

## Power Plant Selection in Mighty River Power Development Projects

Tony Gray

Mighty River Power, 160 Peachgrove Rd., Hamilton 2001, New Zealand

tony.gray@mightyriver.co.nz

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### ABSTRACT

This paper compares different energy conversion rates for some geothermal power plant cycles. These are being implemented at two high temperature, liquid dominated reservoirs; Kawerau and Rotokawa.

The power plant cycle selected for the first development is a dual flash, condensing steam turbine; however, optimisation with higher pressures and enthalpies resulted in a triple flash, condensing steam turbine for the second development. This will be the largest single cylinder geothermal steam turbine in the world. The project is currently under construction with commercial operation scheduled for the first half of 2010.

The environmental consent process in New Zealand provides a fixed average fluid extraction rate and an instantaneous maximum. Geothermal fluid conditions, (including; enthalpy, non-condensable gas content and chemistry) were defined from well test results and reservoir modelling. The owners' financial model has been used to provide key metrics for selection of the plant cycle giving the maximum revenue from the consented geothermal fluid flow, considering life cycle costs. In one example, the selected triple flash cycle developed 6 MW more than a comparable dual flash cycle.

### 1. INTRODUCTION

In 2004 Mighty River Power called for a reality check about electricity generation. It was obvious that while hydro had served New Zealanders well, it was necessary to look at a wider range of sustainable and reliable sources of energy. As well as seeing that demand was increasing, it could also be seen that attitudes were changing about fuel sources for generation. Addressing environmental issues was already becoming a mainstream way of doing business.

Since then, Mighty River Power has committed to developing, in co-operation with its partners, 400 MW of geothermal resources by 2012. A milestone in the programme was the completion of the NZ\$300 million geothermal power station at Kawerau. Originally due for commissioning in October 2008, the plant, which is capable of generating 106 MW(net), successfully supplied power into the national transmission grid prior to the end of June.

Construction of the NZ\$450 million Nga Awa Purua (NAP) project at the Rotokawa Field began in April 2008. This will include the largest geothermal steam turbine in the world, capable of providing 139 MW (gross). This Fuji manufactured equipment will be supplied by Sumitomo Corporation. Mighty River Power has forged strong and successful relationships with these companies during construction of the Kawerau project.

### 2. CONSENTING

In New Zealand the legislation governing "environmental licensing" is called the Resource Management Act" (RMA). At the core of the RMA's resource consents process is the primary need to provide for sustainable management of resources as well as providing for the social, economic and cultural well-being of communities.

Mighty River Power has been involved in widespread consultation with many groups and individuals in communities affected by the geothermal developments. It has provided an opportunity for Mighty River Power to talk with people about its business and goals, and the values that underpin the company's commercial goals. More importantly, the concerns of potentially affected parties were heard and where possible plans were modified or more information provided. These discussions have given a good insight into the concerns and the interests of the local communities, including other major industrial operators.

Mighty River Power applied for resource consent for the NAP project in June 2007 and received 15 submissions, with only four in opposition. This is a remarkable result for a project of this scale. All resource consents were granted by December 2008.

The consenting process described above resulted in an additional permitted average extraction rate of 45,000 tonnes/day, (1,875 tonnes/h) with a maximum (instantaneous) extraction rate of 55,000 tonnes/day at both the Kawerau and Rotokawa fields.

The use of the geothermal resource to generate electricity will assist New Zealand to meet its obligations under the Kyoto Protocol. It has been calculated that the Kawerau Geothermal project will avoid around 240,000 tonnes of carbon dioxide emissions annually when compared with the average national grid emissions levels.

### 3. PROCUREMENT

A procurement strategy was developed to consider the optimised life cycle costs across an entire proposed 400 MW development program. The key elements considered in the strategy were:

- Options to standardize plant across different resources within the proposed development
- The contractual split within the project
- Contract structure
- Nga Awa Purua power plant negotiations

#### 3.1 Standardized Plant

Standardization of plant across a 400 MW development program is intuitively a high value proposition: repetition of design and procurement; reduced spares holdings; operator training and plant familiarity; etc. The contractual split

described below separates the site specific works from the power plant and establishes a framework to standardize the power plant design, whilst customizing the steamfield and grid connection contracts.

