ETN Global

ROTOR LIFETIME ASSESSMENTS: A Reference Report

March 2024

Table of Contents

List of abbreviations

CHP	Combined Heat and Power
CMM	Coordinate Measuring Machine
DTR	Design Target Rate
FEM	Finite Element Method
EOH	Equivalent Operating Hours
EOS	Equivalent Operating Starts
GT	Gas Turbine
HCF	High Cycle Fatigue
LLP	Life Limiting Parts
LCF	Low Cycle Fatigue
LTA	Life Time Assessment
LTE	Life Time Extension
MPI	Magnetic Particle Inspection
NDE	Non-Destructive Examination
NZE	Net Zero Emission
O&G	Oil and Gas
OEM	Original Equipment Manufacturer
POD	Probability Of Detection
TMF	Thermo-Mechanical Fatigue
TYNDP	Ten Year Network Development Plan

Aknowledgements

The "Rotor Lifetime Assessment: A Reference Report" has been issued by the Energy & Turbomachinery Network (ETN Global), as part of the activities of the ETN Gas Turbines Life Assessment and Extension Working Group. The report was directed by Siavash Pahlavanyali (Principal Turbine Metallurgist, RINA Tech UK) with the support of the ETN secretariat.

The knowledge and expertise of the ETN members who contributed to this report added significant value to the publication. We would like to thank especially the main contributors: Siavash Pahlavanyali (Principal Turbine Metallurgist, RINA Tech UK), Rene Vijgen (Senior Technical Manager, ETN Global), Luc Gooren (Cluster Manager Mechanical & Thermal Processes, Engie), Annalisa Maragno (Mechanical Engineer, EthosEnergy), Antoine Mochel (Expert Metallic Materials, Engie), Agnes Jocher (Assistant Professor, Technische Universitat Munchen), Stefan Reh (Founding Director of Institute of Test and Simulation for Gas Turbines, DLR), Christian Amann (Probabilistic Design Engineer, Siemens Energy), Dirk Kulawinski (Development Expert and Project Manager, Siemens Energy), Torsten Neddemeyer (Research and Development Engineer, Siemens Energy), Philipp Engels (Siemens Energy), Dipankar Dua (Principal Engineer, Siemens Energy), and Kai Kadau (Senior Expert Probabilistics and Life Methods, Siemens Energy), Joy Sumner (Head of Centre for Energy Engineering, Cranfield University), Mauro Filippini (Associate Professor, Politecnico di Milano), and Andrew Moffat (Group Manager, Solar Turbines). Contributions to this document were provided by the organisations listed below.

Introduction

This paper summarizes the state of the art of gas turbine rotor lifetime assessment and potential service extension. It was initiated by the ETN gas turbine users that noted the need for extension of these assets in the given technical environment.

The end of the life of an asset is based on its dimension, load, material response and operation. In case of a complex part such as a gas turbine, life limiting parts (LLP) are identified per subgroup and might be exchanged during a planned overhaul. This practice is quite developed within the industry for parts such as compressor and hot section blades and vanes. For rotors this way of working is only established within the aero industry. For land-based engines, exchange programs are still not well developed and require a case-by-case solution. Such an approach can lead to long overhaul periods and reduced availability, if not planned well in advance by the users.

The first part of the report focuses on rotor life definition, discusses the major degradation mechanisms and tries to link them with the OEM (Original Equipment Manufacturer) recommendations. Based on the electricity demand projections and the life of the installed fleet, it will be demonstrated that lifetime extension of the current fleet is needed to secure energy generation. The purpose of this paper is not to describe in details damage mechanisms, but rather to provide information on the general approach of rotor life assessment and extension.

The second part describes the lifetime assessment process in more detail. This paper is referring to the end of the usability of the rotor for service life extension. Essential elements such as data collection (e.g., operational, geometries), numerical simulations, probabilistic risk analyses and measures to reduce potential risks such as dedicated inspections will be discussed. This chapter provides the information on which the current lifetime of rotors and potential extension are based.

The third part of the paper will describe existing flight engine procedures for life limiting parts. It will focus on advisory circulars that define the damage tolerances of flight rotors, risk management and inspection methods and the lifetime extension potential of such parts. Through analogy with land-based engines, learnings were identified from this sector.

Finally, an action plan is discussed, addressing how to build on a procedure that defines the scope to extend rotor life. As a result of that, actions to overcome the gaps identified in the current practices are defined.

1. A definition of the life of rotors (from OEMs), the aging of the GT population, and changing operational conditions: market needs

In this chapter, the considerations that are taken into account by the various manufactures during the end of life/ life-time extension assessment are discussed.

Potential Consequences of Failure

Failure incidents can give rise to various issues for the end user, with escalating severity as outlined below:

- **Forced shutdown and immediate restart**: this entails a short-term unavailability of the system and accelerated degradation of hot parts due to increased starts and stops;
- **Restricted operation**: e.g., power loss and rise in operating costs;
- **Contained failure**: resulting in extended unavailability, unpredictable repair costs, prolonged lead time, and the need for unplanned maintenance;
- **Uncontained failure**: such as wheel burst: in addition to health and safety risks (sometimes extending beyond the boundaries of the gas turbine plant), uncontained failures lead to extreme unavailability and significant additional costs.

