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INDUSTRIAL APPLICATION OF GAS TURBINES COMMITTEE

Life Cycle Impact of Steam Injection on the LM6000PC Turbine Blades

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ABSTRACT

Water or steam injection for NO_x control or power augmentation can impact turbine hot section component life and maintenance interval. This relates to the effect of added water on hot-gas transport properties. Higher gas conductivity, in particular, increases heat transfer to blade and vane, and can lead to higher metal temperature and reduced part life. Part life impact from steam or water injection is also related to the way the engine is controlled.

Life cycle impact of steam injection on the LM6000PC HP turbine blade has been studied. The relationship between steam injection, LP turbine inlet temperature control, blade metal temperature, and corresponding life change was analyzed. The analysis result can be used for the assessment of life cycle impact with steam injection and temperature control limit. In addition, this paper explores the application of this information in a way that balances additional generation revenue with increased life cycle costs and other costs in real time.

KEYWORDS: Gas Turbine, Steam Injection, Life Prediction

NOMENCLATURE

C_P	Specific Heat
k	Thermal Conductivity
M_w	Molecular weight of mixture
x_i	Mole fraction of species i=1,2,3
T_3	HP Compressor Discharge Temperature (^{o}C)
T_{48}	LP Turbine Inlet Temperature (^{o}C)
Φ	Cooling Effectiveness $\Phi = \frac{T_g - T_m}{T_g - T_c}$
μ	Viscosity

Subscripts

c	Coolant
g	Gas
m	Metal
mix	Mixture

Acronyms

EOH	Equivalent Operating Hour
HP	High Pressure
HPT	High Pressure Turbine
LP	Low Pressure
NO_X	Oxides of Nitrogen
TGO	Thermally Grown Oxide
TMF	Thermal Mechanical Fatigue
TBC	Thermal Barrier Coating

INTRODUCTION

The Southdown Cogeneration Facility in Auckland, New Zealand is owned and operated by Mighty River Power Limited. The plant is based on two GE LM6000PC gas turbine generator sets, with two duct fired once through steam generators and one 37.5 MW steam turbine. Air inlet chilling is used to maintain steady compressor inlet temperatures and steam injection is used for NO_X suppression. The Air Discharge Permit for the plant requires stack emissions of NO_X to be 100 ppmvd or less during normal operation. Mighty River Power Limited identified that reducing the firing temperature of their gas turbines extended the life of key hot gas path components, they also identified that increasing steam injection rates enhanced plant output by up to 3 MW per gas turbine on demand.

It is commonly believed that steam injection into a gas stream will cause an increase in heat transfer coefficient due to an increase of the heat conductivity and specific heat of the gas stream properties. The criterion that sets the maximum recommended maintenance interval in industrial heavy-duty applications is based on base-load continuous operation with natural gas and no steam or water injection. For operation that differs from the baseline, maintenance factors are established that determine the increased frequency of maintenance required. Water or steam injection is one of the key factors in determining the maintenance interval requirement [1].

The impact of steam injection on the hot section component life of an aero-derivative LM6000PC gas turbine has been studied. Specifically, HP turbine stage 1 blade was selected as the most representative hot section component in relation to expected change in component temperature, degradation rate and serviceable life produced by the introduction and variation of the amount of steam injection. Liburdi Turbine Services were engaged by Mighty River Power Limited to assess the estimated impact of increased steam injection on the LM6000PC life cycle; this paper is based on that work.

BACKGROUND

The industrial LM6000 gas turbine is derived from the General Electric CF6-80C2 high bypass turbofan aircraft engine. The twin spool LM6000 consists of a five-stage LP compressor, a 14-stage HP compressor, a two-stage, air-cooled HP turbine, and a five-stage LP turbine. The LM6000 does not have an aerodynamically coupled power turbine. A drive flange is available on both LP compressor and LP turbine, offering the option of either cold end or hot end drive [2].

The LM6000PC uprated from the previous “PA/PB” model was developed in 1995. The first production unit was built in 1997. The “PC” model incorporates efficiency improvements in the LP compressor and a larger exit area in the LP turbine. The standard material for the HP turbine stage 1 blades is Rene-142; a high strength nickel based directionally solidified superalloy. The overall pressure ratio for the LM6000PC is 29.5 to 1. NO_X suppression in the LM6000PC is achieved by the injection of water or steam into the combustion process at a controlled rate. Depending upon the injection rates, NO_X emission rates of 100 – 25 ppmvd (and lower) can be achieved. The gas turbine OEM permits continuous operation at 25 ppm NO_X.

The addition of steam into the combustion process of a gas turbine has a number of effects, it decreases the formation of oxides of nitrogen (NO_X), steam injection increases mass flow and power output. In addition it normally reduces the thermal efficiency of a combined cycle gas turbine plant and reduces hot gas path component life. From an asset performance perspective there was a need to establish that enhancing power output by injecting more steam would not damage the machine and that any increase in wear or maintenance costs would be more than outweighed by the marginal revenue derived.

TECHNICAL APPROACH

During service, gas turbine hot section components undergo various types of time-dependent degradation due to exposure in the operating environment. Oxidation, hot corrosion, creep and thermal mechanical fatigue (TMF) can all potentially lead to component failure. The life of turbine components and factors that limit the life vary significantly from component to component due to a combination of design, material, coating and operating condition. By identifying the specific characteristics of degradation for each component and predicting the rate of damage occurred, economical repair, replacement and overhaul interval can be established.

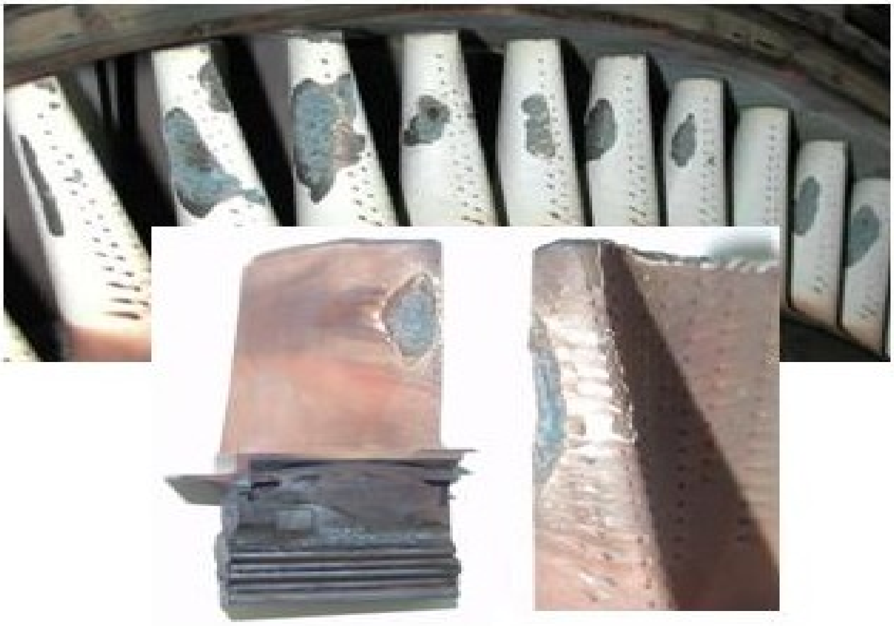


Fig. 1 Coating Loss and Oxidation Damage of HPT Stage 1 Bucket

A historical review of refurbishments of LM600 stage 1 blades revealed coating losses on the suction side leading edge (Fig. 1). The onset of the damage was reported occurring at 10-22K operating hours on PA/PC engines. Metallurgical analysis identified the most likely root cause as oxidation spallation of the thermal barrier coating (TBC). TBC spallation causes increased blade operating temperature and eventual oxidation of the base material. Since the effectiveness of the coating in protecting the base metal from oxidation attack has been identified as the primary life limiting factor - a major decision point in determining engine overhaul period, this analysis is focused on the prediction of the stage 1 blade oxidation life change with steam injection. The calculated life change is converted into an equivalent operating hour (EOH) factor with reference to the engine design base condition.

