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APPLICATION OF AN INTEGRATED ENGINEERING APPROACH FOR LM1600 BLADE LIFE ON-LINE ASSESSMENT

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ABSTRACT

Realistic assessment of the remaining serviceable life in turbine hot section components plays an important role in engine condition-based maintenance and overhaul. Conventional maintenance scheduling techniques are typically based on the OEM's guidelines and applied to all engines of a certain make and model. This approach does not always address the specific operating environment and requirements of each operator. The second approach used by some operators is to combine the OEM's maintenance guidelines with metallurgical life assessment and to adjust life limits with simple algorithms. This approach is still general and not tailored to individual plant or service period.

This paper presents a new engineering approach that integrates mechanical and performance engineering with metallurgy for remaining serviceable life on-line assessment. Unlike OEM life limiting criteria this approach combines engine operating history with an understanding of the mechanical and metallurgical aspects of individual turbine components. By identifying life limiting factors and predicting the rate at which damage occurs, optimum repair, replacement and overhaul intervals can be established. An application of this approach is presented in predicting blade remaining serviceable life for TransCanada Pipelines (TCPL) LM1600 fleet.

INTRODUCTION

During service, gas turbine hot section components undergo various types of time-dependent degradation due to exposure in the operating environment. Oxidation and hot corrosion, creep, thermal mechanical fatigue can all potentially lead to turbine hot section component failure. Assessing gas turbine blade life is a multi-disciplinary task requiring expertise in metallurgy, material, mechanical design, fracture mechanics, aero-thermal dynamics, combined with operation and service history. The life limits provided by OEM are calculated on the basis of a design envelope of expected base load, calculated or measured component stresses and temperatures as a function of operating conditions, expected response of the material to those conditions, and safety factors to take into account uncertainties in the model and natural variability of the materials. Because of uncertainties in each of these factors and variations between the operating conditions of specific engines, the OEM estimated life may be too conservative in some instance, while in others, the OEM design life may not be achieved.

Conventional maintenance scheduling techniques are typically based on the OEM's guidelines and applied to all engines of a certain make and model. This approach does not always address the specific operating environment and requirements of each operator. Using OEM's maintenance guidelines as a starting point, TCPL is interested in developing a more precise program to optimize service intervals and reduce maintenance costs and at the same time to maintain or improve reliability of the fleet.

The General Electric LM1600 gas turbine comprises an aeroderivative LM1600 gas generator and an aerodynamically linked power turbine. The twin spool gas generator features a three-stage low-pressure (LP) compressor and a seven-stage high-pressure (HP) compressor, each driven by a single-stage fully air-cooled turbine. The HP turbine has 64 blades cast from Rene 80 Directionally Solidified alloy. The LP turbine has 82 blades conventionally cast from Rene 80 alloy. The gas generator expected hot section repair and retirement intervals at the rated base load are 25,000 hours and 50,000 hours, respectively [1].

LIFE TREND ANALYSIS

The life of turbine components and the factors that limit the life vary significantly from operator to operator due to a combination of the engine design, application and operating conditions. Thus, life trend analysis must identify the specific characteristics that determine the remaining service life of each component in a given application. By identifying the rate at which damage occurs, optimum repair, replacement and overhaul intervals can be established. One approach that has been successfully employed to more accurately identify the usable life of turbine blades is to perform metallurgical testing on a representative sample blade during major overhauls. This allows the extent of degradation by oxidation, corrosion, micro-structural over-aging, and creep damage occurring under the specific operating conditions of the individual engine to be characterized. On the basis of this testing, the serviceability of the balance of the blade set can be evaluated and an estimate of remaining life can be made [2][3].

Liburdi Engineering Ltd. (LEL) has been performing the LM1600 blade refurbishment and remaining life assessments since the inception of the TCPL fleet. Using this analysis data, a historical review of the HPT and LPT blade repairs and remaining life analyses was first conducted to identify life limiting factors.

Metallurgical Review of HPT Blade

Of a total of 636 service-run HPT blades repaired by LEL from ten TCPL engines, 96 blades were deemed not reparable due to cooling hole (the aft-most row of gill holes at mid-section on the concave side) enlargement, and four blades were scrapped due to foreign object damage, airfoil crack, platform crack, and seal crack. Fig. 1 shows a typical retired blade with 48,500 hours Time Since New (TSN) and 24,500 hours Time Since Overhaul (TSO). The repair was consisted of replacement of external coating with Sermaloy J and tip restoration by welding. No rejuvenation heat treatments were performed. Fig. 2 shows another retired blade with 39,000 hours TSN with external Codep coating (no reported repairs). The selected two blades had different operating and repair history. The two blades, however, were retired by the same mechanism of the cooling hole enlargement.