Rotor life and need for extension

The life of rotor components depends on the damage mechanism that deteriorates the functionality of subject components. The OEMs differentiate between hours-related and starts-related damage. *Figure 1* gives a schematic overview of the leading life limiting mechanisms. The horizontal axis represents the accumulated operational hours and the vertical axis the number of operational starts/stops. Oxidation and creep damage are driven by the temperature and accumulated hours, while cyclic operation (number of starts/load changes) has a large impact on fatigue life.

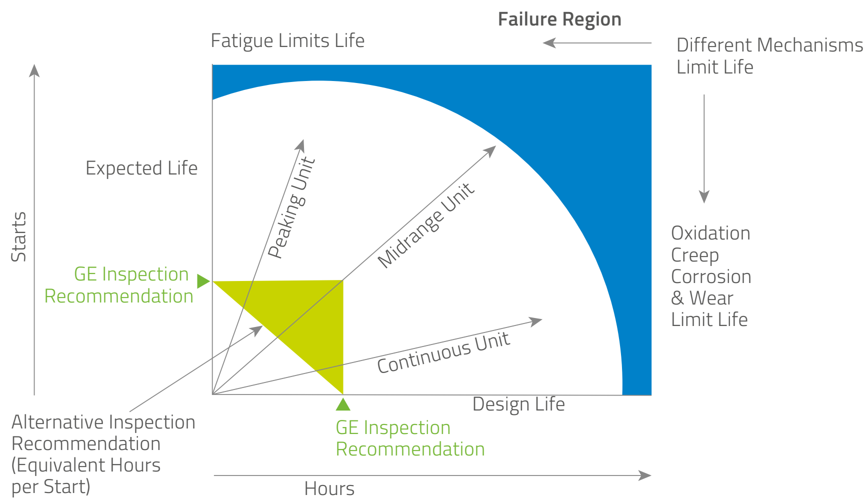


Figure 1: OEM's maintenance and life expectancy requirements based on number of starts and hours [1].

The blue area highlights operational conditions under which a component might fail, resulting in severe damage, both to the component and any interconnected systems. To avoid such an occurrence, a dedicated inspection regime is required upon reaching a particular number of starts/stops, operational hours or a combination of both (Equivalent Operating Hours, EOH). Evidently this should be planned in accordance with OEM operational and maintenance recommendations.

How to deal with interactions between creep and fatigue related damage/life is described in various guidelines such as ASME and EN norms and represented in a creep-fatigue interaction diagram *(Figure 2)*. It shows the consumed creep life fraction on the vertical axis and the fatigue fraction on the horizontal axis. EN 12952 calls for a linear correlation which will only require standard S-N Wohler curves and creep rupture testing. Other norms show a decrease in both creep and fatigue related remaining lifetime. It should be noted, however, that none of these guidelines describe the interactions here listed.

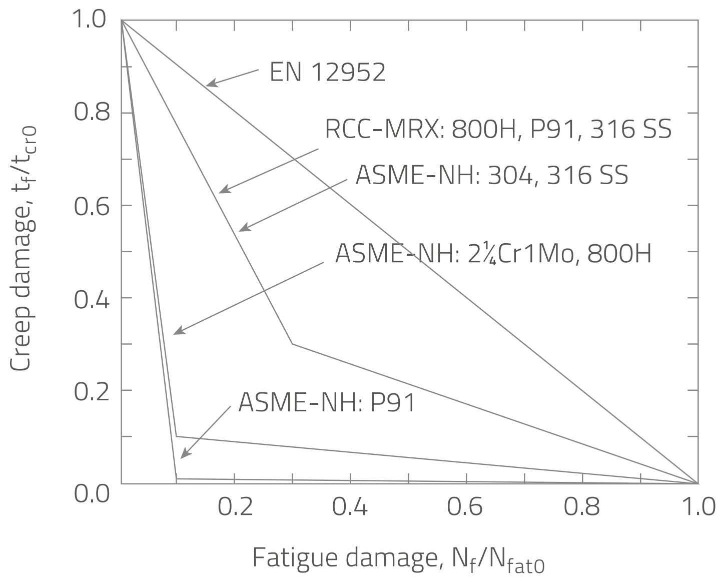


Figure 2: Creep-fatigue interaction diagram, showing the various standards for several materials. [2]

