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AN APPROACH FOR GAS TURBINE LIFE EXTENSION

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- Predictive maintenance
- Cost saving
- Lifing methods
- Flexible operation
- Creep
- GT26

EXECUTIVE SUMMARY

Market and legislative demands have forced gas turbine owners to operate their equipment flexibly, resulting in increased cycling, faster ramp rates and peak-firing. Often these turbines were designed for base loading and creep dominated failures, but are now subject to increased thermal stresses, severely impacting component life. The accurate evaluation of creep and low cycle fatigue requires detailed material properties and an exact model of temperatures, pressures, mass flow and stress for each component. This information is often only available to the OEM. The operator is therefore left with the OEM's calculation of equivalent operating hours, which represents a simplistic method of lifing, and is normally conservative in its predictions particularly in relation to creep. This paper describes an alternative method for creep damage calculation that sits between the established Equivalent Hours calculation and that of the detailed, in-depth, assessment using complex material models and detailed component level analysis. There is no doubt that turbines that operate flexibly will generally have shorter operational lives, however if some of the conservatism can be removed their operational lives can be extended and the potential cost saving is considerable as the case study presented here demonstrates.

The design of a gas turbine includes conservative assumptions both about how they operate and about the material's response to the duty they are exposed to. Removing conservatism and accounting for 'real' operation provides the opportunity to understand opportunities to increase the predicted life of the gas turbine, which tends to be limited by hot gas path (HGP) components. These HGP components are high integrity which presents challenges to determining their condition. Nevertheless, a better understanding of these components can yield improvements in the remaining useful life, or extensions to the inspection and overhaul intervals of the turbines. In the approach described in this paper, we have addressed two key areas of conservatism:

1) Improved material degradation models.
2) The use the more realistic material models in concert with the actual operating histories.

Improved material models: using the basis of design provided by the OEMs it is possible to identify the Equivalent Operating Hour (EOH) degradation models used for lifing gas turbines. Standard EOH degradation models tend to assume a simplified relationship between metal temperature and damage, especially at reduced loads. By supplementing the EOH degradation models with non-linear creep laws, it is possible to take advantage of the physical relationship between damage and metal temperature.

Use of operating conditions: GTs typically operate in a less onerous state than the design conditions for most of their lives. Operators are able to access the operational data and so it is possible to leverage this measured data and the design information provided by the OEMs, to assess opportunities to increase remaining useful life by

capitalising on potentially lower damage rates that accrue during off-design power operation.

In this paper we provide a practical application of our lifing approach to a GT26 gas turbine. We demonstrate how our lifing approach allows us to:

- Provide a more accurate understanding of damage in HGP components.
- Undertake 'what-if' analysis to understand how a change in operation may affect remaining life.
- Understand risk of continued operation to optimise outage planning and predictive maintenance.

BACKGROUND AND BUSINESS NEED

The gas turbine we considered in this example was part of a 1+1 420MW Combined Cycle generating facility commissioned in the early 2000's. Initially the power plant was used for base loading but in more recent times it usage has diverged to load following mode as a consequence of changing market conditions. The GT26 Turbine is a good subject for this study due to its relative high complexity having 2 stages of combustion, meaning that simplistic lifing approaches will potentially include significant conservatism to account for increased operational variability [1].

A 'C' inspection, which is required by the OEM's equivalent hours calculations and lifing strategy, can incur significant costs both in inspection but also due to lost availability, which can be significant during a high profit period. In many cases it is therefore beneficial to look for justification to extend the inspection intervals, even if this is for a relatively short period. Two avenues exist, the first relates to when the owner is not tied into an LTSA with an OEM and is willing to take the risk of these decisions themselves. The second is when the owner wishes to engage with the LSTA provider, where an evidence-based decision can be mutually negotiated. In all circumstances, decisions based on cost and risk need to be explored with credible information to base them on.