ANALYSIS

To simulate operating environment, an engine aero-thermal model for the LM6000PC was first developed. The aero-thermal model calculates average hot gas path inter-stage temperature, pressure, and flow. The calculated aero-thermal values were then used as the boundary condition for heat transfer analysis. A composition-dependent gas property model was developed for the calculation of gas-side steam mixture thermal conductivity and viscosity. These properties were then input into a heat transfer model for predicting blade external heat transfer coefficient. The internal cooling heat transfer coefficient was calculated using an internal flow model, where the cooling flow extraction is calculated by the aero-thermal program. With the external and the internal heat transfer coefficients established, the blade metal temperature can be estimated. Finally, an oxidation life algorithm was used to predict relative oxidation life change as a function of blade metal temperature.

Engine Aero-Thermal Model

An aero-thermal program was developed for predicting hot-gas path temperature, pressure and flow is a combination of a conventional through-flow thermodynamic model with a detailed streamline loss calculation [3][4][5][6]. The model can also handle steam injection and cooling flow extraction. The aero-thermal model was verified against engine performance data. The predicted HP compressor discharge temperature (T_3) and LP Turbine inlet temperature (T_{48}) with steam injection were found in agreement with engine test data ($<\pm 5^{o}C$) (Fig. 2).

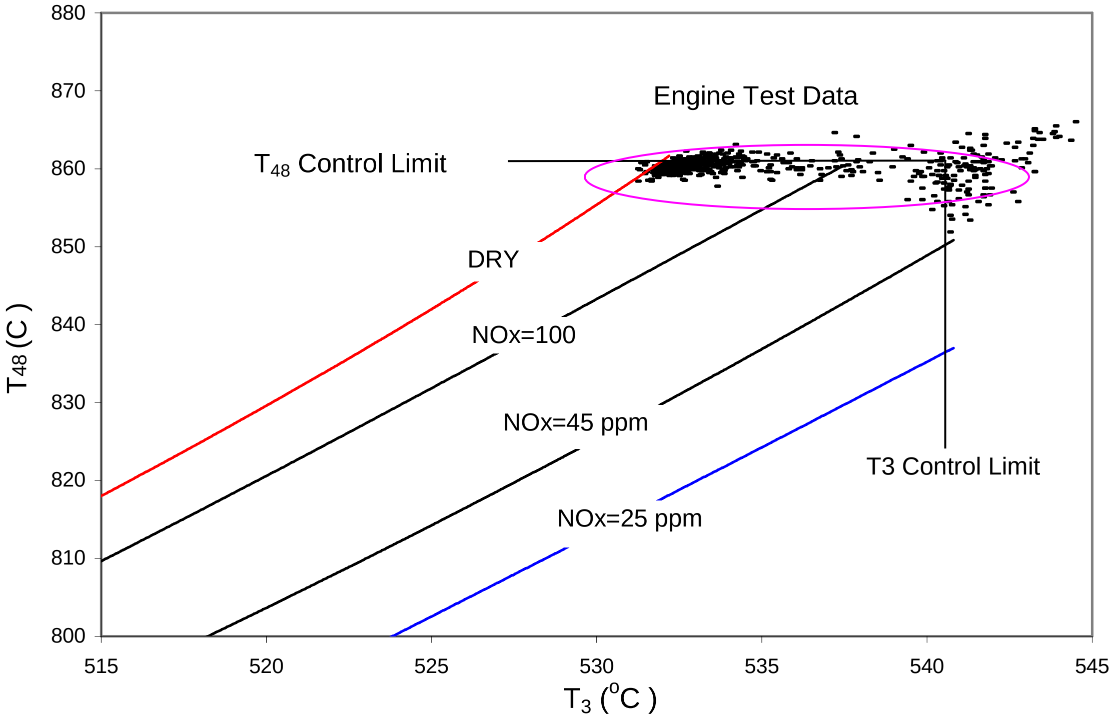
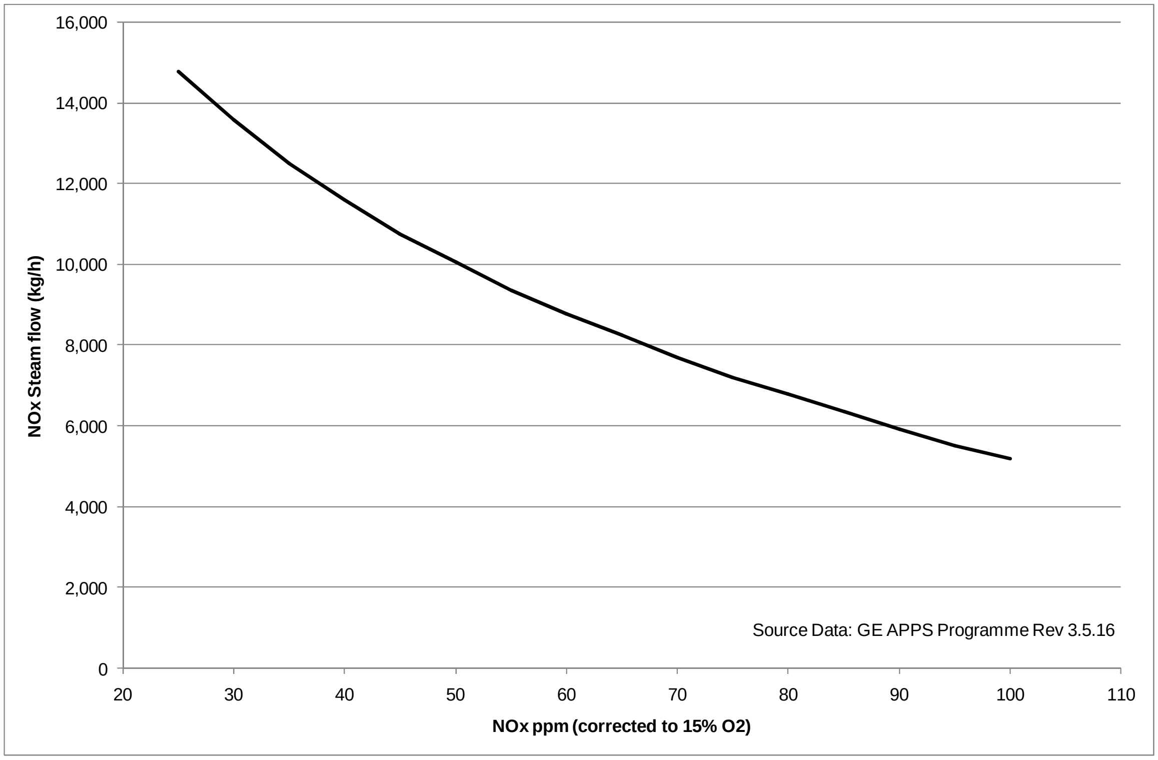


Fig. 2 Engine Performance Prediction with Steam Injection

During the test run of steam injection, experimental data was found beyond the T_3 and T_{48} limits as shown in Fig. 2. Operators observed the engine “hunting” as more steam added in. It is possible that the T_{48} and T_3 limiting controllers were coming into play at the same time. The switching of the engine fuel controller between the T_{48} and T_3 limiting control modes seemed to be creating a region of marginally unstable operation.