Different technologies were reviewed to try to select a particular technology as a basis for power plant standardization. Single and double flash cycles were compared against the predicted performance of Organic Rankine Cycle (ORC) plant, based on historic conversion factors and thermodynamic cycle comparisons. See figures 1 to 3 below.

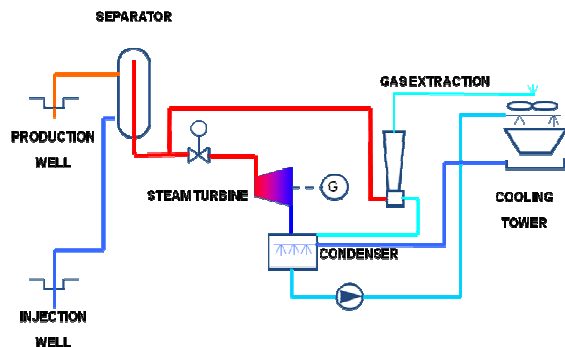


Figure 1: Simplified Diagram for Single Flash Plant

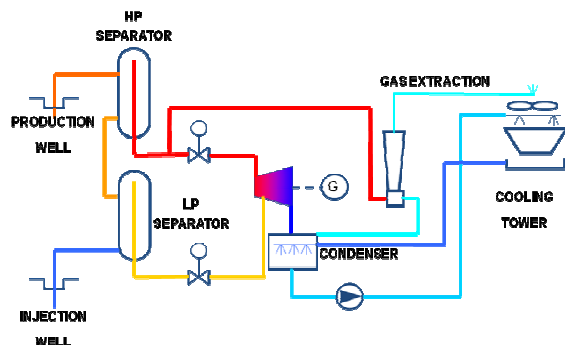


Figure 1: Simplified Diagram for Dual Flash Plant

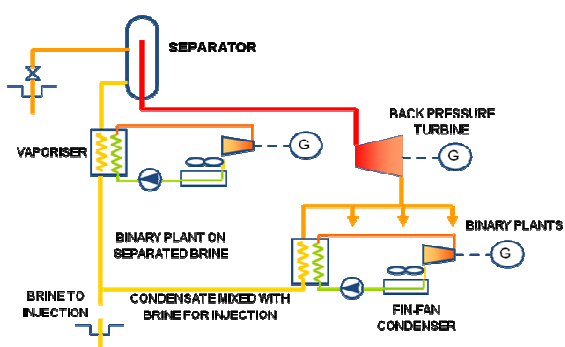


Figure 3: Simplified Diagram for Integrated Flash-Binary Plant

When standardisation this is considered across different resources with different enthalpies, pressures, fluid chemistry and potentially variable extraction rates, there was no compelling case to be made for compromising the design of the first plant to provide for standardization in the future. The focus was therefore, to optimise plant for each reservoir. The performance of the plant and its integration with the reservoir conditions was considered, in particular the maximum delivery pressure and the reinjection temperature

required to prevent silica scaling. The maximum long term delivery pressure was determined from reservoir modeling and silica saturation indexes (SSI) estimated from experience. The maximum allowable SSI for a dual flash plant was selected as 2.25, while a hybrid ORC was given as 2.35. The higher SSI for the Hybrid ORC reflecting the change in chemistry when mixing condensate and brine. The influence of high pressure and low pressure separation pressures are shown in figures 4 & 5 below.

