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A SYSTEMS APPROACH TO HOT SECTION COMPONENT LIFE MANAGEMENT

by

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<u>Biography Session 2.8</u>

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1990 - Present: Liburdi Engineering Limited - Principal Engineer. Responsible for gas turbine performance analysis and engineered component upgrades. Has provided a full scope of engineering services, including performance software development, computational fluid dynamic analysis, finite element stress and heat transfer analysis, compressible flow network analysis of internal cooling systems and aerodynamic analysis of turbomachinery. Some projects include: Redesign and retrofit a W251AA for gasifier service, Redesign of the Frame 6, First Stage bucket for improved cooling and extended life, Provided electric utilities and refineries with Liburdi's *Win*GTAP and *Web*GTAP performance software, Developed PC based software for Dresser-Rand used for quoting aeroderivative site, performance to customers by integrating General Electric's Cycledeck performance code with a selection of power turbines for the LM1600, LM2500 and LM2500+Engineered tip seal performance improvements for Frame 7EA First and Second Stage buckets to improve leakage Steam injection power augmentation analysis of Frame 7EA Developed gas turbine emissions prediction software ,Involved in mechanical analysis of failed turbomachinery components, Publications: Has written papers, given presentation and participated on panels at ASME Conferences. Presented courses dealing with component upgrades, gas turbine performance. Education Received a Bachelor of Applied Science in Mechanical Engineering from the University of Waterloo in 1994. Patent: Extended Tip Turbine Blade For Heavy Duty Industrial Gas Turbine- US Patent 60/309,366

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Robert J. Pistor, Liburdi Engineering Limited

ABSTRACT

Managing combustion turbine hot section components in an economically viable business environment is a multi-disciplinary task requiring expertise in metallurgy, mechanical and performance engineering as well as outage optimization and scheduling. Through the implementation of information technology these expertise subjects can branch together to be fully exploited. The power of the Internet, fast processors and the recent introduction of .NET connectivity can be harnessed by a hot section component life manager to maximize the useful life of their assets. Computer based remaining component life algorithms, remote condition monitoring and component database part tracking can be integrated into one unified hot section life management program. Practical application of this approach is presented in the text to follow.

INTRODUCTION

Operations and maintenance (O&M) of gas turbine hot section components is not a new subject. Combustion hardware, stationary vanes, rotating blades and turbine discs continue to significantly impact the economic success of the gas turbine power plant. Managing component wear, oxidation, corrosion and microstructural degradation are as relevant now as they were a half century ago. Material stability, mechanical strength and unit performance are key factors in the design and operation of the hot section. Figure 1. illustrates the interconnection between various engineering and business disciplines related to hot section O&M.