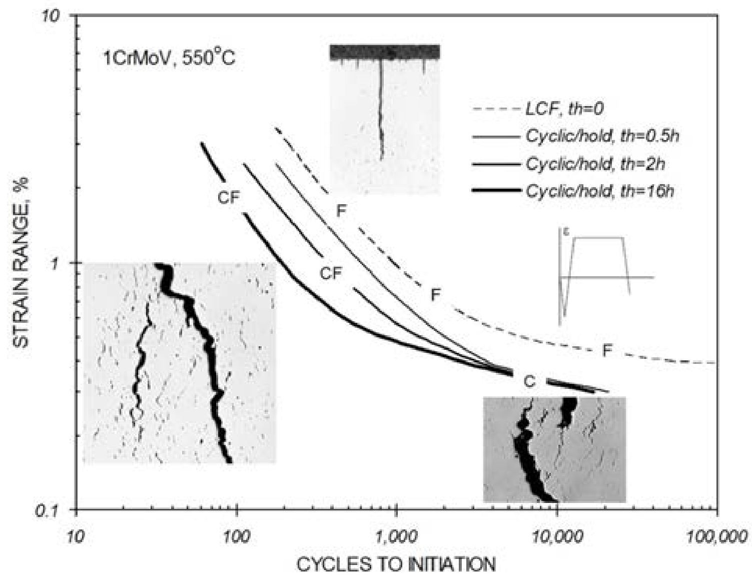


Figure 3: Influence of hold time on the cyclic/hold creep fatigue endurance of 1CrMoV steel at 550 °C.
The leading mechanisms are: creep (C), pure fatigue (F) or creep fatigue (CF). LCF = Low Cycle Fatigue [3].

The time to the initiation of a crack depends on the stress (or strain) range, the temperature, and operational conditions such as operating hours, number of cycles and environment. *Figure 3* shows a rotor steel, 1CrMoV, subjected to cycling at various strain levels (vertical axis) and hold time (th). For pure low cycle fatigue (F, th=0), initiation occurs above a minimum strain level (0,4%). For higher strains, the number of cycles required to initiate a crack decreases. By increasing the hold time, additional creep damage will be introduced resulting in fewer cycles being required for failure to occur (CF). In cases of lower strains and higher hold times, creep is the more likely damage mechanism (C).

After crack initiation, crack propagation will occur until the crack becomes critical and component rupture might occur. *Figure 4* shows the crack growth rate (da/dn) versus the cyclic strain range (de) for fatigue tests and different holding times in 1CrMoV.

Typical values for the crack growth rates range from $1x10^{-3}$ up to $1x10^{-2}$ mm/cycle, depending on the strain range and the hold time. Crack growth rate for high hold times is up to 10 times larger than for pure LCF. This implies that cracks induced through creep and fatigue have a high risk of becoming critical during continued operation. Locations that are subjected to such conditions may need to be exchanged or thoroughly inspected.

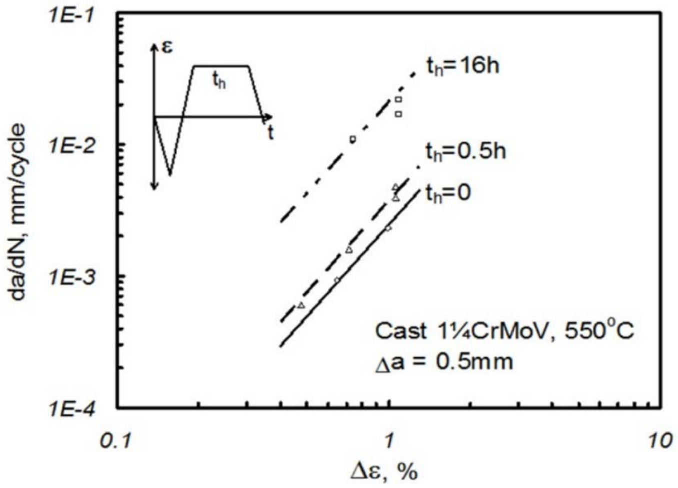


Figure 4: Crack growth rate for 1CrMoV steel at 550 C with an initial crack of 0.5 mm, subjected to cyclic strain and hold time, t_h. [4]

Depending on the gas turbine configuration, with the assumption the rotor reaches end of design life, the rotor inspection interval is foreseen between 3000-7000 start/stops or 100,000-200,000 operational hours, whatever occurs first. Penalty factors are provided for several operational conditions such as emergency stops, different fuels, loads and water injection. In case the relevant inspection interval is reached, a lifetime assessment program may be executed. The condition of the rotor parts is assessed through dedicated inspections, data- and engineering analyses followed by a risk assessment (see Chapter 2). As a result, some components might extend service life while others have to be repaired or replaced. Depending on the analyses, life extension is provided for a limited numbers of hours or start stops.