Metallurgical analyses had found that the most significant damage observed on the HPT blades was oxidation. The external coating was uniform in thickness around the periphery of the airfoil. It became progressively more depleted of protective b aluminum phase towards the hotter trailing edge at both mid and upper airfoil heights. The degree of oxidation on the external surface was in general identified to be within repairable limits. It was observed that not all internal cooling passages were coated, which suggests that the internal coating is the by-product of coating the external surfaces, rather than a design feature of the blade. Different levels of oxidation attack were observed between blades. The oxidation on the internal cooling passages may be partially associated with an internal coating deficiency, high service temperature at the mid-airfoil, possible reduced cooling flow. Metallurgical analysis on the selected scrapped blades found that oxidation had resulted in significant metal loss (enlargement) of the aft-most row of gill holes on the concave side. Eventually, oxidation would have become the life limiting factor due to loss of effective thickness.

Metallurgical testing on the selected blades after 50,000 hours in service had demonstrated that the aging of the blade microstructure was most severe around the airfoil periphery, especially on leading edge and trailing edge. No discernable aging was identified in the well cooled core regions of the airfoil. Rejuvenation heat treatments can be used to restore the mechanical properties of the aged regions by reconditioning the microstructure to a near new condition. After rejuvenation, the blades can be returned to service for another cycle (50,000 hours).

Thermal mechanical fatigue (TMF) results from thermally induced strains generated by start-up and shut-down cycles of the engine. No evidence of TMF damage was identified on the HPT blades. The reported TCPL fleet average cycles between overhaul is ~200, which is much less than the engine design cycles (in general 3,000~5,000). For these reasons, TMF was not considered to be a limiting factor in lifing the HPT blades.

Metallurgical Review of LPT Blade

Table 1 lists three remaining life analyses on the LPT blades. Metallurgical analyses had found that the selected representative blades were in good condition and could be returned to service without repair. Metallurgically there was no evidence of the onset of significant degradation from oxidation, aging, creep or thermal mechanical fatigue. The projected LPT blade life would be greater than 100,000 hours.

Table 1 Historical Review of LM1600 LPT Blade Life Analysis

	Blade S/N	**Operator**	**Coating**	**TSN**	**Recommended return for next service run**
1	PCWC3199	TCPL	Codep	62,684	24,000
2	HL081	TCPL	Codep	65,210	25,000~50,000
3	SRWN4298	TCPL	Codep	50,000	25,000~50,000

TECHNICAL APPROACH

Historically, metallurgical testing of sample blades at major overhaul has provided the basis for the LM1600 blade life assessment and is the most direct and accurate approach for identifying the usable life. Practically metallurgical analysis cannot be undertaken for every engine component. The objective of the LM1600 blade life analyzer is to develop computer models to complement metallurgical testing. By predicting the rate of damage in a given application, economical repair, replacement and overhaul intervals can be established.

The rather complex task of predicting component life was simplified by targeting life limiting factors identified from metallurgical testing and component repair experience. Since the effectiveness of coatings in protecting base metal of internal passages from oxidation attack has been identified as the primary life limiting factor for HPT blades and a major decision point in determining the engine overhaul period, the program was developed to predict HPT blade oxidation life. The calculated oxidation life is then converted into equivalent operating hours (EOH) with reference to the engine design condition at rated base load. Failure mechanisms such as creep of the HPT blades could be added into the program should one of them become life limiting in the future.

ANALYSIS

To simulate blade operating environment, an aero-thermal model for the LM1600 was developed. The aero-thermal model calculates transient hot gas path inter-stage temperature, pressure, and flow using engine operating data. The calculated aero-thermal values are then used as boundary conditions for mechanical analysis. The mechanical model is used to analyze component stress, strain and temperature. Component life consumption can then be calculated from the results of the mechanical analysis. Remaining life is in general calculated by accounting for oxidation, creep, thermal mechanical fatigue separately or in combination. To validate the computer model, periodic metallurgical analysis of blades from certain key engines needs to be performed to monitor deterioration rates and identify other unforeseen failure mechanisms.

Aero-Thermal Model

The aero-thermal program developed for predicting LM1600 hot gas path inter-stage temperature, pressure, and flow combines conventional through-flow thermodynamic model with a state of the art aerodynamic model [4][5][6]. The bleed valve control, cooling and leakage flows are included in the model. The gas generator compressor is modelled with a compressor map. The flow entering each turbine stage produces work at stage efficiency while the cooling flow entering each stage produces work at fractions of stage efficiency depending upon their entry locations. Design, off-design and transient conditions of the LM1600 can all be handled by the model using the following engine instrumentation:

1. Inlet temperature and pressure
2. LP rotor speed
3. HP rotor speed
4. HP compressor inlet temperature
5. HP compressor discharge pressure
6. LP turbine discharge temperature
7. LP turbine discharge pressure

The aero-thermal model was verified using the OEM quoted performance data. It was found that the predictions were in a good agreement with the OEM quoted engine performance at base load as well as part load (Fig. 3).