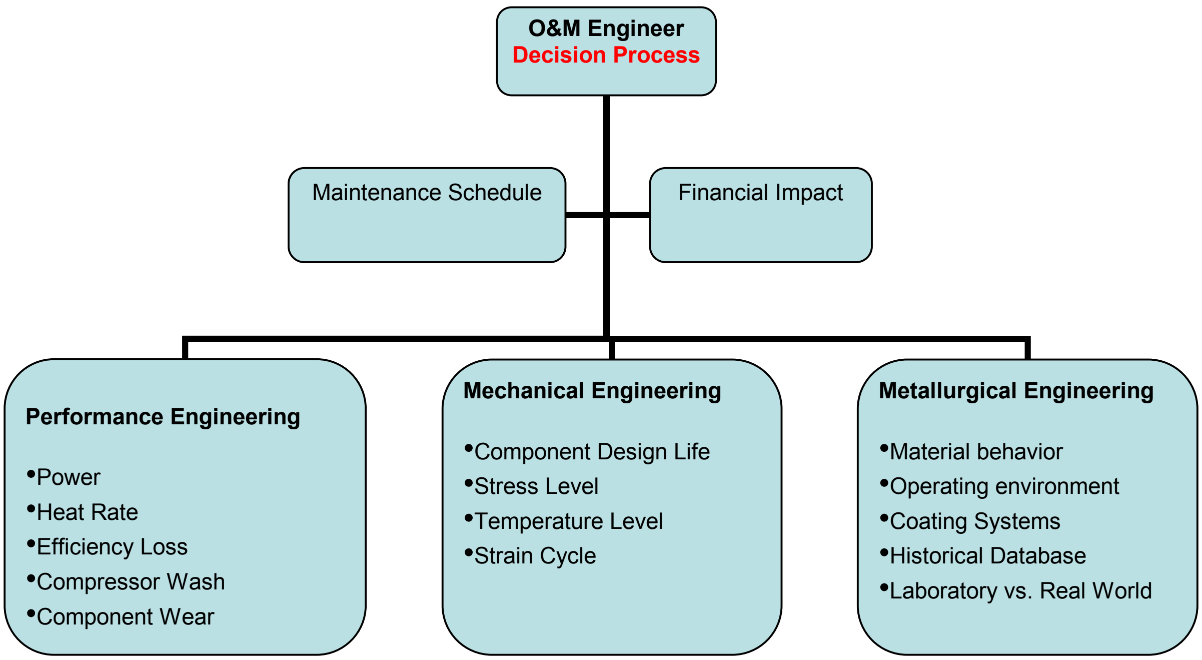

FIGURE 1: Engineering roles in Operations and Maintenance

The degree of success an O&M strategy will achieve depends largely on the ability to tie together metallurgy, mechanical and performance engineering. In the traditional sense this can be managed with an experienced relatively small staff overlooking a modest sized power plant. When an O&M strategy is contemplated for a larger fleet of several power plants extending over large geographical areas, either adequate human resources will have to be expended or the use of a systems approach to O&M maintenance can be adopted.

Systems engineering ties together the three traditional engineering disciplines using information technology tools. Large powerful databases, historians, internet communications, affordable high speed computing and connectivity technology have made tremendous advances in the recent past. Systems engineering is a highly effective way of stitching together different disciplines. Figure 2. illustrates the role systems

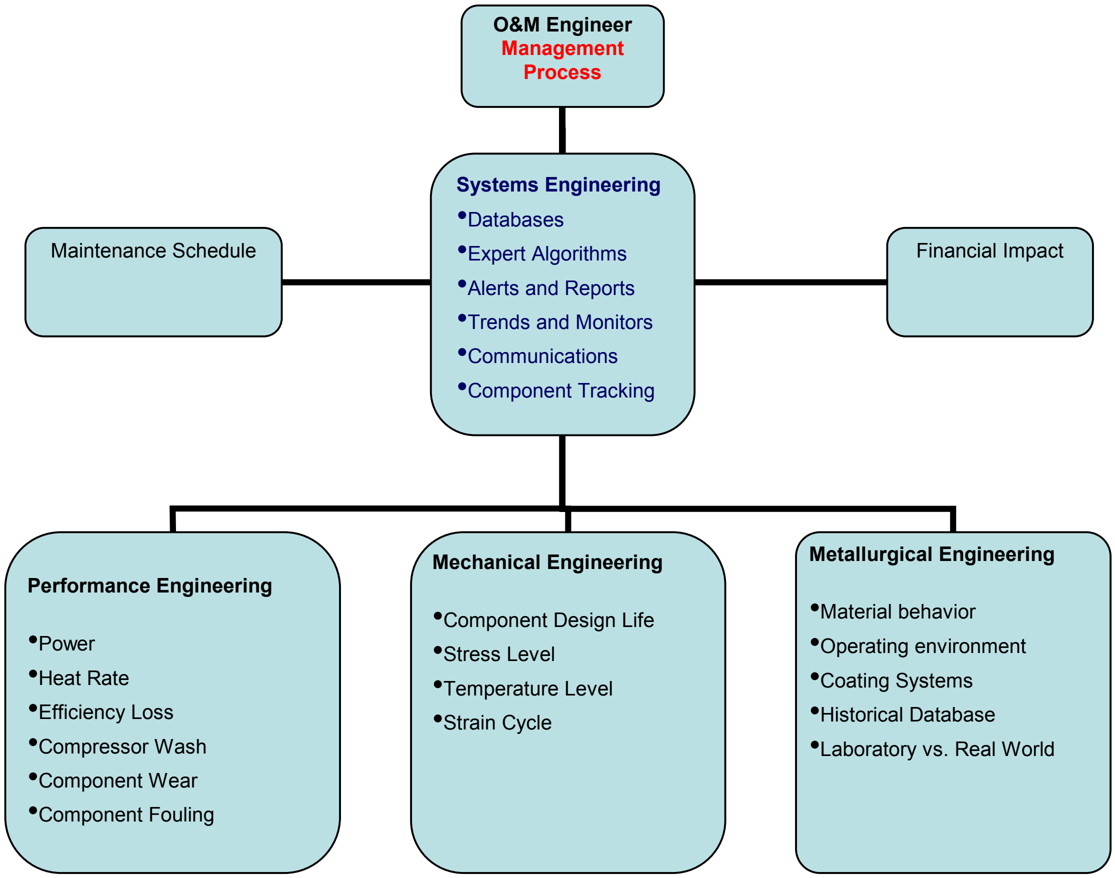

FIGURE 2. System Engineering Approach to O&M

engineering plays in the O&M scheme.

Without the systems engineering tools in place, maintenance practices have largely remained time or start based. In some cases, 'run to fail' may be the only O&M strategy. A Condition Based Maintenance strategy is increasingly favored by gas turbine operators over time based or 'run to failure' maintenance. Determining gas turbine condition relies largely on the technology available to interpret the operating plant data. Modern power plants have an overwhelming capability to collect data, which often outpaces the operator's ability to interpret it without the appropriate systems engineering tools.

