GEOTHERMAL STEAM TURBINE PLANT FOR LONG TERM USE

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SUMMARY – Geothermal steam turbines must maintain their viability over the decades in the face of a steam resource which is subject to uncertainties, depletion and change. Geothermal steam is potentially corrosive, erosive and prone to cause build–up of deposits inside the turbine. These problems are addressed, dealing with initial conceptual design, engineering specification, tender evaluation, design by the equipment supplier, manufacture, installation and commissioning. It is concluded that, given thorough and appropriate attention to these phases, a life exceeding the **25–30** years normally expected in the past should be possible.

1.0 INTRODUCTION

Wairakei geothermal power station is now approaching its 35th year of operation. If the Wairakei turbines can survive for 35 years (and promise to keep running for some years yet) how much longer will machines of a more enlightened era last?

The steamfield permitting, perhaps we should be looking at a station life of more than the 25–30 years normally expected in the past. This raises the question about potential incompatibility between the performance and life of the field and of the generation plant. This paper discusses how this can be addressed during the design phase of the steam turbine plant. It also addresses turbine plant longevity in all phases of the development of the project, that is, during:

- Conceptual design.
- Procurement.
- Design by the equipment supplier.
- Manufacture, installation and commissioning.

2.0 CONCEPTUAL DESIGN

To deal with potential incompatibility between steamfield and station life, the two key needs are "flexibility" and "portability".

2.1 Catering for Steamfield Depletion

Fig. 1 Curve **A** shows a typical steamfield steam flow/pressure characteristic. Over the years this characteristic might deplete to Curves B, C and D. Superimposed on this is the turbine "swallowing capacity". For the geothermal case, with fixed turbine inlet valve position, the swallowing capacity can be taken as:

$$Mass\ Flow\ \alpha\ \left(\frac{P}{v}\right)^{0.5}$$

Where: P = Turbine inlet pressure
v = Specific volume of inlet steam

This applies down to 50% inlet pressure where turbine internal efficiency can be regarded as approximately constant (Tokeley, 1990). The effect of steamfield depletion for a typical case is shown in Fig. 1.

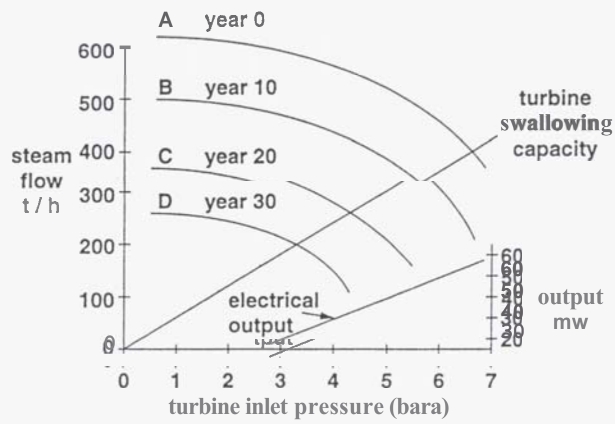

Fig 1. Steamfield Depletion Versus Turbine Output

Thus steamfield depletion causes a significant loss of output and consequently an investment only part–utilised. This can be catered for by providing for initial expansion through a "topping" back pressure turbine unit (Fig. 2).

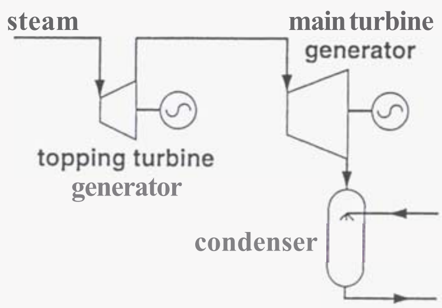

Fig. 2 Use of "Topping" Backpressure Turbine

This can be removed fiom service if the steamfield pressure falls to near the level of the inlet pressure to the low pressure turbine. Such a philosophy was used at Ohaaki (Tokeley, 1989).

The topping turbines were two of the four redundant HP machines transferred from Wairakei. Portability was not a feature of these machines. Designpower has recently completed a study on converting the remaining two 6 MW HP sets at Wairakei to skid-mounted transportable units. Such a concept is easily attained with back-pressure turbines.

The other feature that the designer may specify is some overload capability to give the operator more flexibility.

2.2 Catering for Steamfield Demise

The concept of portability can be carried further to allow the whole power station to be moved between fields, to take best advantage of the resources over the decades.