Heat Transfer

As the next step of the analysis, external gas flow and heat transfer analysis on the HPT blade were performed. It is noted that the accurate prediction of the convective heat transfer distribution around high-pressure and transonic gas turbine blades still represents a significant challenge to the turbo-machinery community. A program developed by NASA known as TSONIC was used to calculate external velocities. The program was selected for its ability to obtain a transonic flow solution on a blade-to-blade surface between blades of the turbomachine, and good agreement between the prediction and the experiment data [7]. The program input consists of blade and stream-channel geometry, stream-channel weight flow, relative stagnation conditions, and relative inlet and outlet flow angles. These input values were generated from the aero-thermal model. Fig. 4 shows the predicted external velocity distribution at the mid-section of the HPT blade at rated base load. With the blade geometry and surface velocity information, adiabatic wall temperatures and heat transfer coefficients can be calculated [8].

A FORTRAN program was developed to calculate blade surface temperature using a flat plate heat transfer model. The flow in the internal cooling passages is assumed to be turbulent. The cooling flow parameters were calculated using the aero-thermal model. The cooling flow heat pick up was calculated through iteration process. The model was calibrated using metallurgical metal temperature estimations (Fig.5). For example, blade metal temperature can be estimated using historical metallurgical data, e.g. service exposure time and aging. The calculated cooling effectiveness at mid-section on the concave side is 49 percent at the rated base load, which agrees with the open literature. The effectiveness of cooling was kept unchanged in the off-design. Fig.6 shows the variations of the predicted base load rotor inlet temperatures, the exhaust gas temperatures, and the HPT blade local temperatures at different ambient conditions. It is noted that at ambient temperatures greater than ~20 ^{o}C, with constant exhaust temperature control, the rotor inlet temperature slightly decreases with the increase of the ambient temperature. The HPT blade metal temperature increases with the increase of the ambient temperature due to the reduced flow extraction from the compressor for blade cooling and increased cooling flow temperature. At ambient temperatures less than ~20 ^{o}C, the engine is operated by the flow / compressor discharge pressure control with low firing temperatures and exhaust temperatures.

Oxidation Life

Oxidation damage in general occurs at temperatures over ~700°C. The oxidation damage initially starts via the formation of a thin protective oxide layer at the alloy surface. This protective oxide layer continually undergoes sublimation, wear and spallation. Oxidation attack can be estimated based on the kinetics of oxide growth. The oxide growth rate is dependent on diffusion through the oxide layer at the alloy surface [9]. Activation energies associated with these oxides can be used to determine oxide growth rates as a function of temperature and relative oxidation life of the components [10].

Degradation by oxidation is also a function of the thermal cycling encountered during normal operation. On cooling, protective oxide layer formed during operation may spall due to stresses resulting from the difference in coefficient of thermal expansion between the oxide and the underlying metal. Weight change behavior in cyclic oxidation is typified by an initial parabolic weight gain response curve that eventually exhibits a maximum, then transitions into a linear rate of weight loss due to spalling [11]. Chan's model [12] was used to correct cycling effects and the baseline for the model is the TCPL fleet average 200 cycles between overhaul and 24,000 hours life.

Significant operation at higher firing temperature requires more frequent maintenance and replacement of hot section components. It was found that one hour of operation at peak load (+100^{o}F/56^{o}C) is equivalent, from a blade life standpoint, to about five hours of operation at base load (Fig. 7). Higher firing temperature reduces hot gas path parts lives while lower firing temperature increases parts lives. It should be noted that the temperature effect on blade life is not a linear relationship. Each hour of operation at 100^{o}F/56^{o}C under base conditions is equivalent to 0.2 hours of operation at the base load. These predictions were found to be consistent with the effects of firing temperature on hot gas path maintenance described in GER-3620k [13].

DISCUSSIONS

The aero-thermal model, the heat transfer model, and the life algorithm developed were compiled into a dynamic linked library and embedded into a Microsoft Excel file. Engine operating data can be loaded into the Excel file and the program calculates accumulated EOH with reference to the engine rated base load. The GE approach to maintenance planning, a gas fuel unit operating at continuous duty, with no water or steam injection, is established as the baseline condition, which sets the maximum recommended maintenance intervals [13].

Service data from five engines were used for testing the program. Fig. 8 shows a comparison of the actual operating hours, the TCPL Hot Hours, and the predicted EOHs using the life algorithm model. The TCPL Hot Hours were calculated based on a simple algorithm, in which one operating hour is counted as one Hot Hour if the EGT is greater than a reference temperature. No operating hour is counted if the EGT is less than the reference temperature. The reference temperature was determined empirically on the basis of metallurgical life assessment during major overhaul. The same reference temperature was applied to whole fleet. Historical review on TCPL fleet showed that a significant rate of early retirements of HPT blades due to oxidation attack had occurred using the Hot Hour model. Comparing to the predicted EOHs (Fig. 8), the Hot Hour model is found conservative in some cases (e.g., Hussar 8 and Knight 4), while in others too aggressive (e.g., Hussar 6 and Farrell 1). The Hot Hour model only looks at the EGT as a measure of remaining serviceable life without considering other operating conditions or engine degradation. It was found from Fig. 6 that while the EGT is kept as constant, the HPT blade temperature increases with the increase of the ambient temperature. The increased blade temperature indicates a fast rate of life consumption which was not taken into account by the simple Hot Hour model.