In designing a systems based approach to O&M, a solid understanding of the traditional engineering disciplines is paramount. Information technology applied with inadequate attention to mechanical, metallurgical and performance engineering can be a costly investment in plant operations and even worse of little use. An appreciation how different disciplines approach O&M should be built into the expert system.

ENGINEERING APPROACHES TO O&M

Beyond normal visual, dimensional and boroscope inspections, eventually some type of engineering evaluation will have to be undertaken to determine the disposition of the hot section components. In many cases a tallying up of the equivalent operating hours is done and the hot section parts are replaced or refurbished based on the manufacture's recommended interval. This is known as time or start based maintenance. It is relatively straightforward to apply and consequently widely adopted. Time/Start based maintenance is most effective when the established manufacture's life guidelines accurately reflect the condition of the parts. In one extreme of the accuracy scale the part may be retired/refurbished too early in it's life cycle, on the other extreme the part could have failed before the manufacture's recommended equivalent operating life. Both extremes can be costly to the operator and could be improved if a more detailed engineering assessment were made to determine the actual condition of the part. This is known as condition based maintenance.

Metallurgical, mechanical and performance engineers will make life assessments on the hot section in different ways. For example a metallurgical engineer could examine the microstructure of a sectioned turbine blade and determine the amount of material damage the blade has suffered compared to a new casting to make a life assessment. Likewise, a mechanical engineer would extrapolate the chronological running stresses and temperatures of the part and compare it to the design life. Even more abstract, the performance engineer will can conduct a thermal heat balance of the equipment and deduce how much performance degradation a component has suffered since new. All of these engineering approaches are valid to some degree and depending on the situation may be considered individually or in combination.

METALLURGICAL ENGINEERING APPROACH

One approach which 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 [1]. This allows the extent of degradation by oxidation, corrosion, microstructural over aging and creep 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.

In instances where unacceptable lives are obtained from blades, the information obtained by metallurgical testing can be used to identify appropriate changes to operating conditions, blade material or coating to extend life. The reparability of unserviceable blades can be assessed on the bases of the same tests.

OXIDATION AND HOT CORROSION – At the temperatures at which gas turbine blades operate, significant interaction between the blade alloys and the gas environment occurs [2]. In clean gas environments, the principal reaction is with oxygen resulting in gradual oxidation of the airfoil. However, in environments which contain contaminants such as sulphur, sodium, potassium, vanadium or lead as contaminates in the fuel or air, a more aggressive form of attack, referred to as hot corrosion, occurs. The main factors affecting the severity of hot corrosion is also influenced by contaminant levels. Thus there can be significant difference in environmental attack in identical blades operating in different service.

The most important effect of oxidation and hot corrosion on the turbine blade life is the change in airfoil section resulting from attack (Figure 3). The reduction in load bearing area and resulting increase in stress can lead to failure or creep or fatigue. To measure the loss in section resulting from environmental attack, metallographic sections are prepared from the airfoil surfaces and examined by optical or scanning electron microscopy. The depth of attack includes the thickness of the scale, as well as internally oxidized or sulphidized zones and alloy depleted layer which may have formed.

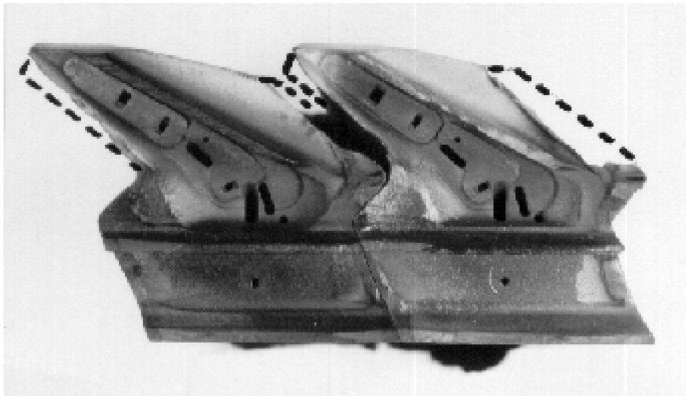

FIGURE 3. Oxidation of RB211 Shrouds

MICROSTRUCTURAL DEGRADATION – Gas turbine blade alloys are primarily strengthened by precipitation of second phase particles of gamma prime (Ni_3Al) and carbide phases along grain boundaries ($M_{23}C_6$ OR M_6C). During exposure at service operating temperatures, these phases are subject to aging reactions which alter their morphology. In addition, topologically close packed phases, not present in the new alloy, can be formed in certain alloys during service. These changes alter the mechanical properties of the alloy and, thus, can significantly influence the life of the blade.