For the gas turbines at Southdown the relationship between the NOx level contained in the exhaust gas and the quantity of steam injected into the combustion process is described Figure 3.



Source Data: GE APPS Programme Rev 3.5.16

Fig. 3 Relationship between NOx ppm and Steam Injection Flow

Mixing Model

A new added part of the analysis is to model the effect of steam injection on hot-gas transport properties. The viscosity and thermal conductivity of pure species of typical combustion gas components were first compiled from various references as a function of temperature. The transport properties of steam were calculated using ASME 97 steam property subroutines. Through curve fitting, the pure species transport properties were then used by the air-fuel-steam mixing model to calculate the mixture viscosity and thermal conductivity based on the following simple square-root rule [7]. It was found that in comparison with other gas components the thermal conductivity of steam/water increases significantly at elevated temperatures (Fig. 4).

Thermal Conductivity: $$k_{mix} = \frac{\sum x_i k_i M_{wi}^{1/2}}{\sum x_i M_{wi}^{1/2}}$$

Where

x_i is the mole fraction of species i

M_{wi} is the molecular weight of species I

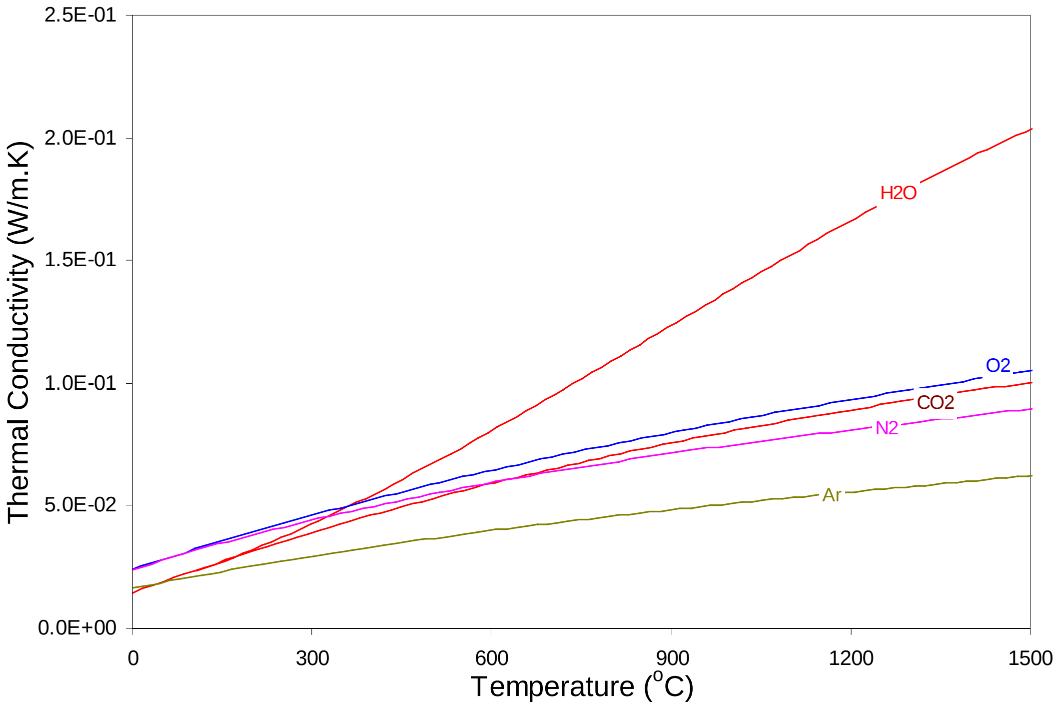


Fig. 4 Thermal Conductivity

Heat Transfer

For air-cooled turbine blades, heat transfer coefficients on both sides of the blades have to be established before a detailed heat transfer calculation can be performed. One difficulty associated with external heat transfer analysis is that the hot-gas is accelerated in the nozzle row to a very high Mach number. The relative temperature is substantially less than the absolute temperature. As wheel speed increases, the relative velocity tends to decrease, which also decreases the relative temperature. The local relative velocity distribution carefully prescribed by the aerodynamic design would determine the distribution of the external heat transfer coefficient along the blade surface. In this analysis, only the leading edge regime was analyzed where the coating loss and oxidation damage occurred.

At the leading edge, the flow is laminar. The heat transfer correlation for flow passing a cylindrical section was used from the stagnation point back to the points of tangency with the pressure and the suction surface. A two-dimensional program developed by NASA known as TSONIC [8] was used to calculate the inlet relative velocity and relative temperature. With the gas stream properties established by the gas-steam mixing model, the external heat transfer coefficient can be calculated [9]. Figure 5 shows that the gas-side heat transfer coefficients increase with increased steam injection.