Hourly-averaged data from test engines at ISO temperature (15°C) were compared with the OEM rated base load (Table 2). The equivalent operating hours were calculated in the range of 0.6~0.8. The reduced EOHs can be explained by the factors of site elevation, CDP degradation, and low EGT control settings.

Table 2 Predicted EOHs at ISO temperature (15 °C)

Test Engines	LPC Inlet Temperature (°C)	Exhaust Gas Temperature (°C)	N1 Speed (RPM)	N2 Speed (RPM)	HPC Inlet Temperature (°C)	HPC Discharge Pressure (KPA)	Predicted EOH
OEM Rated Base load	15	743	13002	15735	182	1917	1.0
Hussar6	15	743	12882	15663	170	1740	0.72
Hussar8	15	743	13080	15668	174	1860	0.73
Knight4	15	745	12866	15622	172	1755	0.77
Schrader3	15	740	13135	15741	178	1821	0.64
Farrell1	15	731	13130	15680	176	1836	0.61
Crowc -H1	15	733	13088	15698	177	1786	0.57

CONCLUSION

In summary, there are three approaches for an operator to determine turbine hot section component service life for a specific plant. Conventional approach is based on OEM's maintenance guidelines and applied to all engines of a certain make and model. This approach does not always address the specific operating environment and requirements of each operator. The second approach is to combine the OEM's maintenance guideline with metallurgical life assessment during major overhaul, and to adjust life limits with simple algorithm (e.g., TCPL Hot Hour). This approach is still general and not tailored to individual plant or service period.

This paper presents the third approach that integrates mechanical and performance engineering with metallurgy for engine on-condition maintenance and overhaul. Unlike OEM life limiting criteria this approach combines engine operating history with an understanding of the mechanical and metallurgical aspects of individual turbine components for remaining serviceable life assessment. By identifying life limiting factors and predicting the rate at which damage occurs, optimum repair, replacement and overhaul intervals can be established. To validate the computer model, periodic metallurgical analysis of components from certain key engines needs to be performed to monitor deterioration rates and identify any unforeseen failure mechanisms.

The LM1600 blade life analyzer developed has focused on oxidation as a life limiting factor for the TCPL fleet. Although it has not been identified as a life limiting factor, creep damage may be life limiting for some operators. Caution should therefore be used in applying the calculated EOH as a basis for increasing operating intervals. It is recommended that, while the period for hot section repairs may be extended beyond 25,000 actual hours based on the EOH model developed, the period between overhauls should not be extended beyond 50,000 actual hours without rejuvenating the blades. The incorporation of a creep damage model into the EOH calculation would allow extension of the blade life beyond this point.

REFERENCES

1. GE Marine & Industrial Engines, LM1600 Gas Turbine

2. P. Lowden, J. Liburdi, “Application of Metallurgical Testing to Gas Turbine Blade Life Assessment”, ASM & EPRI International Conference Life Assessment and Repair Technology for Combustion Turbine Hot Section Components, Phoenix, AZ, April, 1990

3. V. Swaminathan and P. Lowden, “Gas Turbine Blade Life Assessment and Repair Guide”, EPRI Report GS-6544, EPRI Project 2775-6, Electric Power Research Institute, Palo Alto, 1989

4. D. Little, H. Nikkels, and P. Smithson, “Incremental Fuel Cost Prediction for a Gas Turbine Combined Cycle Utility”, ASME paper 89-GT-88

5. R. Pistor, “A Generalized Gas Turbine Performance Prediction Method through PC Based Software”, ASME paper 97-IAGT-203

6. R. Pistor and F. Krampf, “Advanced Engine Performance Analysis for PC Computer”, 99-IAGT-204

7. T. Katsanis, “Fortran Program for Calculating Transonic Velocities on a Blade-to-Blade Stream Surface of a Turbomachine”, Lewis Research Center, NASA, NASA TN D-5427, 1969

8. J.W. Sawyer, Sawyer’s Gas Turbine Engineering Handbook, Third Edition, Turbomachinery International Publications, Norwalk, USA, 1985.

9. T. Chester, S. Norman, C. William, Superalloys II, John Wiley & Sons, Inc., 1987

10. V.P. Swaminathan, J.M. Allen, G.L. Touchton, “Temperature Estimation and Life Prediction of Turbine Blades Using Post-Service Oxidation Measuremnets”, Journal of Engineering for Gas Turbines and Power, pp922-929, vol.119, October, 1997

11. J.L. Smialek, “A Deterministic Interfacial Cyclic Oxidation Spalling Model: Part 1. – Model Development and Parametric Response”, NASA Glenn Research Center, NASA TM-2002-211906-Part1, 2002