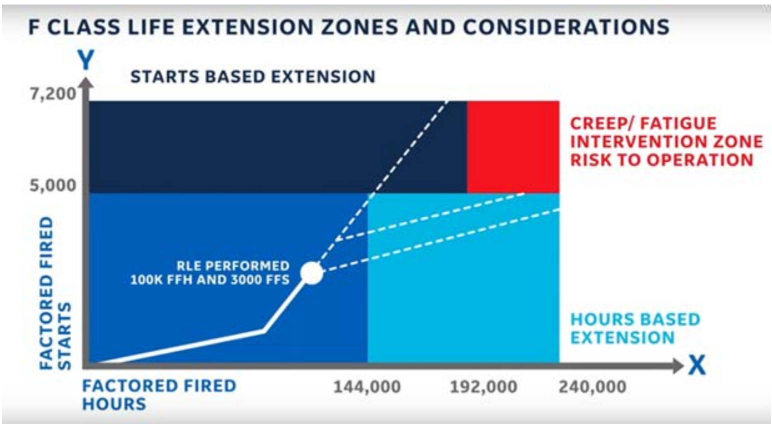


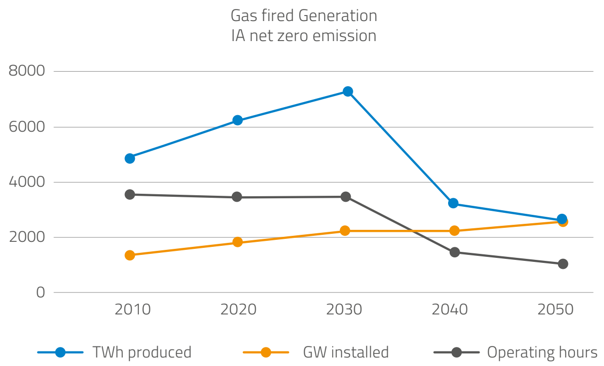
Figure 5: Schematic representation of a starts hours diagram of an F class rotor life extension [5].

Figure 5 shows a typical example of such a lifetime extension. Within an operational window of 5000 starts and 144,000 fired hours, no rotor inspection is scheduled. Outside the window, an hours- or starts-based extension is required. For high starts and long life, interaction between creep and fatigue could lead to increased risk as indicated in the red area and explained in *Figure 5*.

A replacement based on inspection results is difficult to manage for the gas turbine users since lead times of some parts could be extremely long and costs undefined. Several commercial solutions are available to resolve this issue. This could range from predefined component replacements to full refurbished or new rotor sections. Evidently, previous to the rotor overhaul, a well-defined and transparent scope is required. Depending on the engineering and risk analyses, replacement part must be available or mitigation measures defined to minimise the overhaul lead time as much as possible.

Need for rotor life extension

Gas turbines play an essential role in electricity supply. *Figure 6a* shows an IEA projection of the NZE (Net Zero Emission) scenario [6], showing worldwide gas fired capacity, energy generated and operating hours in the power sector. Evidently the need for base load is changing to a two shifting operation and finally resulting in a peaking unit. For Europe this change in operational mode is less pronounced. In the Ten Year Network Development Plan 2022 (TYNDP) [7], gas turbine capacity and produced energy remains stable and operating hours remain around 2000 hours/plant on average, so calling for a two shift duty cycle *(Figure 6b)*.



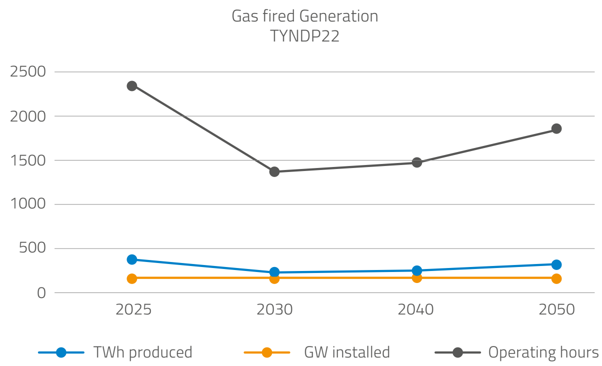


Figure 6: Gas fired generation worldwide (graphic at the left) and EU27 (graphic at the right)

Based on the current or conventional operational regime, gas turbine rotors are generally inspected between 3000-7000 starts or 100.000-200.000 hours intervals. However, in case of a two shift operation, rotors are subjected to between 300 and 600 cycles annually, resulting in an inspection interval of approximately 10 years. This interval is shorter than the creep-related hourly based scenario (>50 years, based on a need of 2000 operating hours p.a.). Based on these simple analyses, cyclic related damages, such as low cycle fatigue, fretting of fir trees and transient behaviour become the relevant life limiting factors in the electrical utility sector. For base load applications, such as in industry (e.g., combined heat and power and oil and gas), creep related damages remain the leading cause for concern.

What does that mean for the installed base in the electrical utility sector? *Figure 7* gives an indication about worldwide installed capacity in operation. This is approximately 2000 GW, of which the majority was installed between 2000 and 2020. An additional 500 GW is projected between 2020 and 2050.

