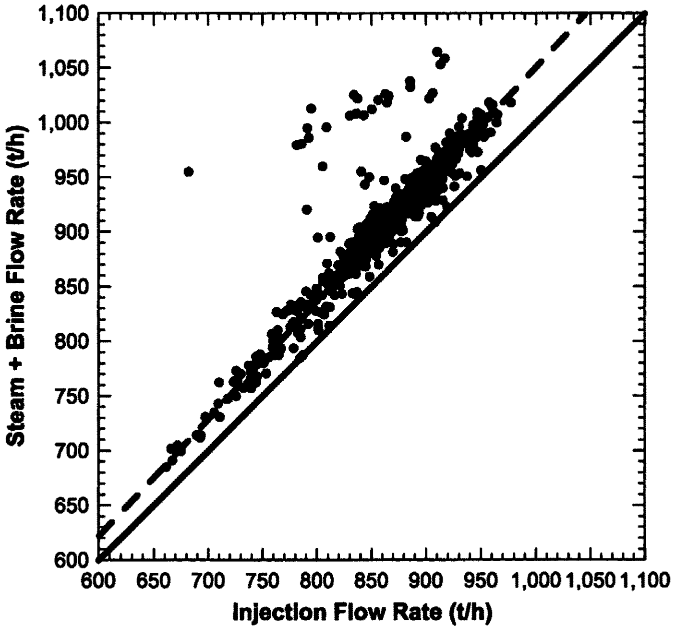

Figure 10. Comparison of Plant Flow Measurements.

For the steam + brine data, there is only a limited data set available as difficulties have been encountered at various times with blocking of the tappings for the brine flow meters during operation.

The total flow rates estimated from the steam + brine measurements are plotted against injection flow measurements in Figure 10. If the two data sets were consistent, the plotted points should fall close to or along the 45° "equality" line. It is apparent, however, that there is a systematic difference, with the steam + brine flow averaging 50 t/h higher than the corresponding injection flow, which cannot be explained by the "normal" losses from the system. Hence, it may suggest there is a systematic difference in the calibration of the flow meters. However, the difference of 50 t/h has little effect on the calculations of power plant efficiency.

Tracer Dilution Technique

The steam and water flows from the individual wells have been measured periodically using SKM's tracer dilution (TD) technique (Lovelock and Stowell, 2000) and the mass flows and discharge enthalpy estimated from the TD results, are included in Figures 4, 5 and 8. There is good agreement between the measured data and the TD results, further suggesting that the measured data are adequate for the analysis of plant performance.

Comparison of Mokai GCCU with Other Plant

The Mokai power plant was designed to take advantage of the relatively high discharge pressures available from the production wells, with a design inlet pressure to the back pressure steam turbine of 17.6 bara. This is significantly higher than typical inlet pressures (<11 bara) used for condensing steam turbines in geothermal power plants, which have generally been constrained by exhaust wetness and erosion on the back end blades. However, by removing the moisture as it forms in the steam turbine and increasing the length of the last row of blades, it is possible to both increase the inlet pressure and reduce the condenser pressure. For example, the Mitsubishi steam turbine installed at the Darajat II project in Indonesia (Saito, *et al.*, 1998) has a design inlet pressure of 13.3 bara, exhaust pressure of 0.06 bara and rated output of 81.3MWe. It can also be operated at up to 100.7MWe by increasing the inlet pressure to 16.5 bara.

Plants that include an Ormat GCCU configuration similar to Mokai have been installed at:

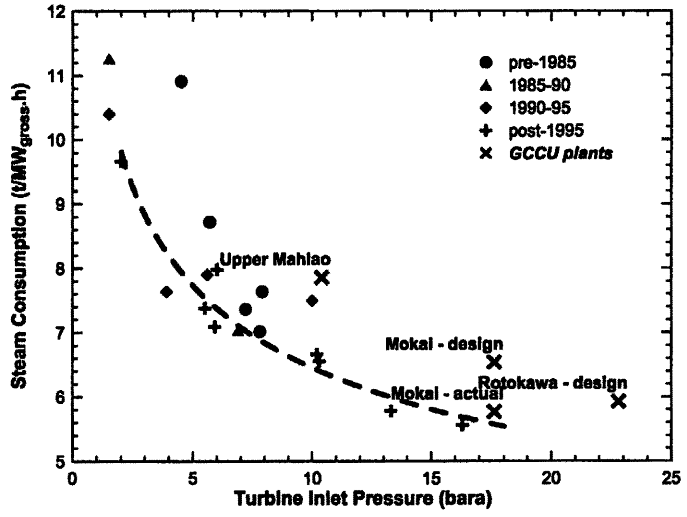

Figure 11. Steam Consumption vs Inlet Pressure.

- Rotokawa, New Zealand
  design inlet pressure = 22.8 bar.a
- Upper Mahiao, Philippines
  design inlet pressure = 10.4 bar.a

Figure 11 presents a plot of specific steam consumption (steam flow requirement per gross MWe produced) for a number of existing conventional and GCCU power plants as a function of turbine inlet pressure. This is a relatively crude comparison, as the data are affected by variation in unit size and site specific conditions, such as ambient temperature, NCG content, elevation, etc, which influence the back end conditions of the turbine and therefore power plant efficiency. It does, however, show the development towards higher inlet pressures and how unit efficiency has improved with time.

Figure 11 indicates that the design specific steam consumptions for the Upper Mahiao and Mokai GCCU power plants are generally higher than for condensing steam turbines with equivalent inlet pressures while for the Rotokawa power plant, it isn't possible to make a direct comparison. For the Mokai power plant, however, the measured specific steam consumption is similar to the design value for the condensing steam turbine installed at Darajat II, which is the only conventional power plant with a similar inlet pressure. Figure 11 also shows that specific steam consumption is a strong function of inlet pressure and the use of higher pressures in either a condensing steam turbine or GCCU power plant will result in a significant improvement in efficiency of steam use. At the present time, however, there are very few power plants with inlet pressures of greater than 10 bara; most are still designed with lower inlet pressures due to historical precedence and/or possible resource constraints, which limits the available discharge pressure.

Conclusions

Based on the data presented in this paper regarding the Mokai geothermal power project, the following conclusions can be reached:

The Mokai geothermal power project has been very successful for the Tuaropaki Power Company in terms of both electrical generation and efficiency. In both of these areas, the performance of the Mokai power plant over the first year of operation has exceeded expectations when compared with the initial design parameters.

For the overall power plant, the average ratio of heat in (MWth) to power produced (MWe) of 6.4 is approximately 16% more efficient than the design value of 7.66.

For the GCCU, the average measured specific steam requirement on a gross MWe basis, of 5.8 t/MWe.h is approximately 9% lower than the design value of 6.35 t/MWe.h. This also compares favourably with the design specific steam consumption of the condensing turbine installed at Darajat II, which can be operated at a similar inlet pressure.

For the brine OEC's, the average measured specific brine requirement of 75 t/MWe.h is approximately 14% lower than the design value of 87 t/MWe.h.

There do appear to be systematic differences between the physical flow metering devices installed at Mokai which affect the accuracy of the flow measurements. They do not, however, have a significant effect on the analysis of efficiency presented in this paper.

The SKM tracer dilution technique, which is being used at Mokai as the primary technique for monitoring changes in mass flow and enthalpy of individual wells, has provided additional confirmation that the overall mass flow rates calculated from using physical measurement techniques are reasonable.

The use of higher inlet pressures in either conventional condensing steam turbine or GCCU configurations results in significant improvements in the efficient use of steam, provided that the geothermal field can support the higher pressures.

Acknowledgements

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