The creep strength of turbine blade alloys is strongly influenced by the morphology of the gamma prime precipitates. After heat treatment, new blades typically have either a simple structure of gamma prime precipitates of 10 – 50 nm in size or a duplex structure of large particles of 0.5 -2 μm diameter and smaller particles of 10 – 50 nm size. During service, both types of structure age by an Ostwald ripening mechanism in which large particles grow at the expense of smaller particles causing a decrease in creep strength [3-5]

Metallographic examination of samples from the blade airfoil, after service exposure, allows the degree of gamma prime over aging to be determined (Figure 4) . Because of the small particle size, electron microscopy must be used to image the gamma prime microstructure.

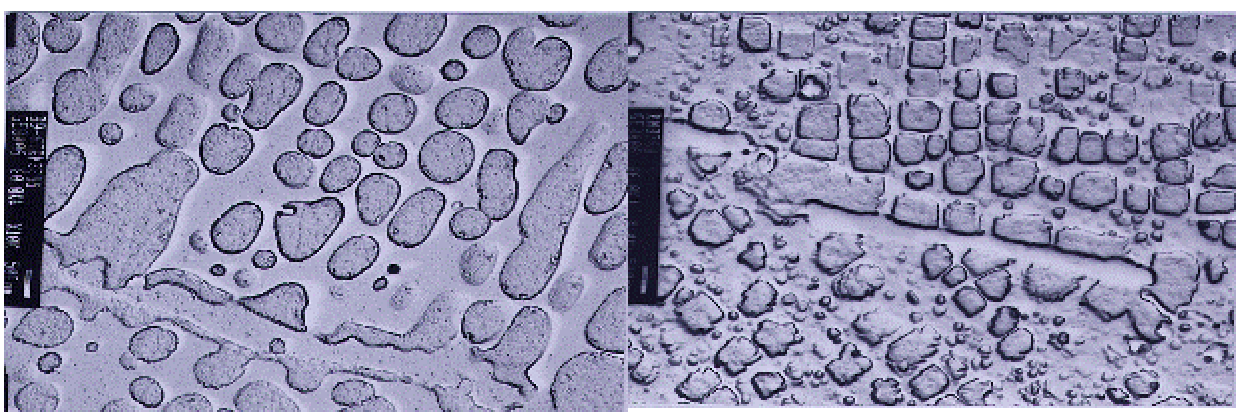

FIGURE 4. GTD 11 material microstructure before (left), and after (right) rejuvenation heat treatment

MECHANICAL TESTING – is frequently performed during metallurgical analysis of service exposed turbine blades to characterize the material properties. The results are largely influenced by the microstructural degradation mechanisms discussed above. However, mechanical test results provide quantitative measure of that degradation and, in addition, can detect some types of damage which are not microstructurally related. Typically creep rupture testing is conducted to provide an estimate of the decrease in safety margin relative to the new part and, by setting appropriate limits, can be uses as a serviceability test.

Impact properties can also be of concern in instances where there is a history of FOD failures. In such cases, Charpy V-notch impact specimens are removed from the airfoil and tested at ambient or elevated temperature conditions [6]. The results are not used predictively but are compared to a serviceability criterion arrived at by previous experience.

Metallurgical Approach Pros-

- The most direct and accurate way to determine remaining life in a component
- A mature O&M strategy that has demonstrated several years of success
- Does not require extensive mechanical design information

Metallurgical Approach Cons-

- Requires a shutdown and overhaul
- Requires destructive testing of one or more components
- Has limited ability to extrapolate future service if different from past

MECHANICAL ENGINEERING APPROACH

In designing hot section components mechanical engineers will target a design life. For example one may target a 24,000 hour life in a first stage turbine blade. This would mean that the designer would limit the maximum steady and unsteady stresses to that which the material can safely endure for 24,000 hours of normal operation. Creep damage, coating life and low cycle thermal mechanical fatigue constraints will dictate maximum allowable stresses and temperatures in the blade. Applying these mechanical constraints on the components during the design phase requires significant modelling of the component and its material system. These models form the basis for design and are used in specifying equivalent operating hour criteria.

FEA AND CFD- Finite element analysis and computational fluid dynamics are very useful modelling techniques mechanical engineers employ to design hot section components (Figure 5). FEA is used to predict the operating stresses and temperature that a component will experience in service. Heat transfer and fluid dynamic boundary conditions determined by CFD are applied to the FEA model. The resulting stresses and temperatures are then entered into a material model to predict the component 'design life'.