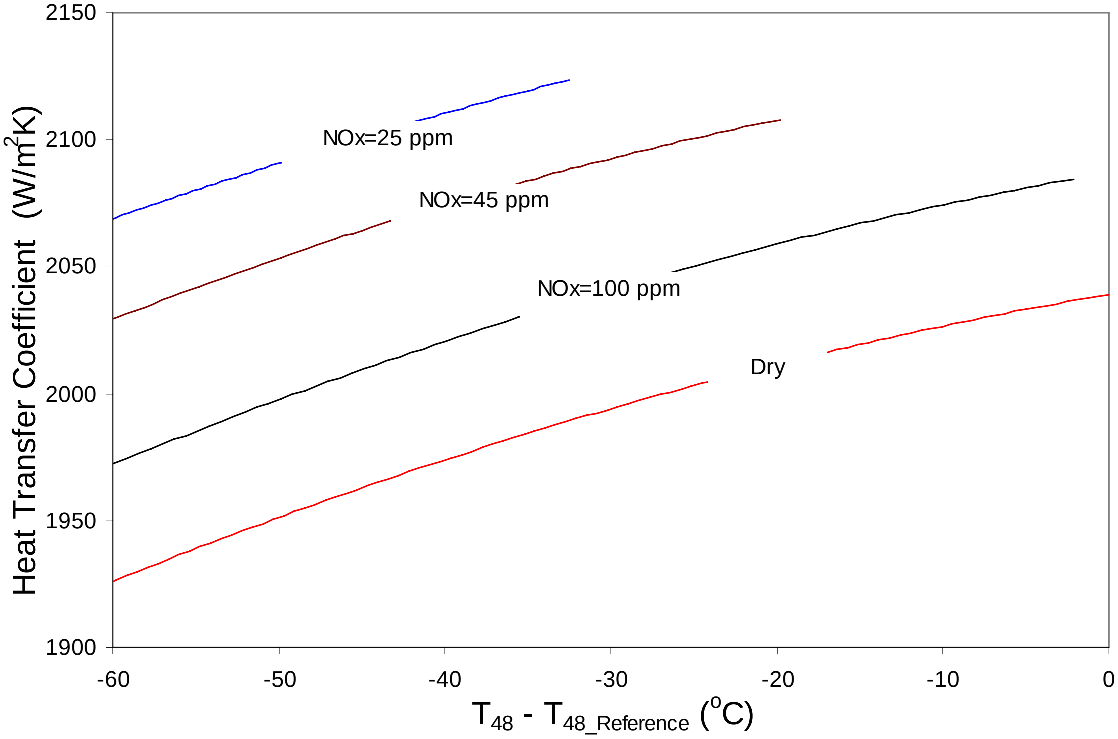


Fig. 5 Gas-side Local Heat Transfer Coefficient

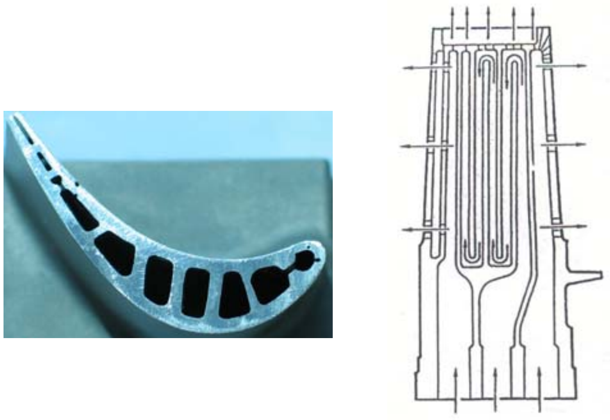


Fig. 6 LM6000 HP Stage 1 Blade Internal cooling circuits

Figure 6 shows the blade internal cooling design. The cooling air is introduced at the blade root and exits at the blade tip. The extracted cooling air flow rate and temperature were outputted from the engine aero-thermal program. Heat transfer correlation for fully developed turbulent internal flow was used to calculate the internal heat transfer coefficients. The internal heat transfer coefficients were found to increase with increased steam injections (Fig. 7). This can be explained by the fact that steam injection increases HP compressor discharge pressure resulting in more cooling flow extraction.

The heat transfer coefficients and gas stream properties as established above can now be used to perform a detailed heat transfer calculation throughout the blade. A steady-state energy balance approach was used to calculate heat transfer over a composite cylinder (e.g., TBC and blade wall thickness). The internal cooling flow heat pick-up was calculated along the radial path. The model was calibrated using metallurgical temperature estimations. Turbine blade metal temperatures can be estimated using historical metallurgical data, e.g. service exposure time and aging [10]. The heat transfer model was also validated using the blade cooling effectiveness Φ. The calculated blade leading edge local cooling effectiveness of 53% with 3% cooling air flow agrees with published literatures [11][12].

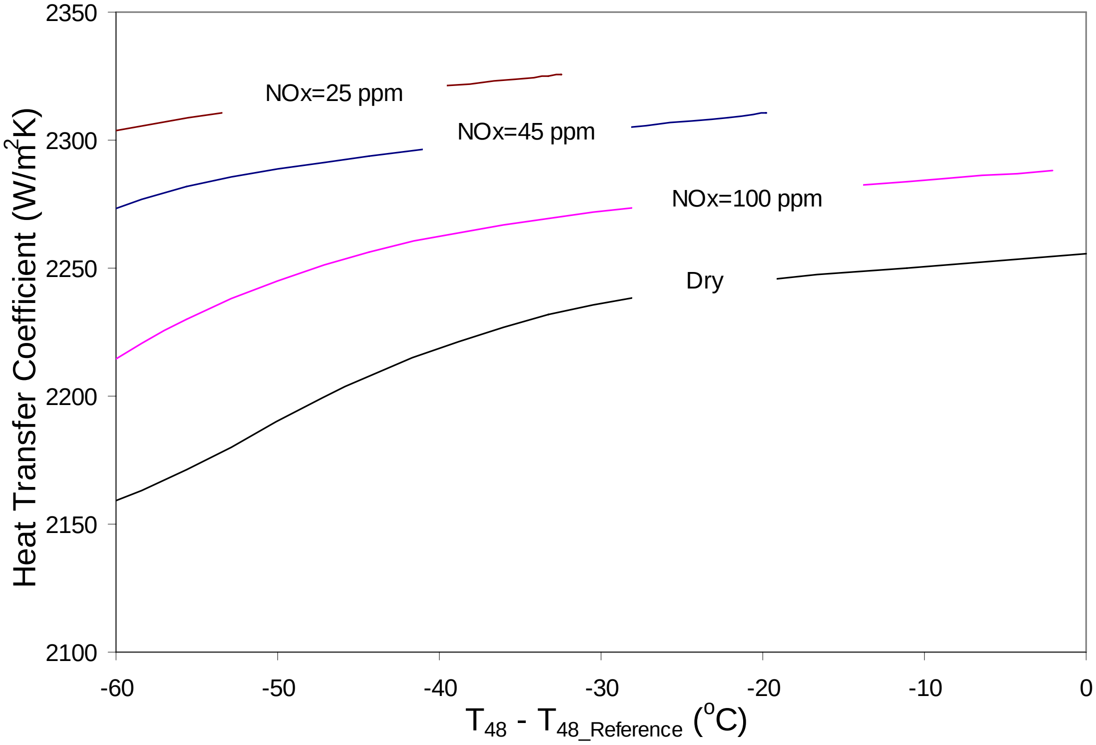


Fig. 7 Cooling-side Heat Transfer Coefficient

Life Algorithm

The external coating of the LM6000PC stage 1 blade was identified as TBC with an electron beam physical vapour deposition (EBPVD) ceramic top coating and a platinum diffusion aluminide as the bond coating. TBCs normally fail by spallation due to delamination of the ceramic layer along the vicinity of the thermally grown oxide (TGO) and TBC interface. The failure process involves several mechanisms including oxidation of the bond coat, thermal mechanical fatigue, sintering, and spallation of the TBC. The formation of TGO and the corresponding compressive growth stresses at the TBC/bond coat interface remain one of main causes of failure in TBCs [13].

Activation energies associated with the bond coating oxides were used to determine the oxide growth rate as a function of temperature and relative oxidation life [14]. The calculated oxidation life change was then converted into an EOH with reference to the engine design base condition [15]. It is important to notice that the physical impact, thermal mechanical fatigue and spallation of TBC are not considered in this analysis. However, their effects on accelerating the TBC degradations have to be taken into account when applying the life prediction results.

DISCUSSION

All turbines, including aeroderivatives, have “base ratings”. In the case of aeroderivatives, when natural gas is used as the fuel and the engine is operated at the base-load power turbine inlet temperature control setting, its base rating corresponds to a hot-section repair interval of approximately 25,000 hours [2]. In this analysis, the calculated blade metal temperature at the design base-load condition was used as the baseline reference. Figure 8 showed the stage 1 blade local metal temperature versus steam injection. It showed that for constant LP turbine inlet temperature control, the blade metal temperatures increase with increasing steam injections.

Part life impact from steam or water injection is also related to the way the engine is controlled. Most aero-derivative gas generators are controlled by the constant power turbine or LP turbine inlet temperature. Heavy-duty industrial gas turbines are generally operated with a constant firing temperature by means of a linear relationship between exhaust temperature and compressor pressure or pressure ratio. The control system on base-load application reduces firing temperature as water or steam is injected. This counters the effect of the higher heat transfer on the gas side and its impact on blade life. If the control system is designed to maintain firing temperature constant with steam injection level, this would result in additional output but the part life consumption would be accelerated.