12. K.S. Chan, “A Mechanics-Based Approach to Cyclic Oxidation”, Met. Mat. Transactions A, Vol. 28A, pp.411-422, 1997

13. GER-3620k, “Heavy-Duty Gas Turbine Operating and Maintenance Considerations”

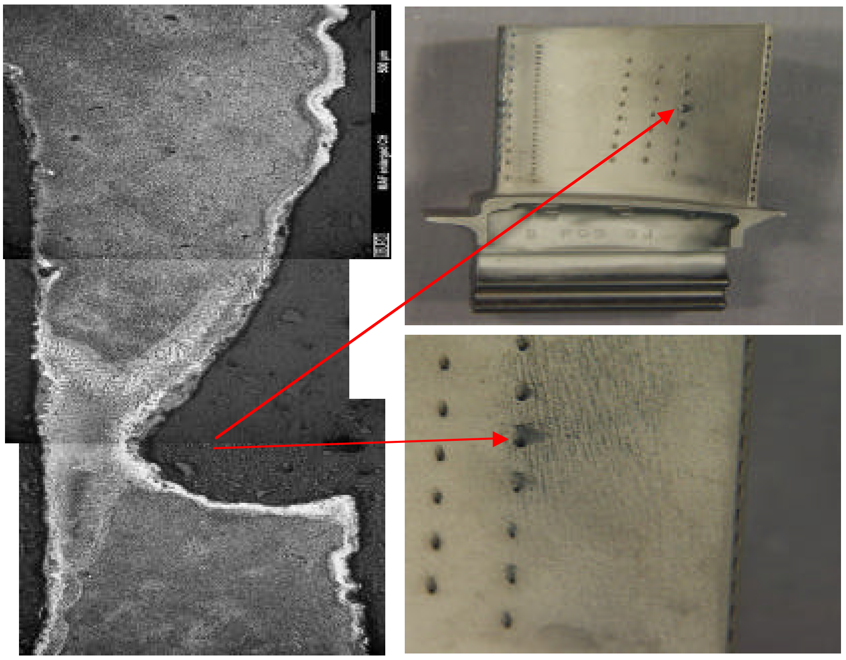

Fig. 1 Retired HPT Blade (S/N: AFMB0035) from Engine (S/N: 751-015) with 48,500 Hours TSN and 24,500 Hours TSO

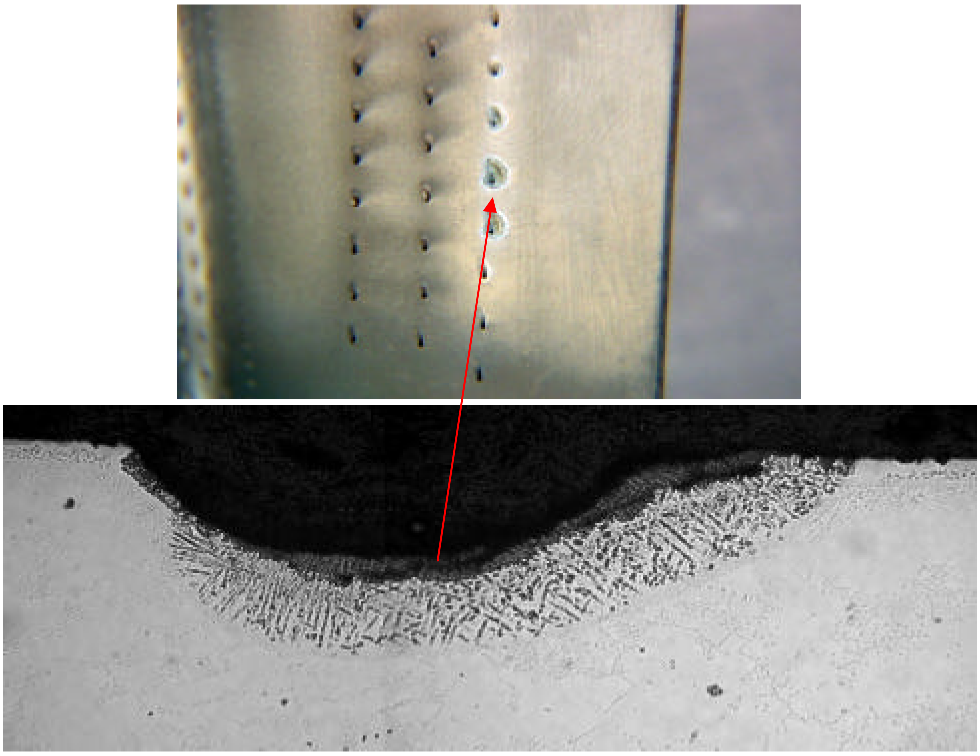

Fig. 2 Retired HPT Blade (S/N: PCWT1662) from Engine (S/N: 751-010) with 39,000 Hours TSN without Repair