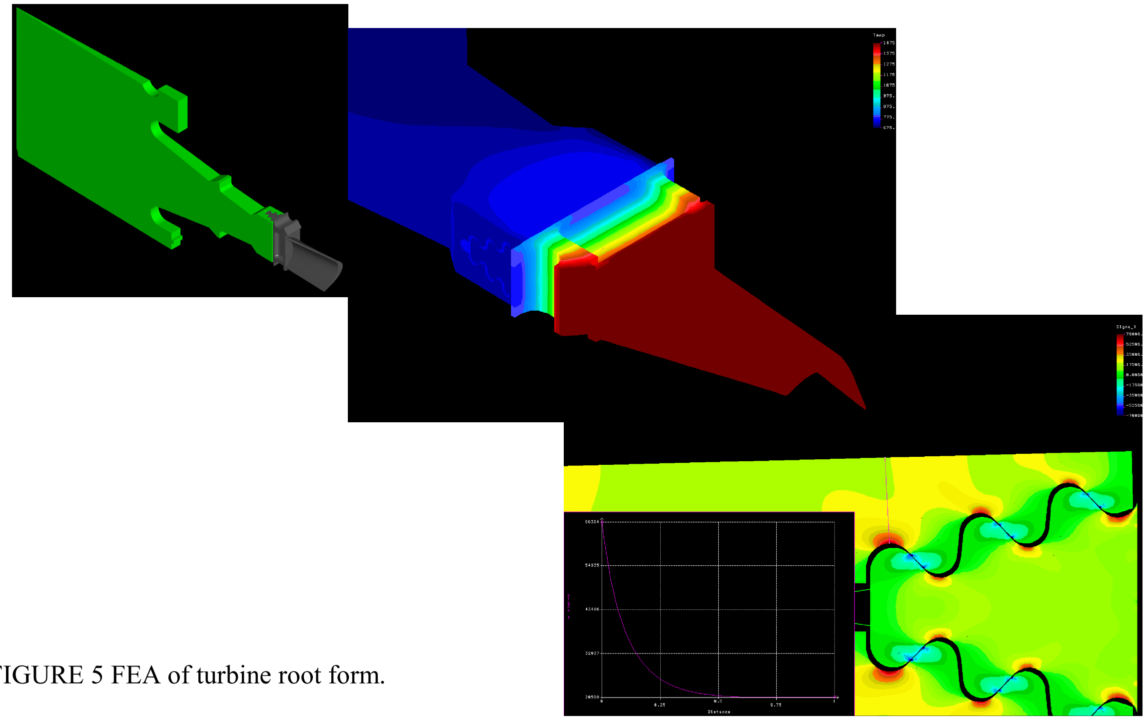

FIGURE 5 FEA of turbine root form.

From an O&M perspective the overall system model can be used to evaluate remaining life. Even more useful, these models can be used to forward predict remaining life based on operating condition. For example, if the user were to operate their components at a different load than design, the life impact of this can be directly estimated with the model.

LONG TERM MATERIAL STEADY BEHAVIOUR- can be characterized using Larson-Miller curves and creep rate equations combined with safety factors to account for the unknowns in the model. The Larson-Miller curve is a generally accepted method used to determine the creep life of a component given time, temperature and stress and is represented in Figure 6. Material creep strain rates are used in modelling the non-linear plasticity experienced in hot section components. For example the long term load shedding of a turbine root form can be estimated to predict a more representative design stress. Material creep strain rates can be represented by the classical power law for creep known as the Bailey-Norton law [7]. The expression for uniaxial creep strain in terms of the uniaxial stress and time is represented in the following equation:

$$\varepsilon_c = C_0 * \sigma^{(C1)} t^{(C2)} e^{(-CT/T)}$$

where;