Turbine manufacturers are now making "portable" units up to 35 MW size (Hibara et al, 1990). The turbine can be mounted at ground floor level, having an upward exhaust routed to a condenser mounted alongside. This saves foundation costs compared with an underslung condenser used with a larger central station unit which is usually of 50-60 MW output.

This also allows a reduction of time to final completion from 27 months for a central station unit to 19 months for two smaller portable units (Mitsubishi). A further advantage is that smaller individual units can be located closer to wells, saving steam pipeline costs (offset by additional electrical transmission costs). Other plant can be skid-mounted or in transportable containers.

This concept of portability was called for in a recent specification for 20 MW modular units. To further increase flexibility, it was specified that the plant be suitable for operating with inlet steam pressure between 5.9 and 7.9 bara. Tenderers offered two solutions:

a) A means of adjusting the area of admission of steam to the first stage nozzles to suit the applicable inlet pressure. This is done by dividing the steam inlet chamber into sections with internal partitions, interconnected with manually operated valves. A drawback of this method is that admission of steam through only a segment of the first stage nozzles introduced a blade passing vibration.

b) The provision of different first stage nozzles tailored for the different steam inlet pressures. To make the changeover the turbine top half casing must be lifted with this method.

In pursuing the "modular" philosophy, the shipping and roading infrastructure needs to be capable of handling large pre-assembled plant. This can be a problem as geothermal

areas are often mountainous and undeveloped. Examples of sizes and weights are given in Table 1.

Table 1 Sizes and Weights of 20 MW Modular Units

	Length m	Width m	Height m	Weight t
Turbine skid	4.5 to 5	5 to 5.5	3.5 to 4	50
Generator skid	5 to 6	3.5 to 5	4	50

A comparison of the total power station cost gives, approximately:

Central Station (1 x 50 MW)	US$ 1,000/kW
Modular (2 x 25 MW)	US$ 1,030/kW

The extra cost of modular sets must be weighted against:

- the benefit of earlier revenue due to 8 months saving of installation time.
- the potential for revenue earning over a longer period due to easier transfer of the station elsewhere if the field loses viability.

2.3 Size of Units

Economy of scale encourages use of large turbine units. Single cylinder double-flow units up to about 60 MW are in common use. For larger outputs from a single cylinder, the effects of greater flow and stress on longevity need careful consideration (refer 3.1).

3.0 PROCUREMENT

The turbine plant specification and subsequent tender' analysis has a major influence on longevity. Apart from commercial conditions and schedules the turbine plant specification should cover:

- Main parameters, plant scope and interface details.
- Testing requirements.
- General mechanical and electrical requirements including standards and quality control.
- Tender schedules and guarantees.

Procurement phase aspects are discussed below.

3.1 Efficiency Versus Longevity

Greater efficiency means lower steam consumption which reduces steam cost and prolongs field life or increases power plant output and revenue.

In the guaranteed performance schedules the tenderer is asked to guarantee the steam consumption or heat rate within a tolerance. The tenderer is held to this by performance testing at site and the threat of damages for failure to perform. The same monetary value as in the damages is applied during evaluation when comparing the tenders submitted.

The upshot of this concentration on maximising efficiency may be to sacrifice longevity as discussed below. The need for efficiency must be tempered by a specified need for longevity. When comparing tenders it is easy to evaluate efficiency, as a monetary value can be assigned. But to evaluate longevity is a more diffuse, subjective operation.

To cater for longevity, the specifier needs to give careful consideration to the merits of specifying some design limits and to the questions asked in tender schedules. As far as efficiency versus longevity is concerned this includes:

- Condenser pressure
- Last row blade steam velocity/tip speed
- Last row blade length
- Last row blade end loading
- Turbine internal clearances and spacing between stages.

There is a need for caution in specifying limits because of conflicts and inter–relationships as indicated below:

Condenser Pressure – A lower condenser pressure will allow greater output but the steam wetness will increase, with greater potential for erosion. Maximum tolerable wetness in the turbine exhaust is around 13–15%, so the condenser pressure or the cooling water conditions need to be specified at a level to achieve this.

Steam Velocity/Blade Tip Speed – Erosion is largely the result of water which collects on the stationary blading leaving the trailing edges in the form of drops entrained in the steam flow and colliding with the moving blading. The erosive effect depends on:

- The stationary blade leaving velocity.
- The moving blade tip speed.