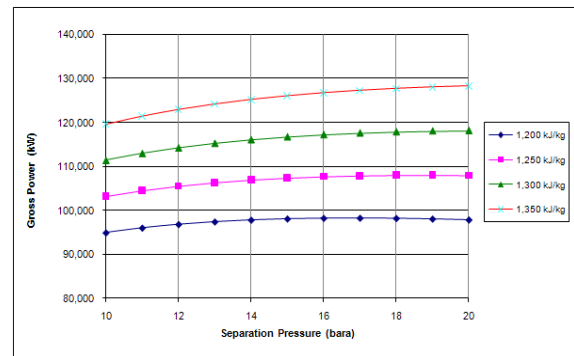


Figure 4: Gross Power against HP Separation Pressure for Dual Flash Plant for Different Enthalpies

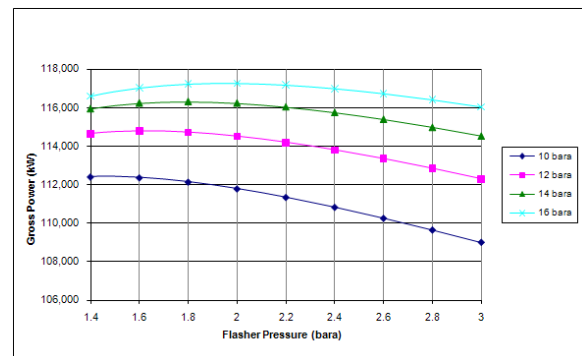


Figure 5: Gross Power against LP Flasher Pressure for Dual Flash Plant for Different HP Separation Pressures

The simplified process design comparison was used, in conjunction with in-house price estimates, to look for an optimal solution applied across different geothermal fields. The result was that no one technology was identified as having a clear technical advantage that would translate into an optimal commercial solution.

Mighty River Power elected to use a competitive tender process to select a power plant design optimized for the Kawerau geothermal field, then negotiate for a second similar plant. This provided a balance between optimizing a plant for particular reservoir conditions and enabling the standardization of plant and equipment between projects.

### 3.2 Contractual Split for the Projects

Understanding the risk profile and value equation associated with the geothermal reservoir and associated well drilling, is key to a successful geothermal development. This resulted in the establishment of an in-house team of experts to closely manage the fuel supply over the life of the plant. The fuel supply (i.e. all geoscience and drilling) is managed by Mighty River Power.

The balance of each project is split into three main contracts:

- Power plant: with terminal points at the separator inlet, brine and condensate discharge, and low voltage side of

the main step up transformer. This is discussed in more detail below.

- Fluid gathering and injection systems: The scope and design of the fluid gathering and injection systems carries significant uncertainty until all wells are drilled and tested. This resulted in a design build contract for Kawerau, with the design portion limited to the detailed design only. The process design, including line sizing, two-phase flow, pressure loss calculations and life cycle cost optimization was developed by Mighty River Power and provided to the main contractor.
- Electrical connection facilities: The contract to provide the connection to the grid is a turn-key, Engineer Procure and Construct (EPC) contract, with the main step up transformers being free issued by Mighty River Power.

### 3.3 EPC Power Plant Contract with Performance Based Specification

Mighty River Power chose to use a Federation International Des Ingenieurs-Conseils (FIDIC) based EPC contract, with appropriate portioning of the risk between Employer and Contractor. The plant specification (Employers Requirements) was chosen to be a performance-based specification, giving tenderers maximum opportunity to provide an optimised design. The consented fluid extraction rate, design point and range for all pertinent geothermal fluid conditions were defined. Tender evaluation criteria, such as \$/kW, were defined to enable the tenderers to optimise the plant output against capital cost. Optimization of each power cycle requires that as much energy is taken from the fluid as is technically and economically possible. A major limitation under current design practice is the lowest cycle temperature achievable for the brine being returned to the reservoir. This is governed by the deposition of silica from solution as indicated by the Silica Saturation Index (SSI). (Note: an SSI = 1 represents a silica solution in equilibrium; SSI<1 will not lead to Silica scaling; SSI>1 means that the solution is super-saturated and it is only the dynamics of the reaction which may prevent silica deposition.) It has been shown that the deposition reaction dynamics can be slowed down by modifying the fluid pH; however, this is not easy to predict with any accuracy. Therefore the optimization of the thermodynamic cycle was subject of experimental validation to predict silica deposition.