T	=	Temperature
σ	=	Stress
t	=	Time
C_0, C_1, C_2, CT	=	Material Constants

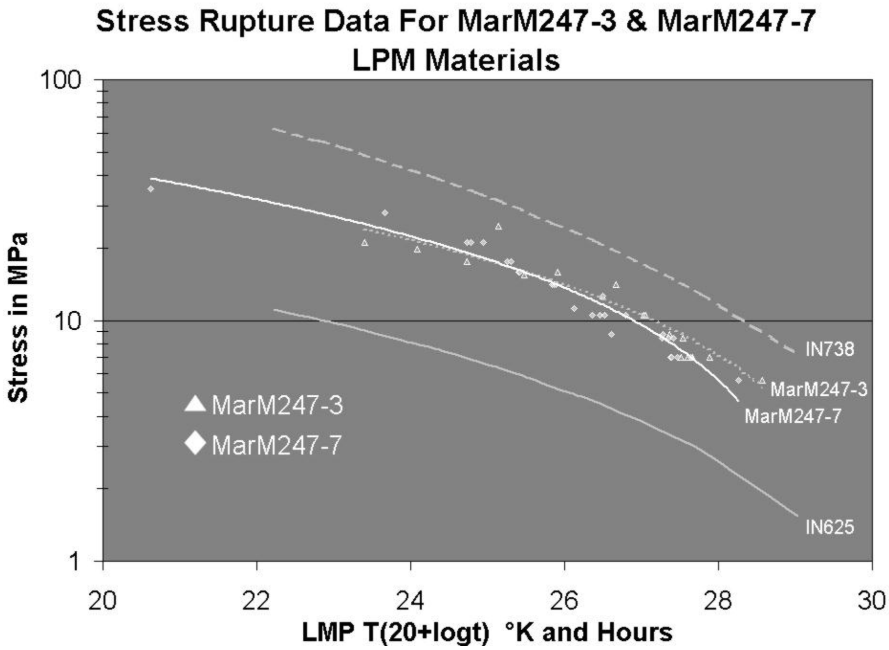

FIGURE 6. Larson Miller plot

LONG TERM MATERIAL CYCLIC BEHAVIOUR- can be classified as either high cycle or low cycle fatigue. The classification of fatigue behaviour into two types characterizes the different material model damage mechanisms. Low cycle fatigue or LCF deals primarily with 1000's of cycles. Practically LCF is tied with engine starts or load variations which are linking with thermal and stress cycles. High cycle fatigue or HCF results from cycles much greater than 1000's and more likely in the 10^7 range. Practically HCF is associated with cyclic stress loading tied to the engine operating speed. For example, blades rotating past a number of vane wakes will accumulate a number of stress cycles every time the blade passes by during 1 revolution. Both HCF and LCF are dealt with using different material models.

HCF can be modelled using a Goodman Diagram as illustrated in Figure 7. A mechanical designer will design the HCF loading of the part to fall in a region on the Goodman diagram where safe operating stresses occur that ensure near infinite operating cycles.

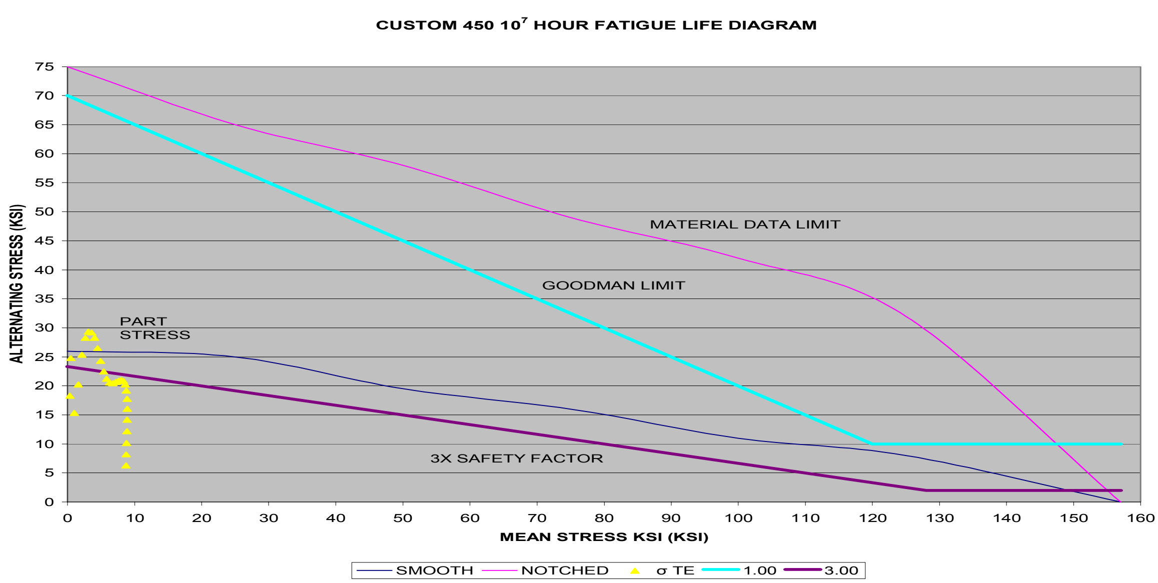

FIGURE 7. Goodman Diagram

LCF material properties are primarily deduced from laboratory testing. Most of the laboratory testing conducted to characterize the low cycle fatigue resistance of materials is carried out at constant temperature using simple waveforms with steady strain rates. By, contrast a start-up or trip cycle on a gas turbine hot gas path can generate quite a complex stress cycle with transient thermal loading.

To predict the fatigue life of a component exposed to the more complex cycles based on the lab test results, some simplifications must be made. The first simplification addresses the isothermal nature of most lab testing. The assumption is made that the damage accumulated during the thermal-mechanical fatigue cycles is equivalent to damage generated in isothermal testing at the peak temperature of the thermal-mechanical fatigue cycle. Secondly, the differences between the complex strain cycle experience by parts and the simpler cycles used in lab testing must be addressed. Under low cycle fatigue conditions, fatigue life is a function of the strain range (the maximum strain in the cycle less the minimum strain in the cycle) and test results are most commonly presented as graphs of cyclic life to failure versus strain range. The complicated strain cycle a component sees in service is thus characterized by the strain range, to predict low cycle fatigue life from simple lab cycles. The predicted life can then be read from the LCF curve for the material at that strain range (See Figure 8).