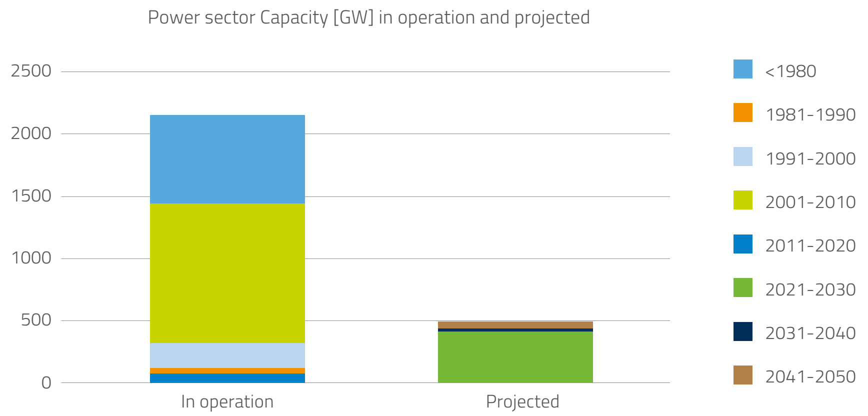


Figure 7: Worldwide estimated installed and projected gas turbine capacity (in GW) in the power sector [7]

In order to get an understanding of aging of the current gas turbine fleet due to cyclic operation, an average number of cycles per year is required. Unfortunately, there is hardly any cyclic operational data available in literature. Energy Brainpool reports an average numbers between 40 and 80 cycles per annum (in 2015) for large frames in the Power sector [8]. Due to an increasing feed-in of variable renewable energy, especially solar power, the number of cycles will increase significantly. Depending on the height of the necessary dispatchable load Energy Brainpool reports in their simulation more than 700 cycles per year.

In our assessment, the following operational assumptions are taken into account *(Table 1)*:

	Cycles per annum	Period of operation
Base load	40	1980-2020
Two-shift	400	2020-2040
Peaking	800	2040-2050

Table 1: Start/stop assumptions for the several operational regimes and date of installation

For gas turbines installed before 2020 a base load operation is taken into account with an annual of 40 start/stops. For engines in operation between 2020 and 2040, dual shift operation is considered, with 400 start/stops per annum. After 2040, it is considered that turbines will run a peaking regime with 800 start/stops per annum [9].

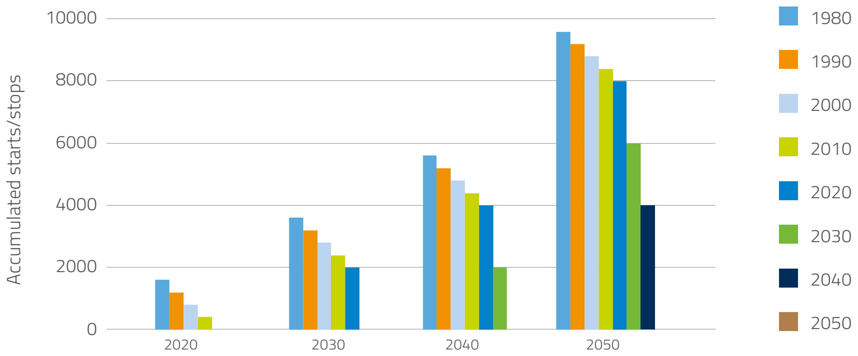


Figure 8: Accumulated number of cycles for a given period of installation.

Figure 8 gives an overview of the total cycles accumulated over time for GTs from a given period of installation, taking the operational assumptions (*Table 1*) into account.

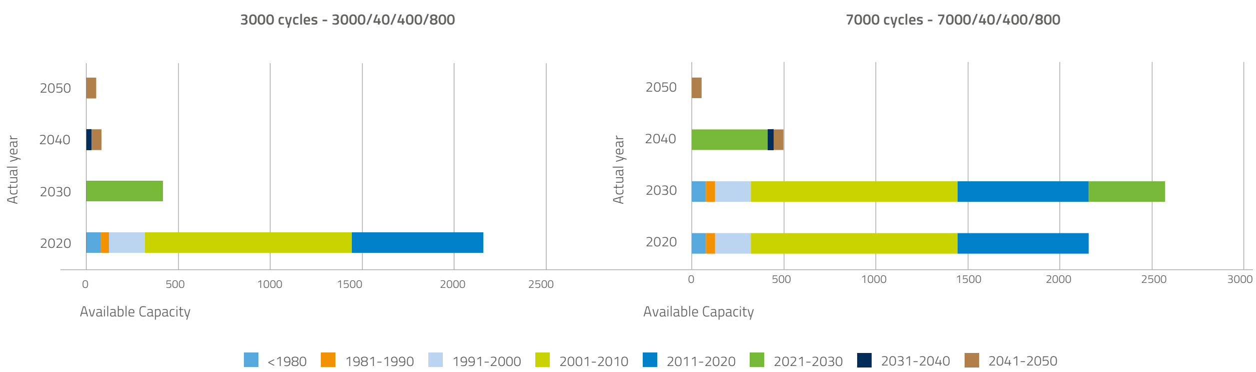


Figure 9: Available global GT capacity for a rotor life of 3000 cycles and 7000 cycles

Figure 9 shows the consequence for the installed and projected gas turbine base in the power sector in cases where the rotor is limited to 3000 cycles (a) or 7000 cycles (b). For the 3000 cycle case, by already 2030, there is not enough installed capacity to secure global electricity demand. For the 7000 cycles, this issue occurs in 2040.

Although simplified, these assumptions show the technical need for rotor lifetime extension. Obviously, economics support this thinking.