The tender process confirmed that there is no clear technological basis for choosing a particular plant (process) design.

## 4 NEGOTIATED CONTRACT FOR NGA AWA PURUA

The geothermal fluid conditions are significantly different between the Kawerau and Rotokawa fields, as shown in table 1 below.

The technical aspects of the negotiated Nga Awa Purua plant design were focused on: maximizing the plant efficiency; standardizing plant and equipment; incorporating lessons learnt from the Kawerau project; and improving the plant layout. Efficiency increases were realized by using a triple flash cycle as discussed below. Identical (or at least similar) equipment was used for: the Cooling Tower; Control System (DCS); Hot Well Pumps; Auxiliary Transformers; Electrical Switchgear; Compressed Air and other utilities; and parts of the Gas Extraction System. Technical details developed during the Kawerau project design reviews were

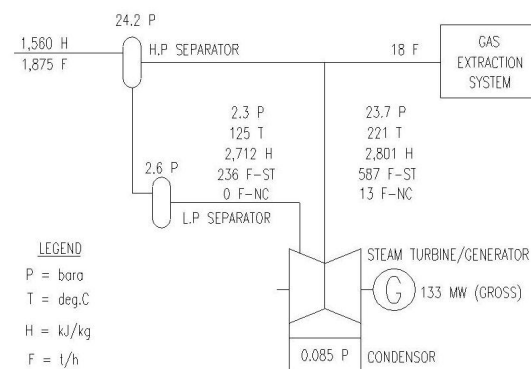
incorporated in the contract specifications and improvements discussed and mutually agreed.

**Table 1: Comparison of Power Plant Design Inputs**

	Nga Awa Purua (Rotokawa field)	Kawerau
Consented extraction (Tonne/day)	45,000 (ave.) 55,000 (max.)	45,000 (ave.) 55,000 (max.)
Design enthalpy (kJ/kg)	1560	1300
Non condensable gas content (wt%)	0.7% of total flow	0.6% of total flow
Maximum available delivery pressure (Bara)	26.4	14.1
Silica Saturation Index (LP Brine)	2.8	2.35

### 4.1 Dual Flash

The dual flash cycle was the first and most obvious choice for Nga Awa Purua, being the selection previously made for Kawerau. Applying the Rotokawa geothermal reservoir conditions resulted in a gross power output of 133 MW compared to 96 MW for Kawerau. The additional output is mostly due to the higher enthalpy fluid available.



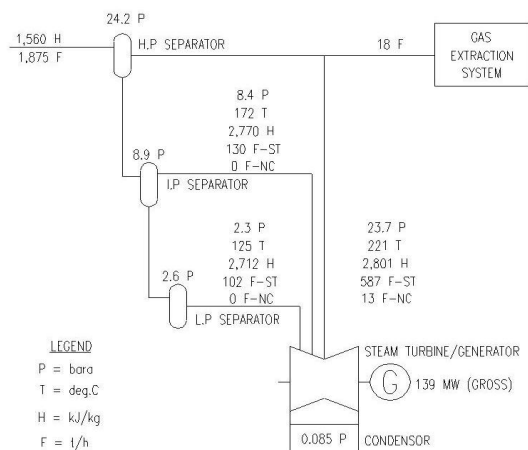
**Figure 6: Dual Flash Heat and Mass Balance Diagram**

### 4.2 Triple Flash

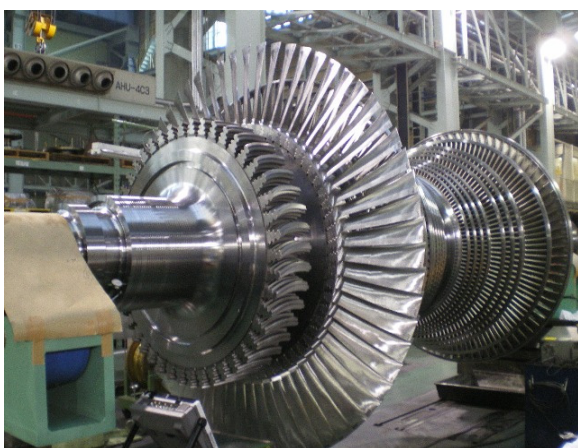
Comparison of the heat and mass balance diagrams in Figs 3 and 4 shows that 6 MW additional electricity generation is available from the same geothermal fluid by using a triple flash rather than a dual flash cycle.