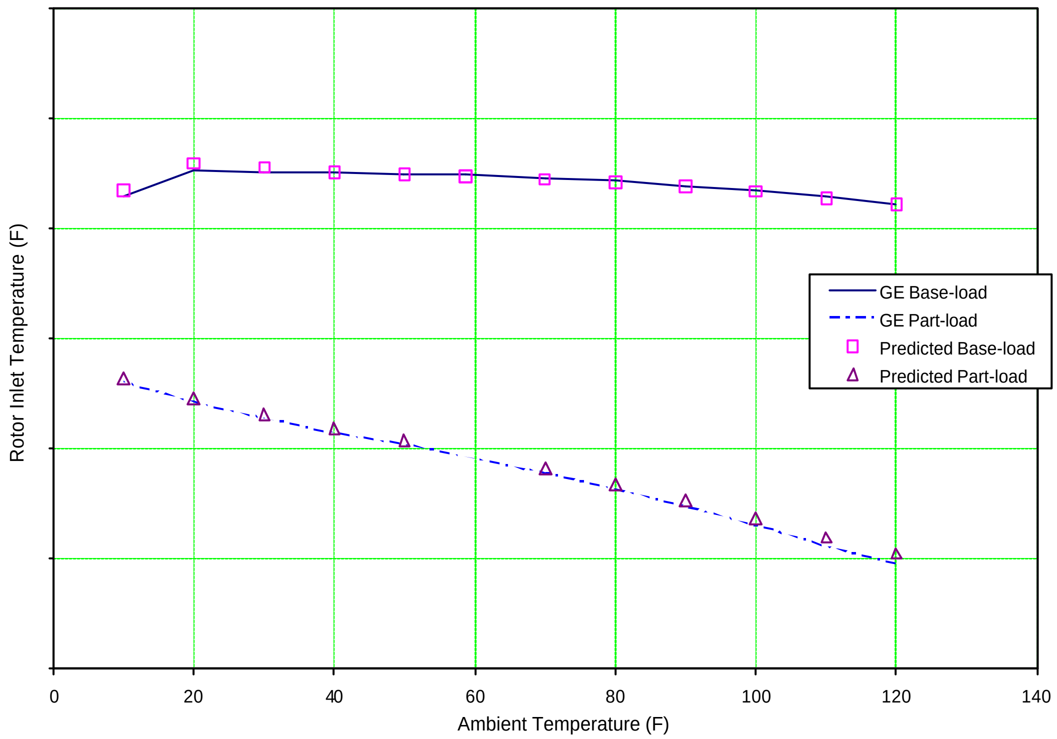

Fig. 3 Verification of the Aero-thermal Model

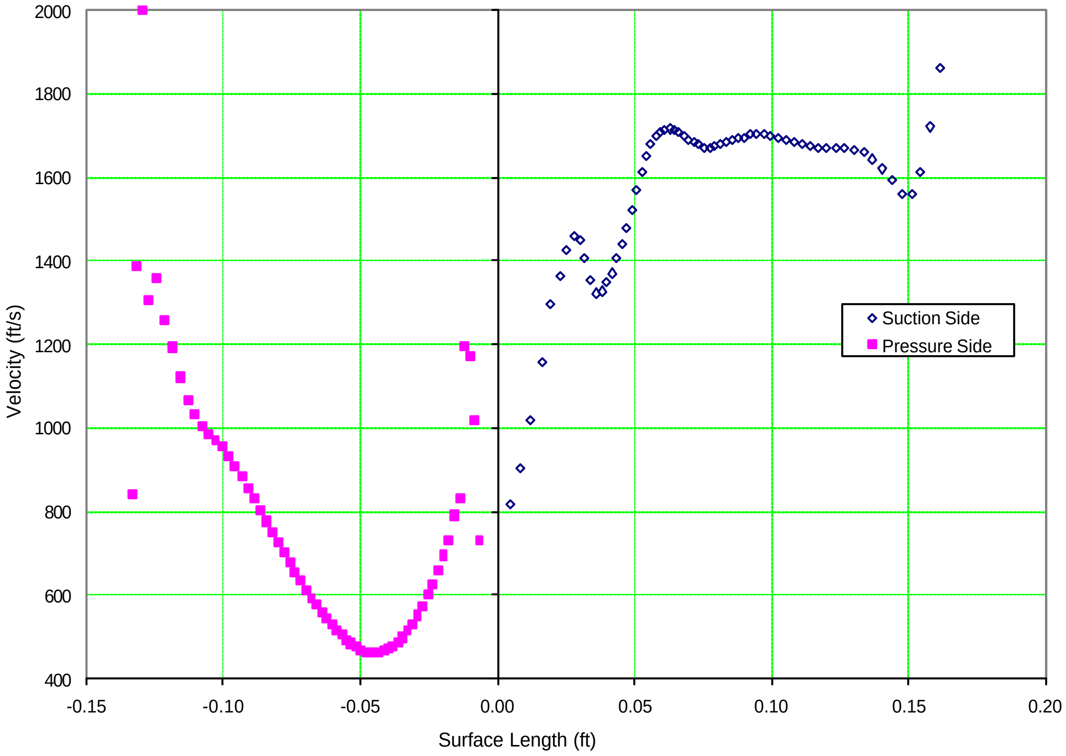

Fig. 4 External Velocity Distribution at Blade Mid-section