The second part of this paper will provide more technical details of rotor lifetime extension programs.

2. Description of the current LTA processes (simulation, condition assessment, risk assessment) and the commercially available solutions

LTA Program

The aim of the Lifetime Assessment (LTA) program is to evaluate the condition of rotors after service, and, when combined with the Life Time Extension (LTE) program, to prolong their operational lifespan. This initiative stems from the realization that risks associated with aging, including forced outages, increase exponentially when rotor components are operated beyond their design life. LTA program allows the identification of factors that limit the rotor life, providing service solutions to eliminate or mitigate associated risks. This can involve the replacement of life-limiting rotor components with newly designed and manufactured alternatives [10]. By adopting the LTA/LTE approach, end users can avoid the costly replacement of the entire rotors and instead, economically and securely, operate aging assets well beyond the initially recommended design life of the rotor.

Limiting Factors

Rotor life is limited, which is why they are subjected to a maintenance program; this includes removal, disassembly and thorough inspection. Numerous factors can contribute to a limited lifespan of the rotor. In order to highlight the most consequential ones, it is crucial to address the high levels of stress and temperature endured by the rotor, which sometimes may be higher than the material's allowable stress, as well as the cumulative effects of time and start/shutdown cycles. These factors significantly impact rotor components creep life and their cyclic fatigue resistance in terms of low and high cycle fatigue (LCF, HCF). Consequently, a comprehensive Lifetime Assessment analysis becomes useful to ascertain whether the rotor design fulfills the designed requirements for Equivalent Operating Hours (EOH) and Equivalent Operating Starts (EOS).

Main phases of LTA Program

The program can be summarized in three main phases.

PHASE 1: Rotor Component Design Analysis

With reference to operational regime and technology class, both OEMs and non-OEMs have Component Models and Mechanical Integrity (MI) models available with varying levels of detail (although not verified independently), to assess the stress and temperature distributions. These models can be and, in many cases, are already used to provide component life extensions to gas turbine users at the point of maintenance, typically as part of a maintenance service agreement.

However, the aim of this paper is to substantiate the knowledge for the owners and the operators, and assist them in well-defined decisions when extending the life of the critical assets such as gas turbine rotors.

Throughout the design analysis phase, it is recommended to rely on past design experiences and knowledge acquired from working cycles, service loads, design criteria, process data, and material databases since they can provide valuable insights.

The main steps of this phase are the following:

1. **Material characterization:**

    Gaining a comprehensive understanding of the chemical compositions, mechanical properties, and metallographic characteristics of all materials under analysis holds significant importance. In this instance, a highly valuable resource can be provided by a well-established material database, which has been strengthened through extensive testing endeavours and supplemented by observations of material performance over hundreds of thousands of operational hours. However, if the material in question is not included in the database, a thorough characterization campaign must be undertaken to acquire mechanical properties. This campaign should encompass various tests such as creep tests, low-cycle fatigue (LCF) tests, and high-cycle fatigue (HCF) tests.

    Careful consideration must be given to the influence of surface degradation resulting from corrosion. If corrosion coincides with other aging mechanisms like HCF, LCF and creep, adverse and non-linear interactions between the individual damage mechanisms are to be expected and the time to failure is expedited. In steels, microstructural changes and their effect on these material properties can be considered. Time-Temperature-Transformation (TTT) diagrams can help assess this if materials data are not available.

2. **Geometrical characterization:**

    This phase is indispensable to obtain a precise 3D model of the rotor. An example of a typical gas turbine part 3D model is shown in *Figure 10*.

    It is noteworthy that the geometrical characterization is often conducted on serviced components, but deformations arising from service are then typically excluded from the scanned model. To accomplish this, components of multiple rotors undergo scanning procedures, and the optimal fit is determined to establish the final geometry which is expected to be as similar as possible to the design one. These activities can be performed in conjunction with manual dimensional inspections to ensure comprehensive accuracy.

    However, when signs of damage like scratches and pits are eliminated from the component before reuse, it becomes crucial to integrate these geometric changes into the simulation and ensure that they do not lead to inappropriate behaviour of the part.

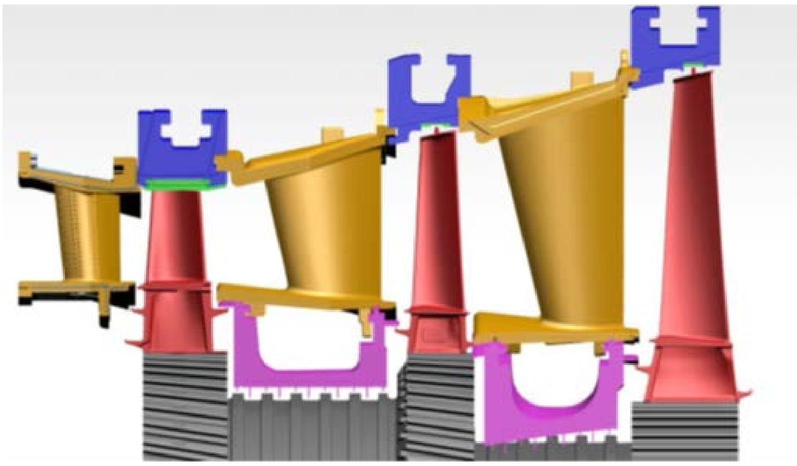


Figure 10: Turbine 3D modelling

3. **Main operational data and operating condition:**

This information is fundamental for the development of a predictive model. By acquiring gas turbine operational data, such as speed, temperature and pressure curves, it becomes feasible to assess the optimal boundary conditions for simulating the actual rotor behaviour. These insights are also obtained through direct experience gained from maintenance services.