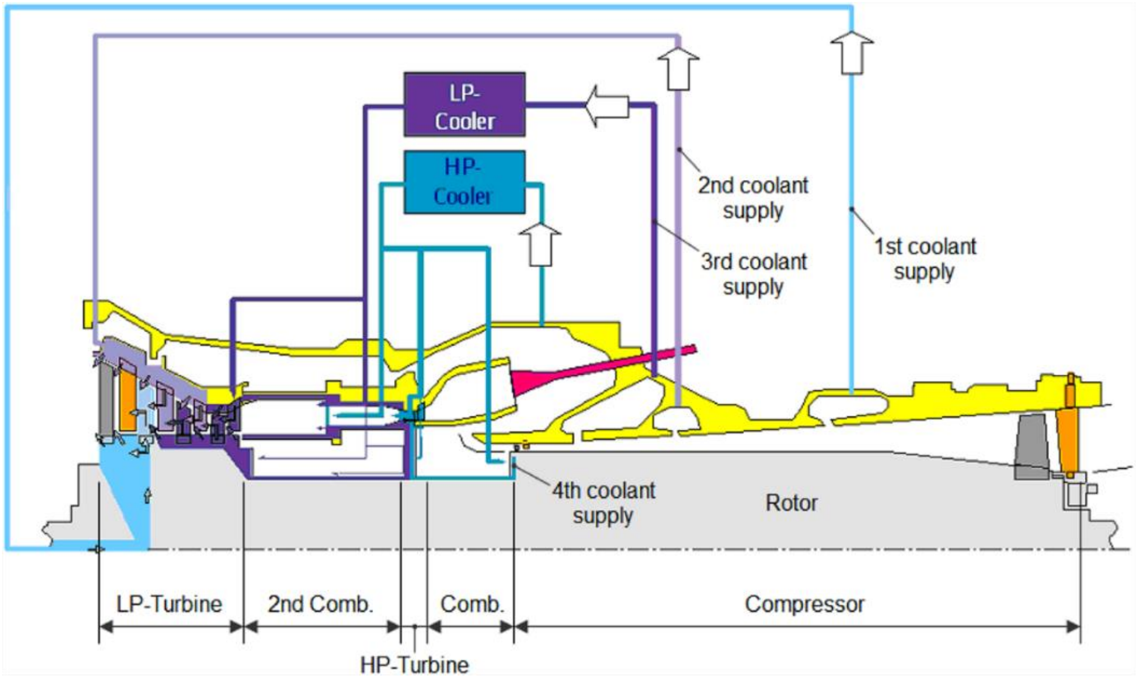

Figure 1: An illustration of the cooling flow paths within the GT26 (Referenced from source: M. Henze, L. Bogdanic, K. Muehlbauer and M. Schnieder, Effect of the Biot Number on Metal Temperature of Thermal-Barrier-Coated Turbine Parts—Real Engine Measurements [2])

WHAT WAS DONE?

The approach that Frazer-Nash took to compare the OEM style inspection interval policy with alternative, and potentially more accurate and less conservative approach for a typical high pressure (HP) blade, are presented below.

1. A review of the OEM's EOH inspection interval policy, the example presented here is the methodology outlined in GE's publicly available document GER3620 [3]

GT outages are typically scheduled based on Equivalent Operating Hours (EOH), which are a function of:

- Number of starts
- Type of start (hot, warm, cold)
- Operating hours
- Fuel (natural gas, fuel oil)
- Load
- Type of trip

EOH is an indicator of the damage accumulated and is designed to ensure that inspections, overhauls and parts replacements are undertaken prior to any component failure. There are numerous approaches to calculating EOH, varying by OEM and turbine, and the calculations are intended as an indicator and are conservative in nature with safety factors incorporated. A more detailed analysis (i.e. using FEA, CFD, fracture mechanics) can show that the turbines are safe to operate, but this can be expensive, time consuming and often requires data that will only be available to the OEM, or obtained through invasive inspections and materials testing.