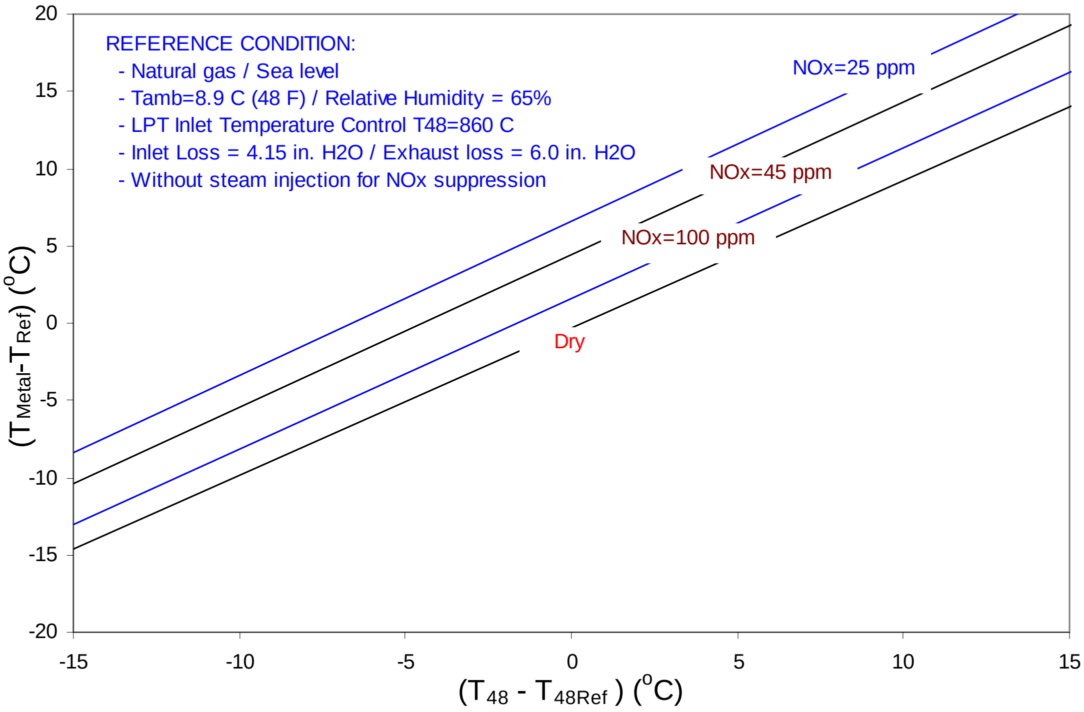


Fig. 8 Predicted Blade Metal Temperatures

Unlike most aero-derivative gas turbines, the LM6000 is controlled by the LP turbine inlet temperature (T_{48}) as well as the HP compressor discharge temperature (T_3). With increased steam injections, engine operation would be primarily limited by the HP compressor discharge temperature. In this case, fuel flow (firing temperature) would be regulated by the engine control system to operate within the maximum allowable HP compressor discharge temperature and pressure limit.

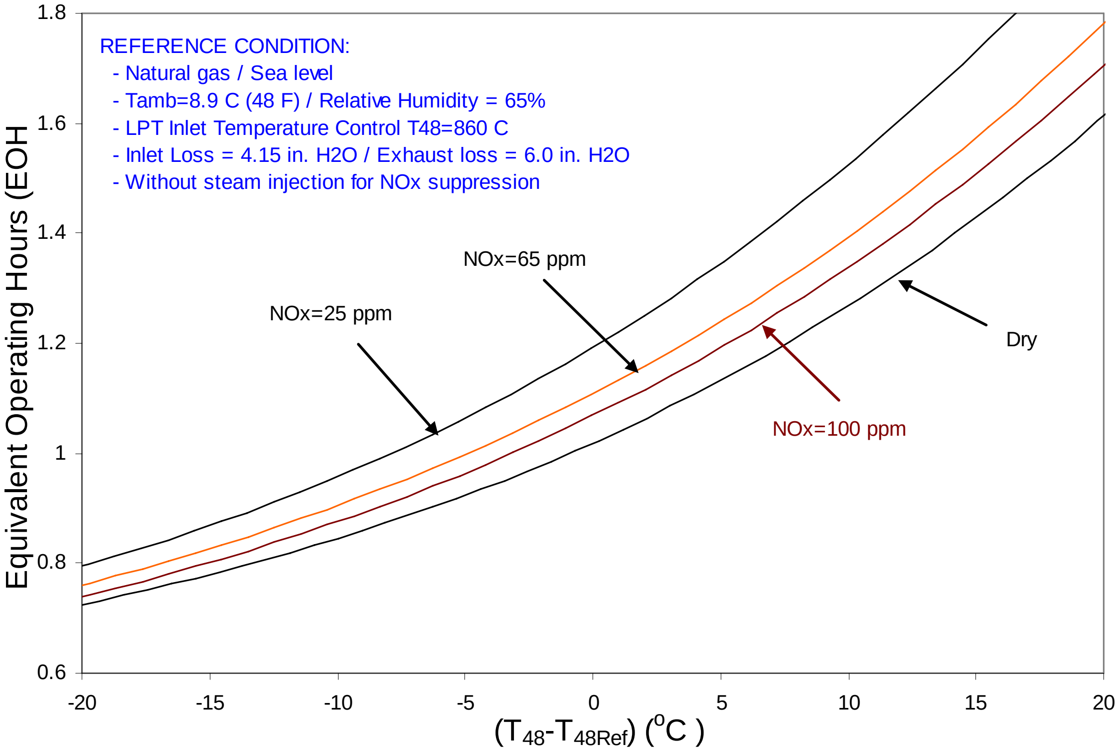


Fig. 9 Predicted Blade Oxidation Lives with Steam Injections

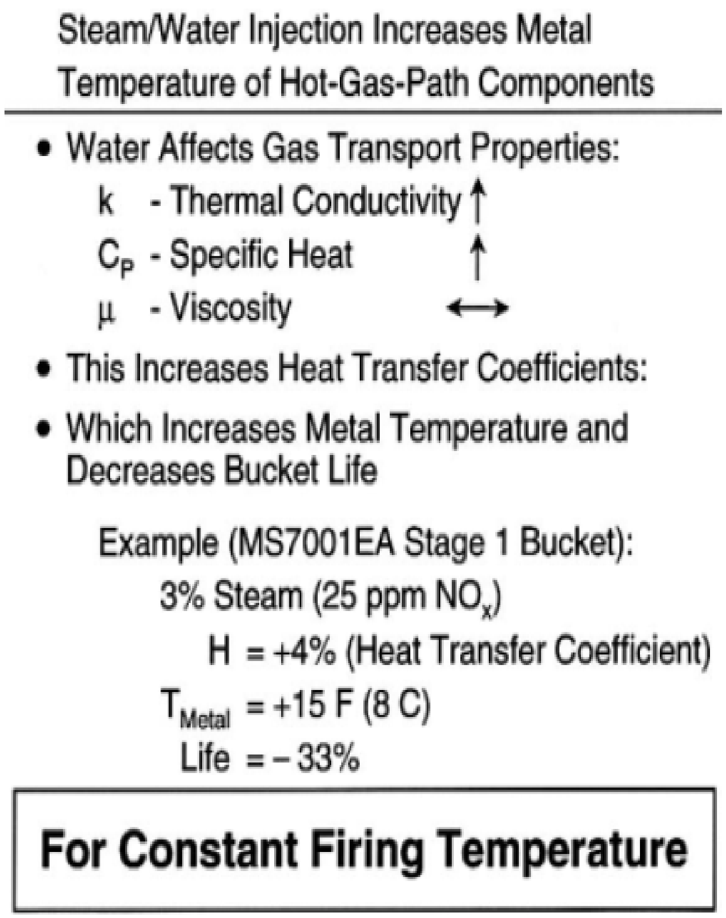
Figure 9 shows the predicted stage 1 blade oxidation life change with steam injection. With the constant LP turbine inlet temperature, a 3% steam injection rate (25 ppm NO_x) increases the hot-gas thermal conductivity by 3.5%. This would cause a 6.2% increase in the gas-side heat transfer coefficients. It was found that the internal cooling-side heat transfer coefficient was also increased by 3.4%. The increased heat transfer led to an average 6.6°C (12°F) increase in the local metal temperature resulting in an approximate 20% reduction in the part life.