The effect is greatest at the last blade row. The stationary blade leaving velocity is commonly reduced by using reaction blading (where the pressure drop is shared equally between moving and stationary blade rows). It is also reduced by increasing the blade annulus area. However, if this is achieved by increasing blade length it is likely to conflict with the need to minimise blade tip speed,

Tip speed depends on rpm, blade base diameter and blade length. Examples are given in Table 2 from tenders received in the past from a range of suppliers.

Table 2 – Last Row Tip Speeds/Length

Tip Speed (m/s)	Last Row Base Diameter (mm)	Blade Length inches (mm)	Revolutions per minute
390	1214	25 (635)	3,000
399	1372	23 (584)	3,000
427	1400	26 (658)	3,000
467	1651	26 (660)	3,000
468	1214	25 (635)	3,600

Last Row Blade Length – For geothermal steam turbines, last row blades are used up to 26 inches (660 mm) in length. In geothermal steam the rotor and blading are susceptible to stress corrosion cracking and corrosion fatigue. This is reduced by suitable materials and design (refer 4.0). It is also reduced by decrease of blade length, which lowers centrifugal stress. However, this also reduces the annulus area, lowering efficiency.

Last Row Blade End Loading – A typical last row blade end loading for 55 MW double flow unit 23 inch (584 mm) last row blades is 52,500 kg/h m² (Ohaaki and Kamojang).

Higher end loading will increase blade stressing from steam force and vibration exciting force. This leads to a conflict where reducing blade length to reduce centrifugal stress increases end loading.

Turbine Internal Clearances and Spacing Between Stages –If turbine internal clearances are small, efficiency is better because of reduced losses. But if a build–up of deposits occurs, it will lead to problems as discussed in 3.2.

It is desirable for the space between moving and stationary blades to be large because this minimises erosion. The drops of water leaving the trailing edge of the fixed blades have a chance to break up into less destructive smaller drops if the space is large. It also minimises blade passing vibration.

3.2 Steam Quality

Mitsubishi have analysed failures of rotating parts and attributed causes as follows:

Erosion	26
Scaling	21
Stress corrosion cracking	18
Corrosion	15
Corrosion fatigue	15
Other	5
(Hibara, 1986)	100%

Steam quality has a profound influence on longevity. The initial design and specification plays a vital part in ensuring that impurities in the steam are adequately dealt with. The specification and tender schedules need to establish:

- Impurities and limits
- Control of impurities
- Guarantees and testing
- Monitoring

Influence of Impurities – Impurities in geothermal steam cause erosion, build–up of solids and corrosion in the steam path through the turbine.

Erosion is a result of wet steam or solid particles in the steam such as sand and dust.

Impurities such as silica (SiO_2) and calcium carbonate ($CaCO_3$) tend to build up on turbine internals. This build–up occurs particularly in areas where the steam is dry such as at the first stage nozzles where there is no washing effect from wet steam. It also occurs in areas where the steam velocity is low. Build–up of solids can cause performance loss, rubbing between moving and stationary components, vibration and build–up of thrust load. It can also retain acids and chlorides, increasing corrosion.

The key corrosive chemicals for the turbine are hydrogen ions (pH), chloride ions (Cl), hydrogen sulphide (H_2S), carbon dioxide (CO_2) and oxygen (O_2). These can cause problems with uniform corrosion, pitting, stress corrosion cracking and corrosion fatigue. A potential site for stress corrosion and crevice corrosion is in the transition zone from dry to wet steam where deposits become concentrated by evaporation.

Control of Impurities – Impurities can be controlled by:

- use of long steam lines to obtain a scrubbing effect.
- use of separators and demisters.
- washing/chemical injection.

Work carried out at Wairakei has confirmed that steam lines can help to remove minerals from the steam. It was found that scrubbing efficiency is greater at low steam pipe velocity or small steam pipe diameter (Table 3). Drainpot efficiency has a greater effect the smaller the pipe diameter. Removal of impurities will also improve with a lower level of insulation. Thus "large diameter well insulated lines even with highly efficient drain pots will do little in the way of removing carryover chemicals unless very long lengths are involved". (Stacey et al, 1981).

Table 3
Calculated Scrubbing Efficiencies at Wairakei

Pipeline Diameter (mm)	Scrubbing Efficiency % perm
1220	0.079
762	0.300
762	0.267
508	0.794
280	2.717

(Scrubbing efficiency is defined as the percentage of the chemical content removed from the steam phase into the condensate phase per unit length).

Atypical steam separator is of cyclone type which assists in reducing moisture and dirt in the steam by centrifugal action. A demister of corrugated plate type downstream of the separator will remove smaller particles and further moisture. This is also effective in reducing chloride, SiO_2, Fe_2O_3 and FeS (Hibara, 1986). Alternatively, a wire mesh type demister can be used. The demister can be incorporated in the same vessel as the separator.