2. Calculate the EOH based on the OEM methods

To establish a baseline Equation 1 was used, which is formulated for the turbine from methods described in the OEM's maintenance manuals, normally provided with the turbine's documentation pack and any technical advisories [3].

The recommended inspection intervals for the hot gas path components are presented in Table 1, where the EOH was calculated using methods consistent with Equation 1. The equation is calculated continuously and integrated over the observed operating duty, and totals are accrued dynamically.

Equation 1:

$$[3]\ EOH = \sqrt{(V \times S)^2 + (A \times OH)^2}$$

Where:
EOH = Equivalent operating Hours
OH = Operating hours
S = Number of starts
V, X, W, A = Penalty Factors (These include fuel, starts weighting and operating hours)

The hours factors which account for any credit in creep life due to part load operation, can be calculated using Equations 2 to 5 from references such as GER 3620P [3].

Equation 2:

$$Maintenane\ Interval = \frac{Baseline\ HGP}{Maintenence\ Fctor}$$

Equation 3:

$$Maintenance\ Factor = \frac{Factored\ Hours}{Actual\ Hours}$$

Equation 4:

$$Factored\ Hours = \sum_{i=1}^{n} (S_i \times Af_i \times Ap_i \times t_i)$$

Equation 5:

$$Actual\ Hours = \sum_{i=1}^{n} (t_i)$$

Where:
I = Number of discrete operating modes
t_i = Fired hours in each operating mode
Ap_i = Load Severity Factor (base / peak load)
Af_i = Fuel Severity Factor (natural gas
S_i = Water / Steam Injection Severity Factor

As an example for this case study, data is presented in Table 2, where the EOH accrued was 3,173h, meaning a consumed life of 77.3% of the operated hours were accrued since the last 'C' (24,000 EOH) inspection, based on the OEM EOH calculation.

Table 1: Baseline Recommended Inspection Intervals for a GT26 [3]

Type	**Interval (EOH)**	**Description**
‘A’ inspection	6,000	Remote visual inspection of the hot gas path components (no engine disassembly)
‘B’ inspection	12,000	As ‘A’ inspection, with additional checks of control systems, protection systems and auxiliaries (no engine disassembly)
‘A’ inspection	18,000	Remote visual inspection of the hot gas path components (no engine disassembly)
‘C’ inspection	24,000	Disassembly of the turbine for detailed condition assessment of the rotor and hot gas path components

Table 2: Case study EOH example

	Operation	**Number of Hours**	**Equivalent Hours Accrued**
Case Study Example	Part Load $TIT_{\_LP1}<1280°C$	3,732	2,799
	Base Load $TIT_{\_LP1}\geq 1280°C$	373	373
	Total	**4,107**	**3,173**

3. Define an improved creep law enhanced EOH approach

To assess HGP components more accurately an alternative component life assessment method was developed, based on an established physics-based creep model. The calculation methodology adopts a normalised approach, providing the benefit that knowledge of absolute temperatures and stresses were not required as an input. This approach represents the physical response of the material in that a temperature change about a nominal metal temperature results in damage accumulating at a slower (or faster) rate.

The standard GT26 EOH calculation method applies the damage adjustment for part load operation in discrete manner. For operating periods where TIT is lower than 1,280°C, some credit is given within the OEM's EOH model – a factor of 0.75 on accrued hours is applied when operating at reduced temperature. However, we postulate that additional credit should be given for firing temperatures significantly lower than the temperature threshold where the 0.75 factor applies.

By acknowledging damage is consistent with a non-linear creep law, a modification to the EOH method can be achieved. Operational time history data is grouped into small (say, 2.5°C) temperature “bins”, and a normalised creep damage calculation is performed for each bin using a Larson-Miller Parameter (LMP) approach. Where the LMP is equivalent to the time to rupture at a given temperature. This method allows application of an additional knockdown factor to the EOH corresponding to a creep law to each temperature bin when operating at any load point. Therefore, it is possible to compare and calibrate the time-integrated damage against a the operating mode reflecting the design point using the OEM’s EOH method, where the turbine operates at continuous base load temperatures for the same duration.