The triple flash process seemed at first to be quite novel, with relatively few reference plants. In fact, Salton Sea Unit 5 in California, USA was the only reference plant on first examination. Further research showed the triple flash process to be the “Grandfather” of them all; – dating back to the first water dominated steamfield development in the world, at Wairakei, New Zealand in 1956. At that time each steam pressure was accommodated by a separate turbine. What is less common is the combination of the triple flash into a single-casing machine. This configuration, combined

with the high inlet pressure and enthalpy will result in the world's largest single-casing geothermal turbine.



**Figure 7: Triple Flash Heat and Mass Balance Diagram**



**Figure 8: Triple Flash Turbine Rotor**

Mighty River Power undertook a detailed review of the risk associated with performance of this turbine. The two main areas of concern were the last stage turbine blades and the acid dosing. The last stage blades are a standard design and it is a generally accepted practice to scale a standard blade design to compare operation at different speeds (i.e. frequencies). In this way, the longer blades operating at 50 Hz can be compared to other installations with shorter, but geometrically similar, blade designs operating at 60 Hz. It was therefore possible to verify that similar LP blade loadings, as measured by tonnes/hour/square meter exhaust annulus area, have already been in service for some time.

**Table 2: LP Blade loading comparison**

Plant	Frequency	Commissioned	LP Blade Load
Nga Awa Purua	50 Hz	2010 (predicted)	100%
Kawerau	50 Hz	2008	88%
Ref. Plant 1	60 Hz	2000	100%
Ref Plant 2	60 Hz	2001	101%

The second concern with the LP blades is the steam wetness, which would be expected to increase with the higher inlet pressure. This is, however, mitigated by the addition of dry steam from the IP and LP flash so that the exhaust steam wetness is within the range of 12% to 15% typical for this application.

Another possible way to achieve a triple flash cycle would have been to take a dual flash turbine and add a topping turbine. This would have been attractive if the Kawerau plant could have been retained for Nga Awa Purua; however, the swallowing capacity of the Kawerau turbine would have limited the development to about 85% of the consented take and produced about 30 MW less capacity. This option was not reviewed in detail.

## 5 SILICA SCALING TESTS

A test rig was constructed to simulate the response of the brine to the different power cycle process conditions. Testing confirmed that the kinetics of scale deposition could be managed by controlling the brine pH to  $5.0 \pm 0.2$  for the dual flash (Kawerau) and triple flash (Rotokawa) cycle parameters chosen. Experience from the test facility also showed:

- Scaling rates of approximately 2mm / year were observed.
- Sulphuric acid is extremely corrosive at the temperatures and concentrations involved.
- Deposition of Antimony Sulphide (Stibnite) was not observed; however elemental arsenic was found just downstream of the acid injection.
- Acid injection must be at the outlet of the HP separator to prevent initiation of silica deposition (silica colloid formation was found at SSI of 1.6). Virtually no evidence of scaling or corrosion was observed in the IP section of the test facility.
- The acid titration curve (pH vs. acid added) is extremely steep at the target pH of 5.0, making control very sensitive.