A venturi scrubber can also be included (Hibara et al, 1990). In this, a fine mist of water is injected upstream of a venturi in the steam line. When installed upstream of a separator and demister the range of particle size removal and quantity removed is greater. For corrosive steam, an aqueous solution of chemicals can be injected upstream of the separator/demister to "wash" the steam (Ansaldo, 1982).

Guarantees and Testing – The specification for the requirements for the steam separator and demister must be backed up by performance guarantees from the contractor and performance testing. This needs to include pressure drop and collection efficiency in relation to particle size removal.

Monitoring of Impurities – The condition of the steam supply can change rapidly, for example if a new well is brought into service or some problem occurs with separators or drains. Likewise, scale can build up quickly on the internals of the turbine. Continuous automatic steam monitoring with alarms and recording can be provided for:

- conductivity
- total dissolved solids
- silica
- chloride
- iron

3.3 Condition Monitoring

The specification scope list must include requirements for condition monitoring. Change of vibration is a symptom of internal problems such as blade failure or rubbing. Increase of turbine first stage nozzle outlet pressure in relation to load and exhaust pressure or an increase of thrust load is an indication of clogging from scale build–up. With an increasing trend towards remote operation, wide–ranging condition monitoring with appropriate datalogging, alarms and tripping is essential.

Consideration should be given to specifying borescope ports along the machine to allow inspection of the internals during an outage, without lifting the covers.

3.4 On–Load Blade Washing

On–load blade washing has been carried out successfully to remove scale deposits in the turbine steam path. At Smudgeo, 1.4% of deaerated pure water was sprayed into the steam main. This desuperheated the steam temperature from 4°C superheat to about 1.5% wet. After 17 days, the steam chest pressure was reduced from 9 barg to the original design pressure of 7.2 barg (Mitsubishi).

Blade washing is typically carried out monthly for a 2 day period at a rate of from 1.3 to 3.7% of the main flow rate (Mitsubishi). Care is needed to avoid heat shock, vibration and erosion.

A suitable source of water is condensed steam. Because a direct contact condenser is often used and the condensate is mixed with circulating water which has high dissolved solids, the main condenser as a source is unsuitable.

A separate indirect contact tubed condenser is required (Fig. 3).

It is desirable to specify blade washing as uncertainty always exists about deposit build up in the steam path under changing steamfield operating conditions.

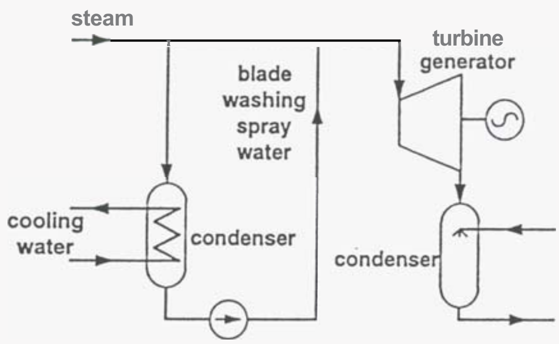

Fig 3. Blade Washing Equipment

3.5 Off-Load Ventilation/Drying

If it is possible that the turbine will be out of service for periods, hot air ventilation should be specified to minimise corrosion. *Also,* the design should allow for easy insertion and removal of silica gel bags.

4.0 DESIGN BY EQUIPMENT SUPPLIERS (Ansaldo, 1982; Fuji, 1990; Kuehn, 1993; Mitsubishi)

4.1 Materials

Turbine rotors must have high fracture toughness and ductility and low sensitivity to stress corrosion cracking. This can be provided with Cr Mo V material, sulphur limited to 0.005%, nickel to 0.5% and quenching temperature limited to 910°C.

With blading, the materials need to resist stress corrosion cracking, particularly in the first rows where concentration of impurities can occur or in the last row where stress is high. In the last row, vibration stress is greater so high inherent damping and resistance to corrosion fatigue are also required. The allowable vibration stress is reduced in the presence of geothermal gas, especially hydrogen sulphide. 12% Cr steel is often used, or 17–4 pH steel, which has a higher corrosion fatigue strength. Use of titanium alloys (e.g. Ti-6AR-4V) in turbines is increasing, the lower weight allowing stress reduction or blade length increase. It is used at Salton Sea No. 1 unit.