This approach also applies a factor greater than ‘1.0’ for operating conditions where high temperatures are experienced by following the same creep law for when the gas temperature exceeds the nominal base load temperature. However, as in the case of the GT26 which normally does not experience these peak firing temperatures, this does not contribute a significant penalty fraction. Conversely, GTs such as a GE Frame 6 or Frame 9 routinely experience peak firing, and the OEM's EOH calculation is already very consistent with a LMP model above this temperature threshold. However, no credit is given for time at low firing temperatures.

Examples of several rupture life test for HGP GT26 superalloy materials in investment cast, directionally solidified and single crystal conditions are presented in Figure 2.

These materials are representative of those used in the HGP of the GT26 turbine. It can be seen that creep and rupture performance are material specific and dependant on material microstructure and cast condition, meaning the creep informed approach described above requires material specific LMP curves and data.

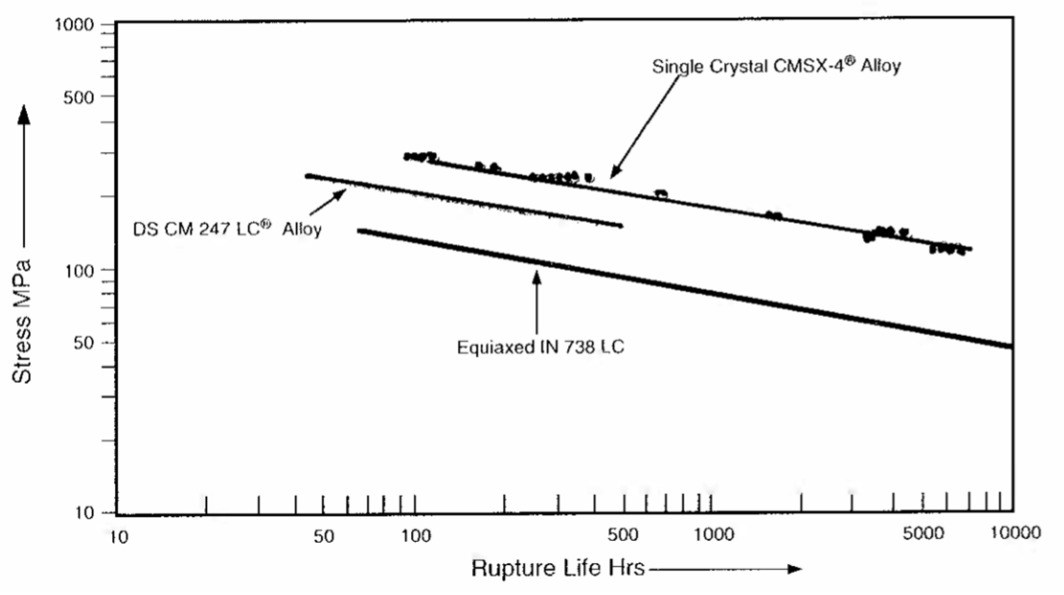

Figure 2: Comparison of stress-rupture performance of three materials used in the HGP of a GT26, CMSX-4, DS CM 247 LC and IN 738 LC (Original Source: G. L. Erickson, Advancements in Turbine Blading Materials fo IGT Applications - Cannon-Muskegon Corporation [4])

4. Determine the indicative available credit

Many HGP components, particularly those in Open Cycle (OCGT) configuration are exposed to higher temperatures when unit load is increased and lower temperatures when load is reduced. However, for gas turbines in CCGT operation, part load can correspond to elevated temperatures. This is presented in the example given in Figure 3. Understanding this relationship is fundamental to predicting temperature at different unit loads, and subsequently accumulated damage. The OEM EOH calculation is underpinned by the operation concept, this defines the relationship between load and temperature. Particular care should therefore be taken when appraising a Combined Cycle Gas Turbine (CCGT) or a unit for process steam cogeneration, because of operating modes where closure of the inlet guide vanes, and reduction in compressor mass flow enables lower shaft power, but sustained high exhaust temperatures for balancing steam production.