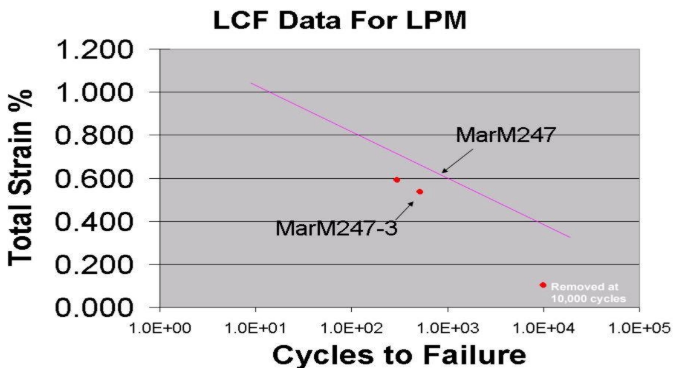

FIGURE 8 Typical LCF curve

Mechanical Approach Pros-

- Has the capability to forecast future component life based on load profile
- Is a quantitative method that can be used to set hours and starts
- Models can be used in an optimization scheme to maximize life

Mechanical Approach Cons-

- Relies on specific design information of component of interest
- Relies greatly on the accuracy of the material models used to predict life
- Relies on the 'state of the art' of FEM and CFD computing resources

PERFORMANCE ENGINEERING APPROACH

The performance engineering perspective on O&M is completely different from the metallurgical or mechanical approach. A performance engineering evaluation will let one know if the component is behaving the way it did historically in terms of its thermodynamic ability. For example one could plot gas turbine efficiency over time and track its degradation. Non-recoverable efficiency loss due to erosion, oxidation, wear, or long term bowing is measured.

Performance engineering diagnostics analyses the gas turbine performance to try and determine the degradation in axial compressor flow, axial compressor efficiency, turbine throat area change and axial turbine efficiency. Data can be gathered real-time from available plant instrumentation and entered into a performance analyser such as GTAP™ [8]. In addition to determining component degradations, GTAP™ can be used to evaluate inter-stage gas path conditions like pressure, temperature and flow (Figure 9).

FIGURE 9 GTAP™

Under certain O&M criteria, compressor washes or component refurbishments may be implemented once performance levels drop below what is considered acceptable.

Performance Engineering Pros-

- Can be implemented inexpensively to gather the most out of data that is already being logged
- Can be used to establish maintenance schedules to improve/maintain performance
- Is largely hands free and automatic requiring no machine down time

Performance Engineering Cons-

- Will not tell you remaining life information about a specific blade row

SYSTEMS ENGINEERING APPROACH

As demonstrated above metallurgical, mechanical and performance engineering take a very different approach to O&M. Although different, each discipline can be tied together in one central computing server and provided as a web service to facilitate O&M. A component tracking and management system or CTMS has been developed to track component data at the serial number level. Its features are listed as follows:

- Designed to track hot section components in and outside of the engine.
- While out of the engine CTMS records repair shop practices implemented by serial number:
  - Dimensional measurements
  - Moment Weights (if applicable)
  - Repair Level and Type
  - Coating
  - Rejuvenation heat treatments and history
  - Life analysis reports
- While in the engine CTMS records by serial number:
  - accumulated hours
  - accumulated starts
  - GTAP™ gas path history
  - OEM specified equivalent operating hours
  - Metallurgical/Mechanical equivalent operating hours
- Designed with a level of automation that will alarm and notify specified personnel of key indicators such as:
  - Performance degradation (fouling, wash cycles etc.)
  - Equivalent operating hours reaches a specified value
  - Step changes in operating performance
  - Combustion Inspection due
  - Blade Path Inspection due
- Hosted by a central server accessible through a secure web connection

Two potential CTMS application examples are listed below:

EXAMPLE 1: Trailing Edge Thinning of Rotating Frame 7EA Row 2 Turbine Bucket

Metallurgical analysis revealed an engine axial inter-granular crack along the span of the trailing edge up to 7/8" long. Metallographic investigation concluded that a creep related mechanism was responsible for the trailing edge cracking. Additionally oxidation and wear had reduced the thickness of the trailing edge to 76% of the new condition.

Mechanical analysis showed that the strain range experienced during a shutdown and a full load trip was between .003 and .004. The boundary conditions that resulted in this strain range were determined from a transient performance analysis which provided the gas path transient temperatures, pressures and flows. The LCF life was predicted to decrease significantly with reduced trailing edge thickness. So much that a 25% thickness reduction limit was set for the bucket's trailing edge before retirement from service.