LM6000PC HPT Stage 1 Bucket

	DRY	25PPM	DIFF
Gas Path Transport Properties			
k - Thermal Conductivity	0.0488	0.0505	**+3.5%↑**
Cp - Specific Heat	0.288	0.288	↔
μ - Viscosity	0.1208	0.1205	↔
Steam Injection (3% as a percentage of airflow)			
- O2	0.154	0.144	
- CO2	0.052	0.053	
- H2O	0.043	0.079	**+3%**
- SO2	~	~	
- N2	0.74	0.71	
- AR	0.013	0.012	
Heat Transfer Coefficients			
- Gas Path	352	374	**+6.2%**
- Cooling Side	396	410	**+3.4%**
Metal Temperature			
- External Surface			**+6.5C**
- Internal Surface			**+6.8C**
HP Turbine Stage 1 Bucket			
- Oxidation Life	1	1.195	**-19.5%**

For Constant LP Turbine Inlet Temperature

Industrial Frame [GER-3620J]



Steam/Water Injection Increases Metal Temperature of Hot-Gas-Path Components

- Water Affects Gas Transport Properties:
  - k - Thermal Conductivity ↑
  - C_P - Specific Heat ↑
  - μ - Viscosity ↔
- This Increases Heat Transfer Coefficients:
- Which Increases Metal Temperature and Decreases Bucket Life

Example (MS7001EA Stage 1 Bucket):

3% Steam (25 ppm NO_x)

H = +4% (Heat Transfer Coefficient)

T_{Metal} = +15 F (8 C)

Life = −33%

For Constant Firing Temperature

Fig. 10 Steam Injection and Blade Life

The predicted life impact of steam injection in general agrees with the reference (Fig. 9). In an example given by the GER-3620J on the industrial Frame 7EA stage 1 bucket, for constant firing temperature, a 3% steam injection rate (25 ppm NOx) would result in an 8°C (15°F) increase in blade metal temperature and 33% reduction in life [1]. It should be noted that the engine control system for the heavy duty MS7001EA gas turbine is different in design from the LM6000PC. The MS7001EA is controlled at the constant firing temperature, while the LM6000PC is controlled at the constant LP turbine inlet temperature. In addition, the blade life criteria used by the GER-3620J may or may not be oxidation as identified for the LM6000PC stage 1 blade.

APPLICATION

Regarding the application of the results above, the EOH factor developed by Liburdi Turbine Services needed to be translated into a format that could be used for making operational decisions and offering the power station into the wholesale electricity market.

In order to correctly identify the costs and benefits expected from additional steam injection for power augmentation, the following methodology was adopted:

1. Confirm that this mode of operation will not increase the risk of spontaneous failure;
2. Determine the impact on hot section and heavy maintenance requirements;
3. Determine the expected quantum of those increased life cycle costs;
4. Determine the other costs associated with this operating mode;
5. Develop a real time tool to determine when this operating mode should be used.

With respect to Item 1, Liburdi had determined that this was a durability issue for hot gas path components, but unlikely to affect forced outage risk due to mechanical failure. Information from the gas turbine OEM and other operators indicated that there did not appear to be any enhanced risk of failure associated with operating at 25 ppm NO_X. For many operators 25 ppm NO_X is their normal operating condition. Items 2 and 3 have been discussed in some detail above.

To determine the other costs of this operating mode, a series of performance tests were undertaken to establish net plant MW and heat rate for different, NO_X ppm setpoints and T_{48} control limits. The set of results presented in Fig. 11 below demonstrates the almost linear relationship between NO_X ppm setting, and MW output for a constant T_{48} control limit setting of 860C.

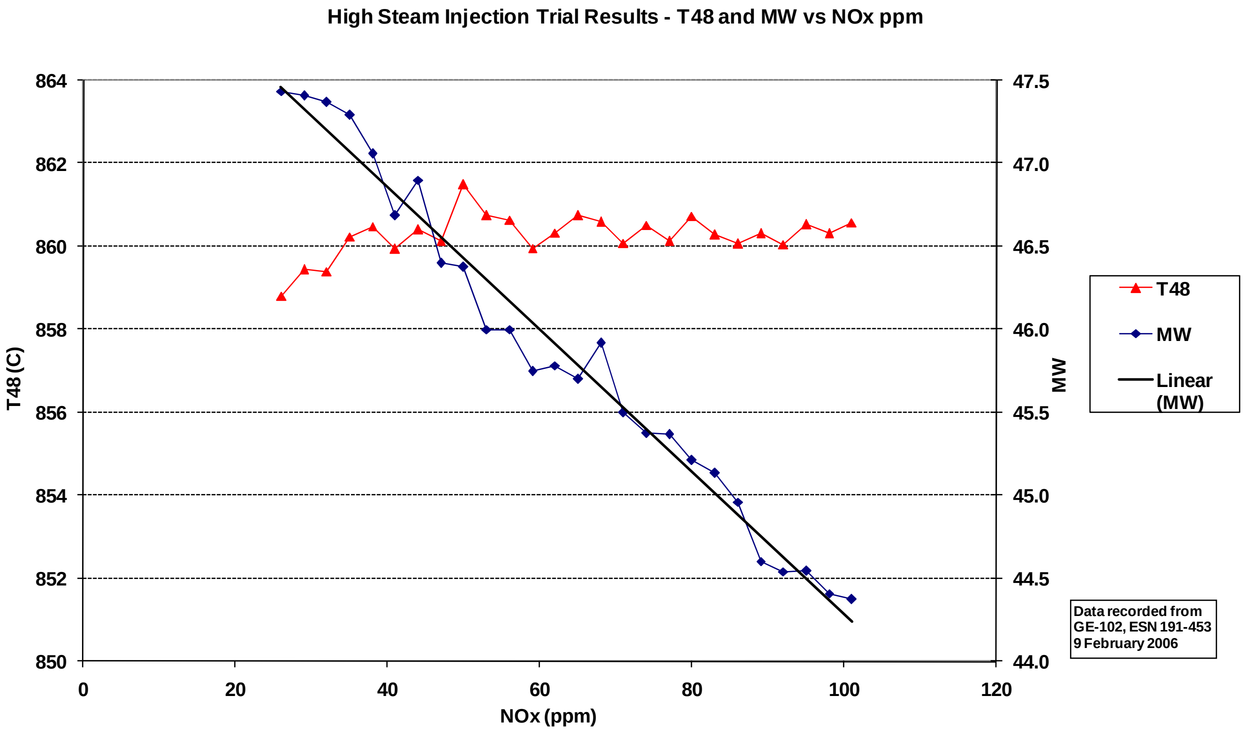


Fig. 11 Trial Results T_{48} and MW vs. NO_X ppm

In terms of parameters that can be manipulated to change the overall GT and plant performance, the main ones were NO_X steam injection setting expressed as NO_X ppm and T_{48} control limit. In broad terms the results were as follows. Increasing NO_X steam injection increased net MW, net heat rate and water consumption. Increasing T_{48} control limit increased MW and decreased heat rate, unless the rate of steam injection was targeting 40 ppm NO_X or less, at which point the gas turbine was operating on T_3 control limit and changes to the T_{48} control limit had no effect on gas turbine performance.