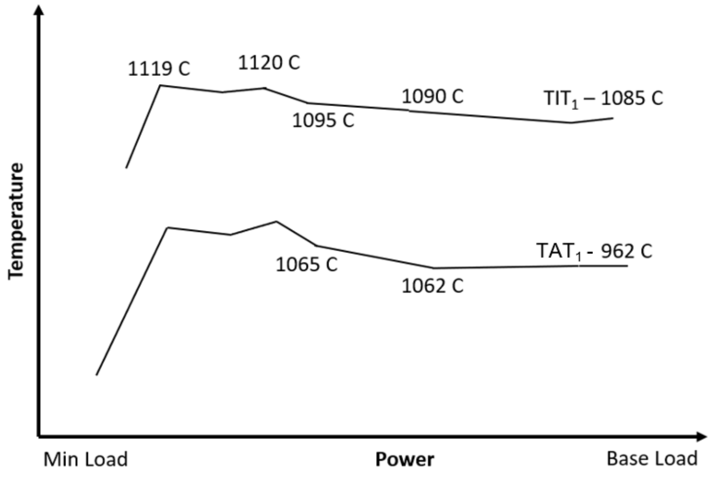

Figure 3: Example of operating concept

COMPARISON OF OEM EOH APPROACH TO CREEP EOH APPROACH

Two representative examples of a low pressure HGP component and a High pressure HGP component for the same period have been presented below in Figure 4 and Figure 5 respectively. In both cases the normalised creep model (blue curve) offers significantly greater EOH knock down factors (red curve) up until the blue creep model line crosses the red OEM EOH method line – the point representing 100% base load operation.