4. **Predictive model creation:**

The collected data can be utilized to construct a predictive model, starting from a streamline analysis of the flow path to simulate temperature and pressure distribution across the stages and aerodynamic loads on the blades. This analysis is coupled with a secondary flow circuit analysis, which includes all the flows that take part to thermal distribution of the rotor, except for the main flow path (considered in the boundary conditions). Secondary flows are typically simulated [11] using one-dimensional elements representing labyrinth seals, cooling pipes etc. These elements are combined to form the flow network as illustrated in *Figure 11*. Solving the flow network, it's possible to obtain as outputs the air temperatures and pressures, heat fluxes and mass flow rates for each element.

These models can be also supported by a fluid dynamic analysis (CFD) for both compressor and turbine flow paths, in case the accuracy provided by the previous methodologies is regarded being not sufficient for the analysis of peculiar features (e.g. advanced stator / rotor blade cooling mechanism, blade tip and shroud block interaction, etc).

Subsequently, a thermo-structural Finite Element Method (FEM) analysis is conducted, employing the obtained values as thermal and mechanical boundary conditions. Axisymmetric models shall be preferred when computing stresses on rotating discs, to accomplish faster computational times. In case that the disc geometry is characterized by circumferential discontinuities (e.g. holes, blade slots, etc) numerical methods are available, for instance adjusting locally the base material property or alternatively considering the 2D body symmetry.

To have a more accurate model, able to predict the interactions between rotor and stator components, a portion of the casings can be included. This allows prediction of the mutual thermal expansions and clearances.

It is feasible to simulate both steady-state and transient conditions, with the latter providing a complete temporal perspective although leading to a higher computational cost. Alternatively, transient scaling factors can be identified and used to consider, in a steady-state analysis, the transient effects for LCF evaluations, with benefits in term of computational cost.

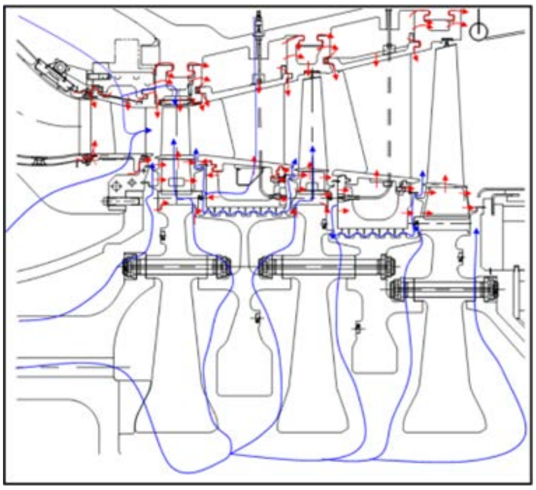


Figure 11: Predictive model of a cooling flow network

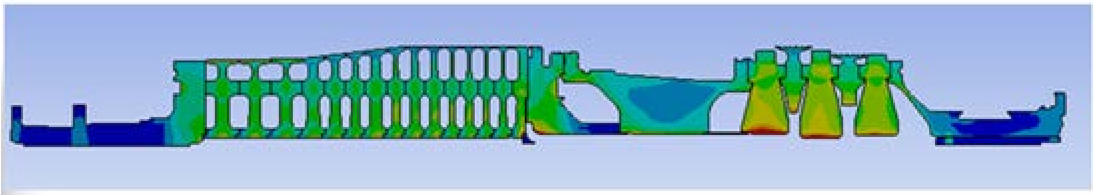


Figure 12: Predicted stress distribution

5. Determination of critical parts and critical areas

The outcomes of the thermo-structural analysis, in particular temperature and stress distribution, are employed to identify the critical sections of the rotor by comparing them with material design curves. This approach enables the determination of the most appropriate Non-Destructive Examination (NDE) technique and facilitates the assessment of the component's remaining lifespan. It is recommended to divide rotor geometry in several regions, in order to identify for each of them the points which can lead to the shortest LCF life and to quantify the rotor lifetime in terms of fatigue life and time driven failure mechanisms such as creep and oxidation. Furthermore, evaluations of rotor crack propagation should be conducted following the Damage Tolerance approach [12] if it is possible to tolerate a cracked item and if the crack propagation interval is so large to well include the period between two inspections. In the event that defects, critical areas or cracks longer than an acceptable limit are detected, the component may be deemed unsuitable. However, with the aid of the predictive model, potential repair solutions can be explored and proposed.