As one can see, each analysis on its own could not establish a minimum wall thickness criterion. Metallurgical analysis revealed the type of failure. Mechanical evaluation predicted strain ranges using the result of performance engineering transient gas path analysis. By combining the results of the 3 disciplines, a retirement criterion has been established. To implement this in practice a systems health monitoring solution would track each bucket by serial number in a database. This database would contain a remaining life quantity for each serial number. GTAP would be added to the health monitor to track gas path conditions to calculate remain life in the part based on the mechanical engineering models described above. This remaining life number would be updated periodically in the database and when it reaches a certain number, alarms and notifications would be given by the health monitoring system to the O&M engineer.

EXAMPLE 2: Over/Under firing a Frame 3 gas turbine.

In some cases when the market conditions are right an operator may elect to over-fire their gas turbine to get additional capacity out of the unit during a peak operation. The economic conditions in certain peak hours can be so advantageous that over-firing is very attractive and the consequential impact on maintenance needs to be estimated. Conversely there are cases where a reduced firing rate would substantially offset the maintenance cost to make it economically viable. These decisions can be made with a greater degree of confidence if a systems approach to O&M were implemented.

By archiving and tracking component remaining life in a database, the life impact of over/under firing can be managed and optimized. Metallurgical and performance history will dictate the life consumed thus far and forward looking mechanical analysis can predict the impact of the load changes on the remaining life. Figure 10 shows the impact of over firing on the Row 2 bucket as a function of the original life and % over fire. The integral of this curve could be taken to estimate the remaining life in the bucket and then be used to optimize load vs. economics.

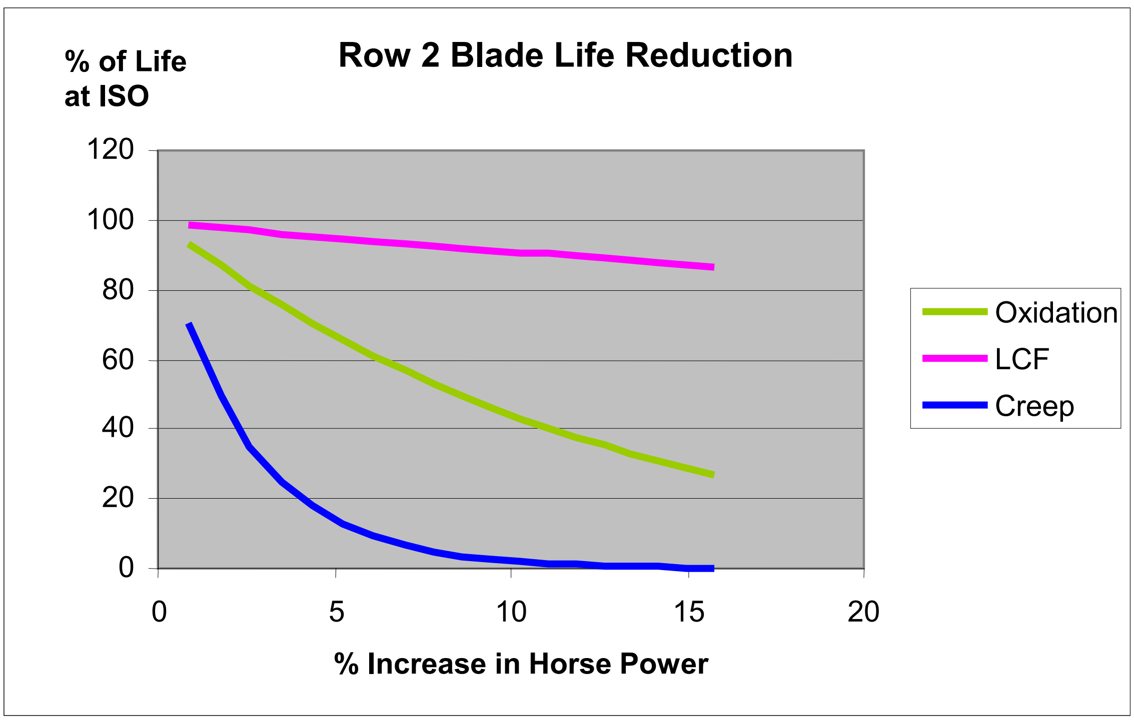

FIGURE 10. Life reduction due to over-firing.

CONCLUSIONS

By combining the strengths of mechanical, metallurgical and performance engineering, a systems approach to operations and maintenance can be implemented to manage gas turbines hot section components. A systems approach will move towards condition based maintenance and refine the equivalent hours approach. The net objective of reduced maintenance costs, extended time between overhauls and load optimization would be achieved using a systems approach to O&M.

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