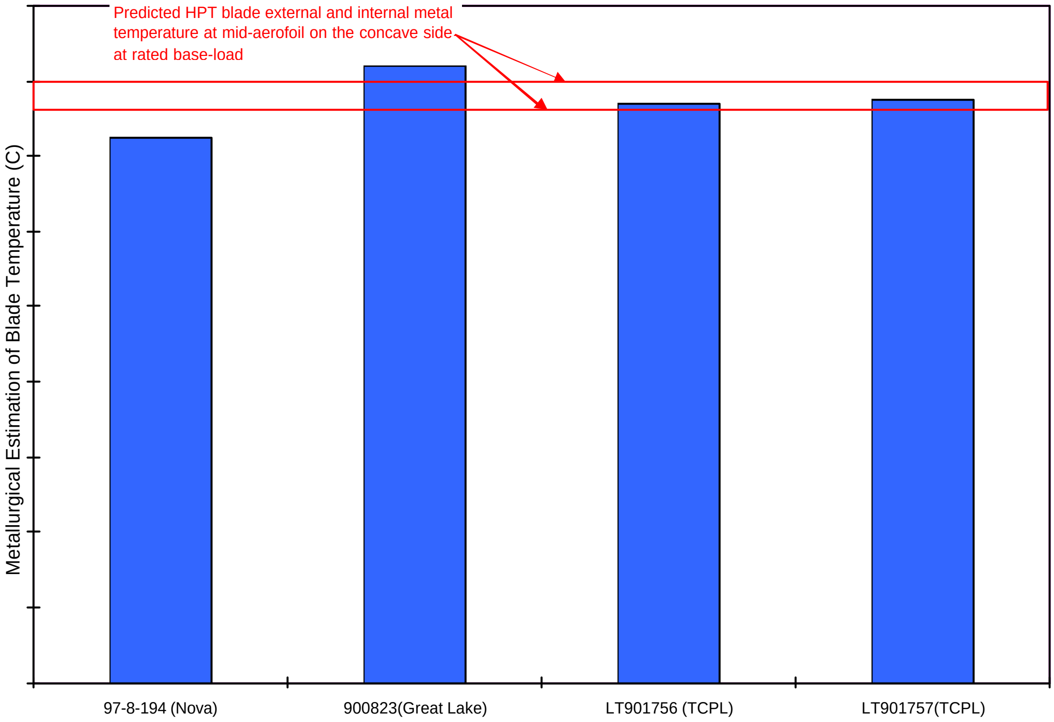

Fig. 5 Verification of Heat Transfer Model

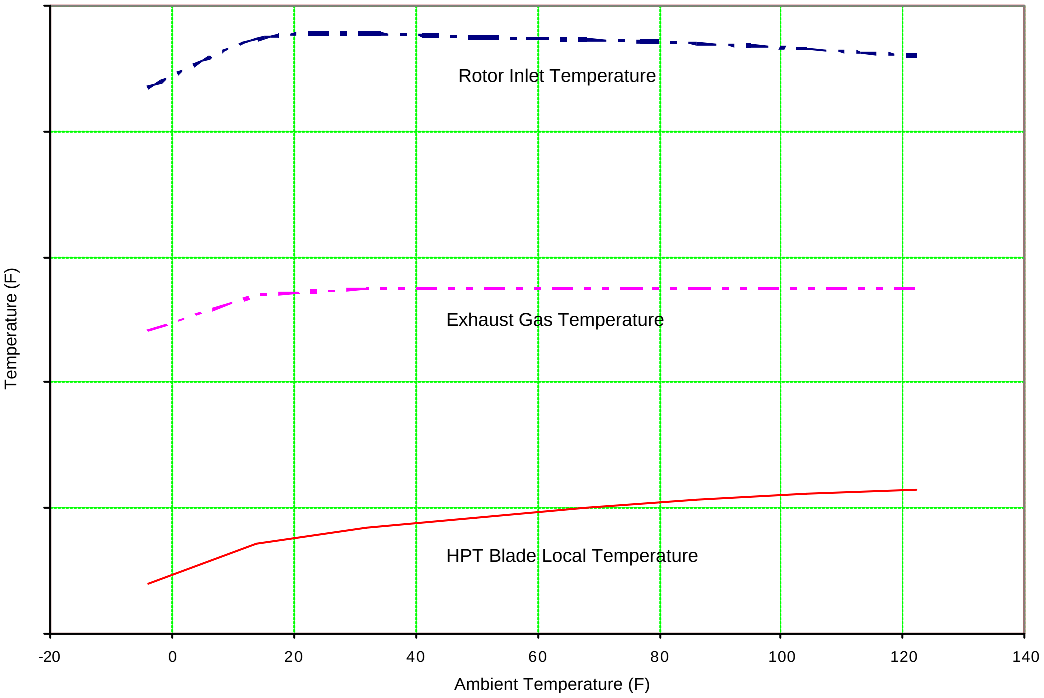

Fig. 6 Predicted Base Load Temperatures