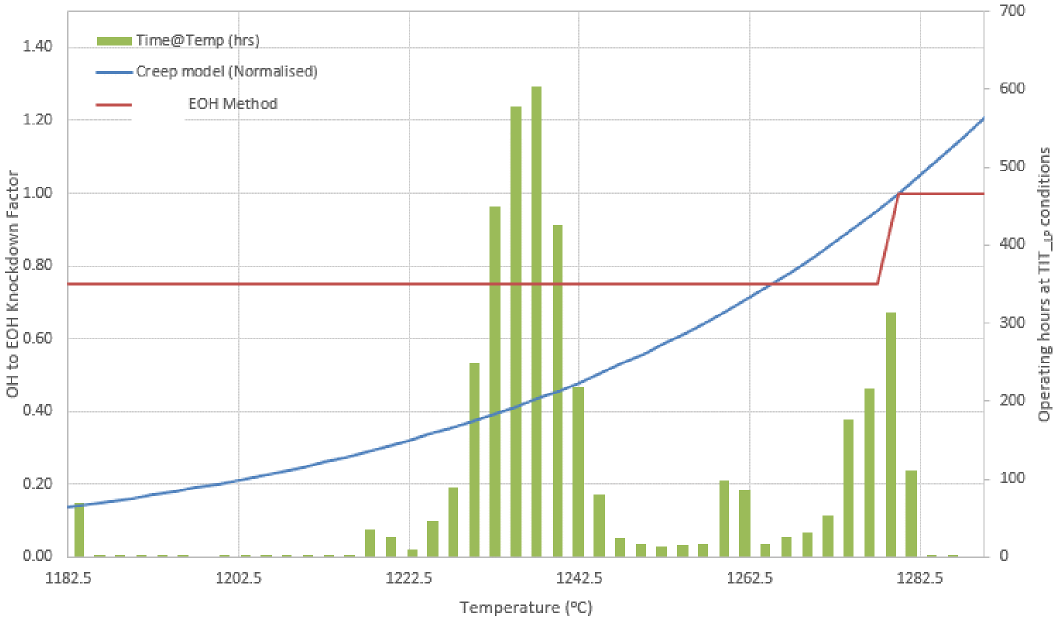

Figure 4: Low pressure HGP component knock down factor comparison

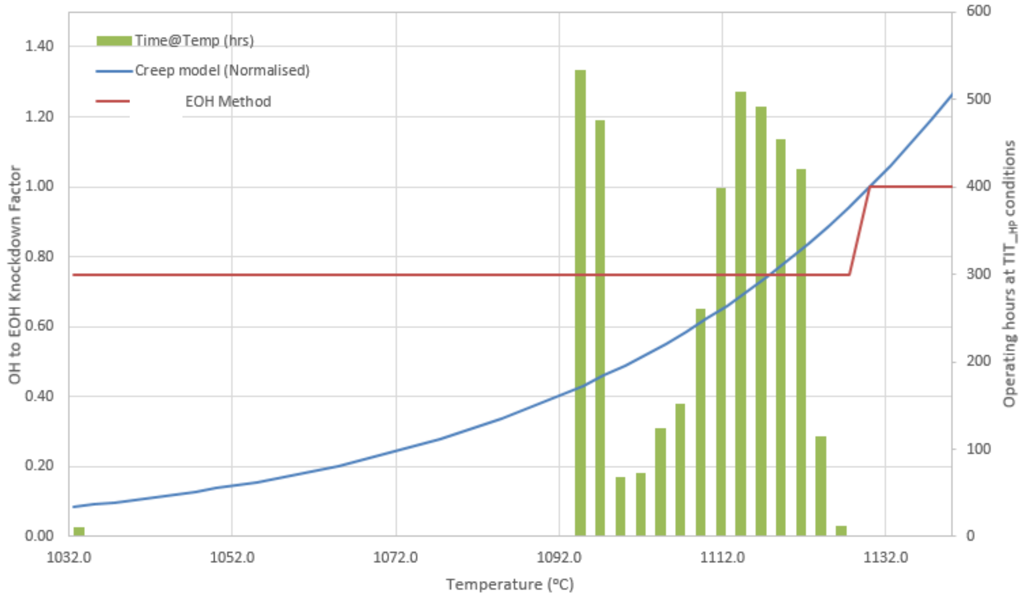

Figure 5: High pressure HGP component knock down factor comparison

It was observed that the updated creep law informed EOH method presented in this paper predicts that time dependant damage is accruing at a slower rate than the OEM EOH informed equation predicts when operated in specific part-load configurations. This is true for most of the operational conditions, except for very high temperatures where the OEM method can be less conservative. However, to predict the potential extension to the inspection intervals, an additional calculation must be made based on the time-based fraction of the EOH, such that the influence of cyclic events is included.

Based on a life limiting component in the machine (in this case, the HP blades), and using a typical operating history, this calculation determined that the HP Blades might be capable of approximately 29,500 EOH, or an extension of approximately 23% on the OEM 'C' Inspection interval – for the specific operating history experienced by the GT being assessed.

CONCLUSIONS

By appraising the operating history with an EOH model derived from creep laws, it was possible to identify an opportunity for an extension of the prescribed inspection interval by approximately 23%, in the example case presented here. This potential for inspection extension in is limited by the component with the lowest enhanced EOH, which will vary depending on how the turbine is operated.

This method is applicable to any type of gas turbine, whether it is a part-load CCGT operation or peak firing OCGT provided sufficient operational and design information is available.

Operators seeking to extend Turbine Inspection Intervals should consider:

- The consequences of OEM updates to the underlying assumptions of EOH calculations.
- The impact on subsequent inspection intervals.
- The relationship with the OEM and whether owners are willing to accept the risk of life extension beyond OEM guidelines.

The OEM EOH method applies credit for part load operation, however it is limited for the following reasons:

- At part load operation, the $TIT_{\_HP}$ temperature increases significantly and potentially increases the rate of damage accumulation, which is not necessarily reflected in the standard EOH calculation.
- The OEM's weight factor assigned to different load operations can be coarse, and does not necessarily follow any physical damage laws, this often leads to conservative damage predictions.

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