The next objective was to take the experimental data relating to improved MW output and measurable operating costs and add in the increased cost of gas turbine hot gas path maintenance. The following table (Fig. 12) provides sample calculations that evaluate the estimated short run marginal cost of the marginal MW produced as a result of additional steam injection.

Sample Calculations		**Base**	**New**	**Delta**
Steam Injection	ppm	100	25	
T48 Limit	C	860	860	
Net Plant Output	MW	122.80	128.91	**6.11**
Net Heat Rate	kJ/kWh	8,100	8,202	
Est. Fuel for Generation	GJ/h	995	1,057	62.59
Steam Injection	t/h	11.00	27.00	16.00
GT Maintenance Multiplier		1.00	1.15	0.15
SRMC for Station Block	**$/MWh**	**57.18**		
Steam Injection	t/MWh			2.62
SRMC of Fuel	$/MWh			$66.62
SRMC of Treated Water	$/MWh			$3.93
Est. SRMC for fuel and water	$/MWh			$70.55
Est. GT Maint Costs	$/MWh			$10.23
Estimated SRMC of Marginal MW	**$/MWh**			**$80.78**

Fig. 12 Sample Calculation of Short Run Marginal Costs

While this analysis provided a coarse go, no-go figure to work, with the actual number of options available at an operational level was nine or perhaps more. In terms of the T_{48} control limit, there were three choices, 860C, 865C and 871C. For the steam injection rate, the setpoint there could be any figure between 100 ppm and 25 ppm NO_X, this gives rise to nine different combinations of T_{48} and NO_X setpoints. There is also the question of whether to operate duct firing or not. Beyond this there are also issues of how the real time gas price and foreign currency exchange rates vary month to month or week to week.

In an attempt to deal with all of these variables in a consistent way, a workbook in Microsoft Excel was built that has the following inputs:

- Current gas price
- Real time electricity price (via plant information system PI)
- Current estimate of long run gas turbine heavy maintenance costs in USD/fired hour
- Current NZ/US dollar exchange rate
- Current estimate of treated water cost

Key outputs from the sample calculations were present in the form of a three by three matrix of NO_X ppm and T_{48} control limit setpoints. The output from the workbook is primarily graphical, and has tailored information for different parts of the organization incorporating the information that they need. For the shift engineer operating the plant he or she is presented with the MW output target and the details of the appropriate combination of setpoints needed to maximize gross generating margin, the difference between revenue and short run marginal costs. All options are analyzed and presented in order of which is most likely to maximize gross generating margin, see below.

Figure 13 shows the results for normal or moderate electricity price scenario, Figure 14 shows how this changes as market prices increase above $100/MWh.

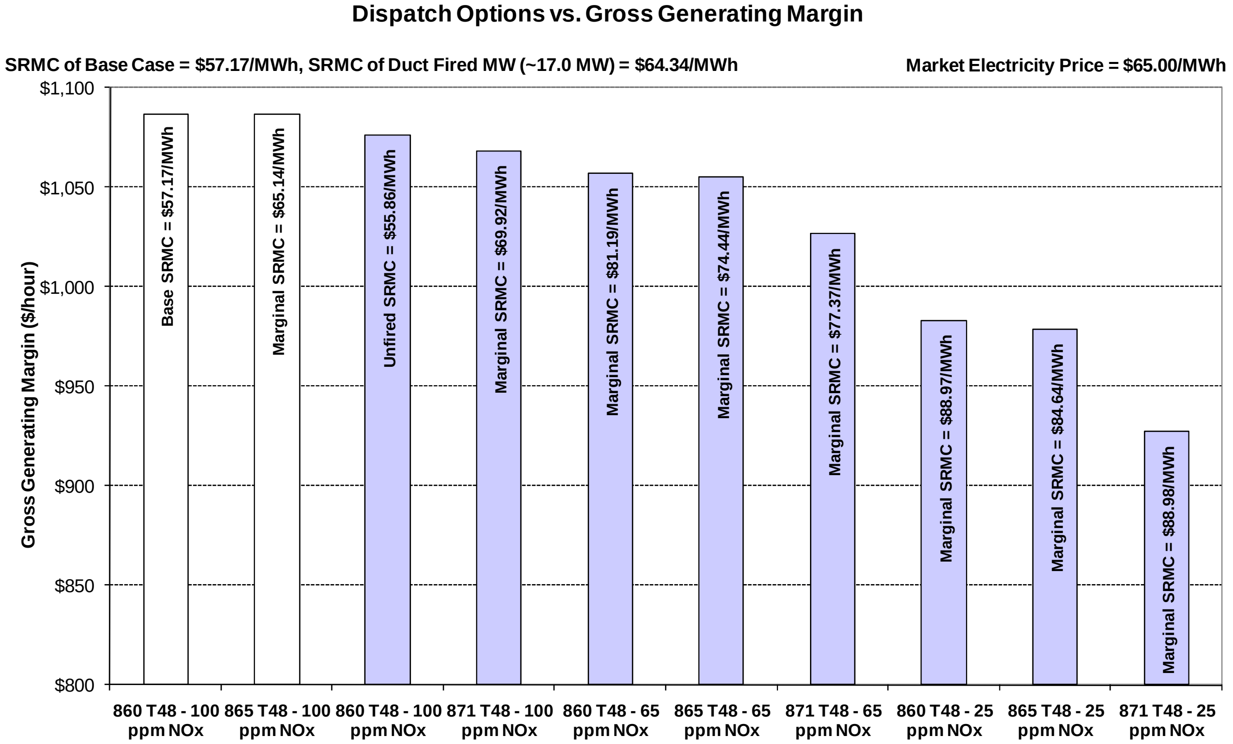


Fig. 13 Shift Engineer Information – Dispatch Options vs. Gross Generating Margin (For Normal or Moderate Electricity Price Scenario)