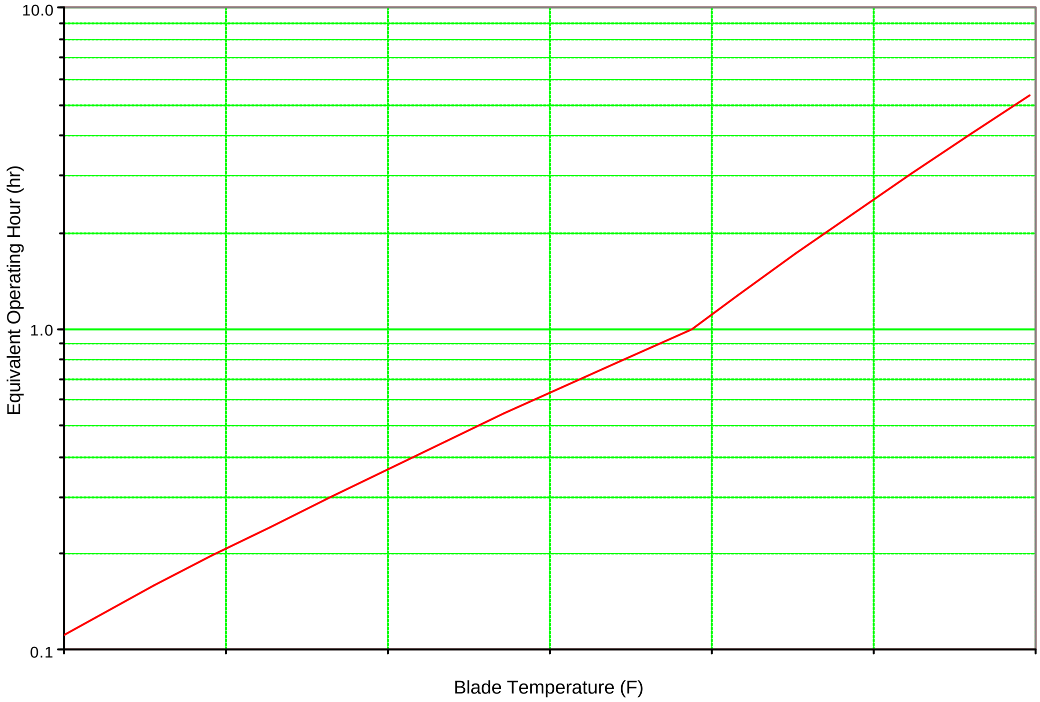

Fig. 7 Temperature Effects on Blade Life

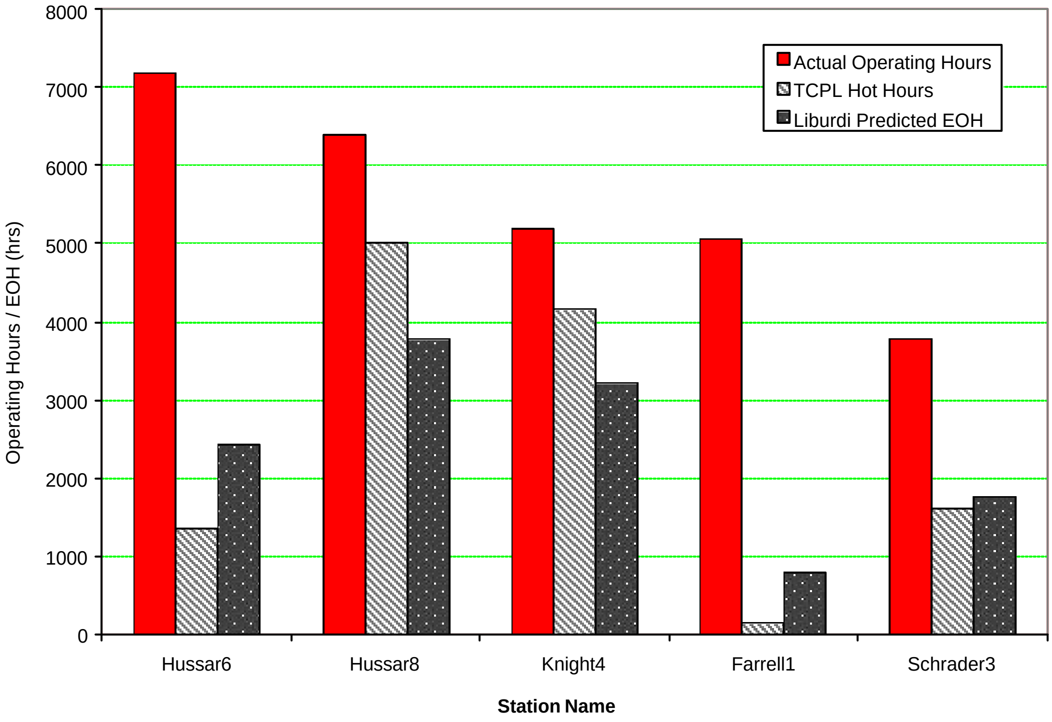

Fig. 8 Comparison of TCPL Hot Hours and Predicted EOH