Blade coating has been used largely for refurbishment to date, but can also be applied during manufacture. At Wairakei, diaphragms are protected by thermal spray. A Californian utility has successfully used coatings on low pressure blading for corrosion protection (EPRI, 1987). There appears to be scope for extending this into geothermal service.

4.2 Design

Methods commonly employed in turbine design are:

- Use of butterfly valves for control and isolation of inlet steam to minimise sticking of the stem fiom deposits. On-load stem free test of inlet steam valves.
- Inter-stage water catchers and drainage. Water collection grooves on stationary blading.
- Stellite attached by silver brazing or spray applied to leading edges of exhaust end moving blades to minimise erosion from water. *Also,* boron diffusion, nitriding and ceramic plasma arc applied coatings have been used.
- Use of stainless steel liners at shaft and interstage seals and at casing locations to minimise erosion and corrosion.
- Wide pitch of blades in the first row nozzles to minimise the effect of clogging in the superheated region.
- Wide spacing between stationary and moving blades (refer 3.1).
- Integral shrouds to eliminate crevices and crevice corrosion. This also eliminates stress corrosion due to residual stress from heat treatment of shroud rivets.
- Dampers to reduce vibration *stress* in blades.
- Generous fillet radii and no balance holes in blade carrying wheels to reduce stress concentration.
- Thick round-head moving blade design and use of three-dimensional flow calculations and finite element analysis. This allows twisted shape and improved profile to reduce stress and improve efficiency.
- Free-standing last row blades without potentially troublesome shroud rings or lacing wire, for more accurate vibration tuning of natural frequency relative to excitation frequency and harmonics.
- Removal of residual stress after machining by stress relief or shot peening.
- Solid rotor construction without separate shrunk-on discs to eliminate crevice corrosion or stress corrosion cracking at the disc bore.
- Improved rotor forging and testing techniques to allow elimination of the central inspection bore hole, reducing stress.
- Use of reaction blading in the last rows to limit steam velocity and consequently, steam force, erosion and blade passing vibration.

5.0 MANUFACTURE, INSTALLATION AND COMMISSIONING

5.1 Contractual Arrangements

Alternatives – There are several alternative contractual arrangements for the development, such as:
- use of a "turnkey" contractor.
- the power station let as a number of packages.
- use of competitive tendering.
- negotiation with a single organisation.
- employment of contractors with an equity in the project.

Potential Problems – If these aspects are not properly organised, turbine plant reliability and life may be sacrificed. For example:

- A turnkey contractor may have little interest or experience in some aspects of the work.
- Having to deal through a turnkey contractor on matters concerning major plant such as the turbine may lead to communication problems (delays, misunderstandings and omissions).
- Selection of contracts on a competitive tendering basis can lead to an adversarial relationship between the purchaser and the contractor. At worst, this can lead to escalating costs, delays and deficiencies not found until failure (several years later).

Minimising the Problems – These problems can be minimised by:

- Use of proper tender documentation and procedures (refer 3.0).
- Checking of all contractor's and sub-contractor's designs, drawings and information prior to manufacture.
- Use of an independent inspection and expediting organisation during manufacture.
- Conscientious project management during all phases of the implementation.

Employment of contractors with an equity in the project can lead to more co-operation and more incentive for the contractor to perform. If the equity extends into the operation phase, reliability and life stand to gain further.

5.2 Quality Standards

Some firms seek to win work with a low-priced tender, using the philosophy of making a profit from subsequent contract extras and "cutting corners". Care during the procurement phase may avoid this, but constant vigilance is required subsequently, assisted by the adoption of quality standards such as the ISO 9000 series.

5.3 Documentation

Proper documentation at the take-over date is essential for keeping the plant in good condition. This must include:

- Installation and commissioning records (e.g. turbine clearances, performance test data).
- As-built drawings.
- Operation and maintenance manuals.

5.4 Training

Training plays a vital part in ensuring longevity. Highly skilled operating and maintenance personnel must be selected well before commissioning. This allows on-the-job training by the contractor during commissioning.

6.0 CONCLUSIONS

A life exceeding the 25–30 years normally expected in the past should be possible for geothermal steam turbine plant given due attention to:

Conceptual Design – flexibility, portability and size.

Procurement – appropriate engineering specification with tender schedules and thorough tender analysis. Particular attention is needed to provisions for dealing with steam impurities and condition monitoring.

Design by Equipment Supplier.

Manufacture, Installation and Commissioning – particularly contractual arrangements, thorough checking during all phases, quality standards, documentation and training.

7.0 ACKNOWLEDGEMENTS

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