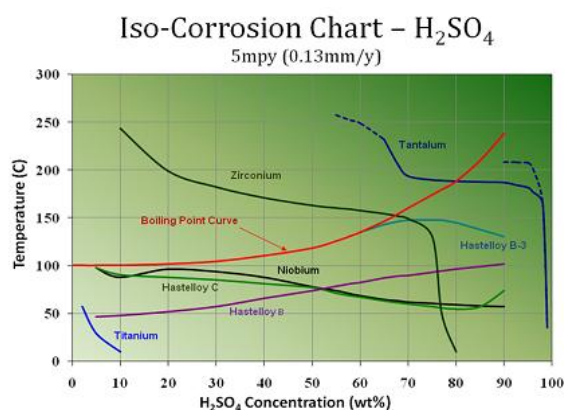
**Figure 2: Picture of Silica Scale Test Facility**

## 6 ACID DOSING

The acid dosing system for Kawerau was originally designed to use a side-stream of HP brine at 180°C and to dilute 98% sulphuric acid to 1%(vol.) in a pre-mixer. The 1% sulphuric acid is then introduced to the main stream to achieve a pH of 5.0 at the outlet of the LP separator. The pH is controlled by

a cascade system with flow ratio control providing the faster, initial response and a measured pH signal providing a trim to that loop. Duplicate probes, with automated cleaning and measuring cycles have proved to be reliable during early operation, but control within tight tolerances can not be maintained during transients. An acceptable solution was introduced to dump brine to surface soakage if pH goes out of tolerance.

The main problem encountered at Kawerau was the corrosion of the pre-mixer. (The main mixer, made from Hastelloy C276, has not shown any signs of corrosion to date.) The original Hastelloy pre-mixer was replaced by a PTFE design, which also failed. As can be seen from the iso-corrosion chart below, temperature is the most significant factor and no materials are shown covering the 98% to 1% dilution range at 220°C for Nga Awa Purua.



Source: Tantaline

**Figure 7: Iso – Corrosion Chart for Sulphuric Acid**

An alternative to hot brine dilution is to take 40°C condensate from cooling tower / condenser circuit. The low dissolved oxygen content of the condensate taken after the condenser (~7 ppm) suggests this would be a suitable medium for the dilution of the acid. Although this has effectively solved the pre-mixer corrosion problems at Kawerau, the introduction of condensate compromises the thermodynamic cycle efficiency resulting in a loss of about 500 to 1,000kW at each plant. Introducing even small amounts of dissolved oxygen also increases the risk of corrosion in other parts of the system, so alternate designs and materials are being reviewed to re-establish the originally foreseen dilution with hot brine.

## CONCLUSIONS

Standardization of plant across a 400 MW development program is intuitively a high value proposition; however,

when this is considered across different resources with different enthalpies, pressures, fluid chemistry and potentially variable extraction rates, no case could be made to compromise the design of the first plant to provide for standardization in the future. Various technologies were reviewed but no one technology was identified as having a clear technical advantage that would translate into an optimal commercial solution.

Mighty River Power selected to use a competitive tender process to select a power plant design optimised for the Kawerau geothermal field. It has negotiated a contract for the Nga Awa Purua power station based on experience gained from the Kawerau project and revised geothermal fluid conditions.

The process design selected for Kawerau was a dual flash plant, whilst Nga Awa Purua steamfield conditions supported 6 MW more generation from a triple flash plant.

	Kawerau	NAP - 2 flash	NAP - 3 Flash
Gross Power (kW)	116,000	133,000	139,000
Approx. Net Power (kW)	110,000	127,000	133,000
Cycle Thermal Efficiency	13.3%	15.6%	16.4%
Overall Plant Utilisation Efficiency	52.5%	55.0%	57.6%

**Table 3: Efficiency Comparisons**

The design challenge for Nga Awa Purua was to optimise a new design, whilst retaining standard designs and equipment where appropriate. A robust risk assessment was completed for a plant based on the triple flash cycle using the largest single cylinder geothermal steam turbine in the world. Lessons learnt from the Kawerau project were incorporated into the Nga Awa Purua design.

## REFERENCES

- Brown K., Rock M. Test Rig Experiments for Silica Scaling Inhibition, *Transactions*, WGC 2010.
- Carey, B., Forty Years of Successful Generation at Wairakei: A Successful Match and Marriage, *Transactions*, 21<sup>st</sup> New Zealand Geothermal Workshop, (255 – 261)
- DiPippo R., Geothermal Power Plants: Principles, Applications, Case Studies and Environmental Impact, ISBN 978-0-7506-8620-4.