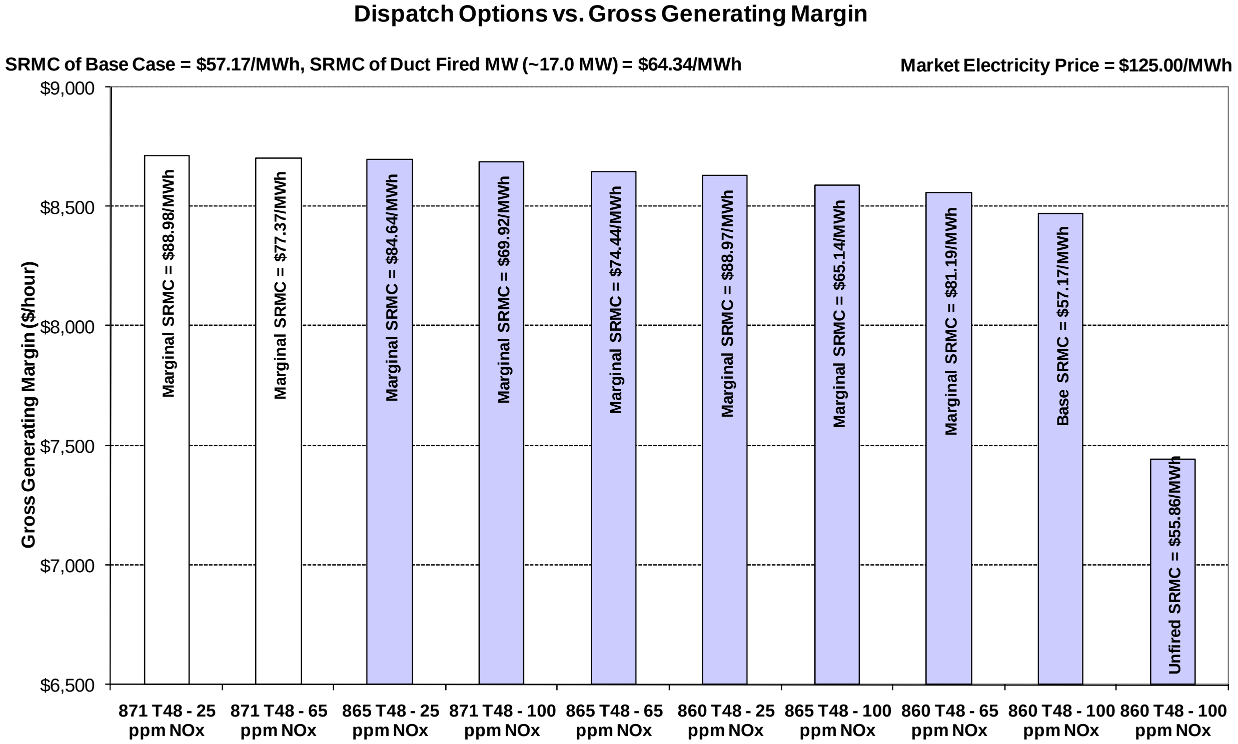


Fig. 14 Shift Engineer Information – Dispatch Options vs. Gross Generating Margin (For Electricity Prices above $100/MWh)

In a similar fashion the same calculations are molded into a format suitable for the Dispatcher to make appropriate offers into the electricity market or set the MW figure to dispatch the plant to if operating off market to a physical MW output (Fig. 15).

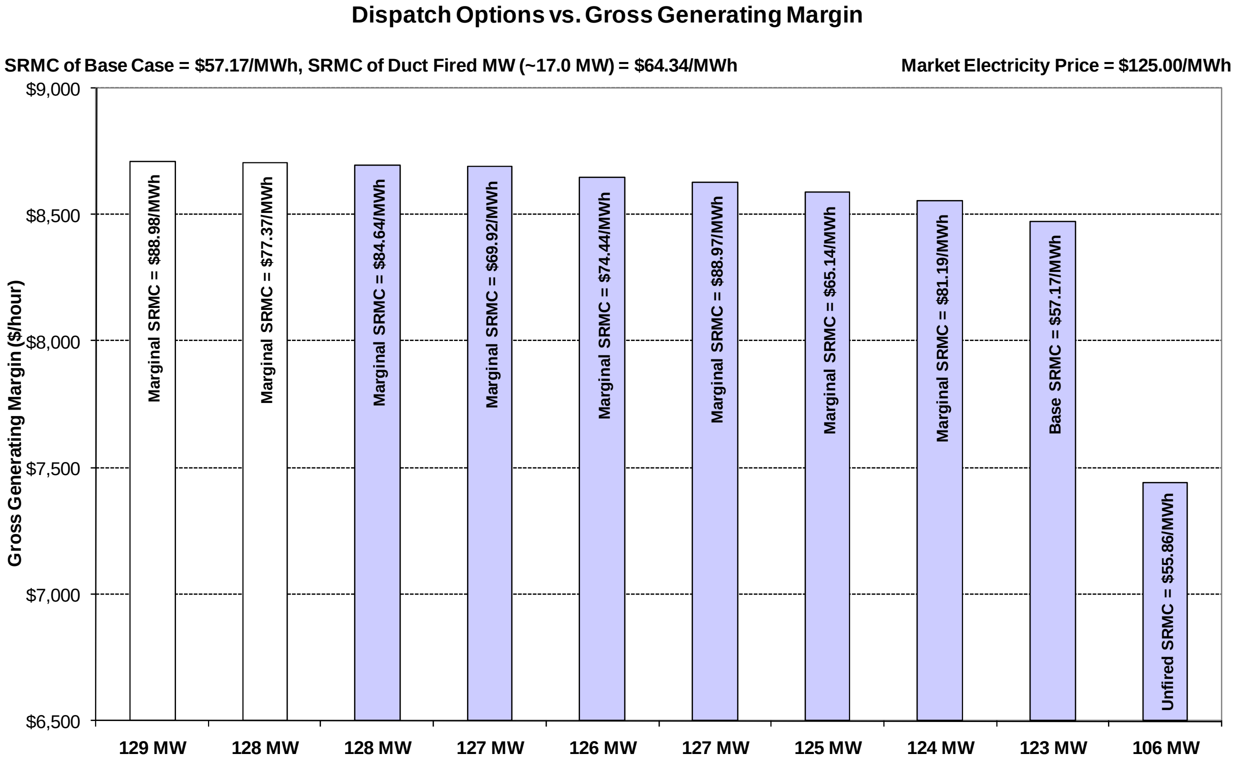


Fig. 15 Dispatcher Information – Dispatch Options vs. Gross Generating Margin

The dispatcher does not need to know the details of the plant settings; just the options with respect to dollars and MW, the shift engineer on the other hand needs different information which is provided from the same estimates. By combining all of the work to date into a workbook where the key variables can be modified to match current costs, Mighty River Power now have a rational framework for evaluating when it is appropriate to augment the plant's MW output by increasing steam injection rates, and a specific tool to guide that process.

CONCLUSION

Life cycle impact of steam injection on the LM6000PC HP turbine stage 1 blade has been studied and the relationship between steam injection, blade metal temperature and corresponding life change was reported. The analysis has focused on oxidation as the life limiting factor for the stage 1 blade. Although they have not been identified as life limiting factors, creep, corrosion, TMF, and high cycle fatigue may also be life limiting for some applications with steam injection. The heat transfer model developed for the analysis assumes an average gas path temperature entering the stage. Caution should therefore be used in applying the calculated EOH as a basis for condition-based maintenance. Future study will include the life model validation with field service experience and further investigation on mixing steam with cooling air for blade internal cooling.

Mighty River Power, the plant's owners believe that they now have a rational framework for evaluating when it is appropriate to augment the plant's MW output by increasing steam injection rates, and a specific tool to guide that process.

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