PHASE 2: Specific Unit Evaluation

This phase is dedicated to the customer unit-specific evaluation. It involves the collection of operational data history, such as operating hours, starts, operation modes, gas path temperatures, air, lubrication and fuel quality and usage. Consideration should further be given to notable events, maintenance data history, inspections and repairs – and any product-specific vulnerabilities.

Furthermore, the previously developed predictive model can be fine-tuned based on the specific operational data of the unit. During this phase, a plan for NDE is devised, specifically targeting critical areas.

For external defects, Magnetic Particle Inspection (MPI) or Eddy Current Testing are considered the most appropriate methods. On the other hand, for evaluating internal defects, the Phased Array Ultrasonic Inspection technique is commonly employed. It should be noted that heavy corrosion and significant surface damage compromises defect detection by the advanced techniques. Surface preparation could be considered, and alternative approaches may be used in these cases to detect flaws.

Hardness testing is typically conducted on the later compressor discs and turbine parts to assess material aging resulting from temperature exposure. Replica tests are often performed to facilitate a metallographic evaluation of surfaces exposed to high temperatures, allowing for an assessment of alterations through grain size and configuration to evaluate the material degradation. An alternative method is the Small punch (SP) Test, a miniaturised procedure where a punch indenter exerts compressive force onto the surface of a disc sample. This method has its limitations in the measurement of material properties and temperatures, and the quantitative assessments and interpretations are not trivial. However, this testing approach is valuable to assess tensile and fracture properties, beyond the material cyclic response. A notable benefit is that the method in question needs limited material portions, leading to a noteworthy cost reduction [13].

PHASE 3: Life Time Extension

The final phase of the program is dedicated to the extension of the rotor's operational lifespan (*Figure 13*), encompassing comprehensive inspections, overhauls, and manufacturing activities. A potential solution for managing a rotor end-of-life is the complete substitution with a newly manufactured rotor. Alternatively, by implementing LTA/LTE Programs, it is possible to selectively replace only the selected parts of the rotor which are critical to the safety and integrity , thereby significantly increasing the rotor lifespan while minimizing costs. Apart from the major structural components, there are typically several parts located along the gas path in a gas turbine that are not typically replaced during the turbine initial design lifespan. When considering extending the turbine operational life, it is crucial to evaluate the condition of these components. Neglecting this assessment could lead to an engine failure, which, although sometimes not posing a direct threat to human safety, would render a considerable number of hot gas parts irreparably damaged and cause a significant outage [14]. This review paper focuses on the integrity of the rotor. Further topics will be touched upon in other ETN activities. To initiate the rotor overhaul, it is necessary to carefully disassemble the rotor to facilitate thorough inspections of all its components. Furthermore, new critical replacement parts are manufactured. This entails a rigorous qualification process for forging, machining, coating, and surface treatments. Ultimately, the worn or damaged critical parts are replaced, and the rotor is reassembled, ensuring optimal functionality and performance.

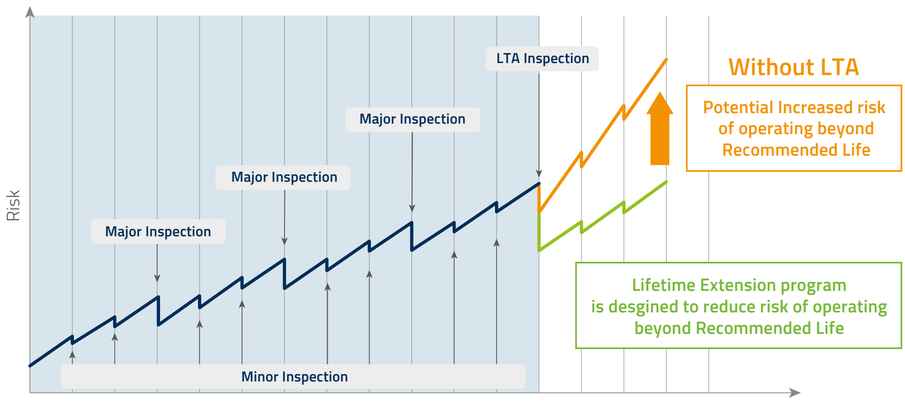


Figure 13: LTA/LTE benefits

Structural health monitoring is required to mitigate the operational risks from the introduction of new gas turbine technologies, maintain their fuel consumption benefits through the engine life cycle and allow for new opportunities in the design space of gas turbine development. For this purpose, the following health monitoring technologies may be implemented:

- Failure diagnosis to mitigate risks due to increasing system complexity and degradation diagnosis to assess performance degradation due to damage phenomena (fatigue, creep, wear, ...) in the presence of increasingly high pressures and temperatures.
- Performance prognosis, by means of a condition-based forecast of remaining useful life until the next maintenance action.
- Predictive Maintenance, allowing of predicting the performance gain of a maintenance action based on the individual engine's service record and a data base of the shop visits of all engines in the past.
- On-line structural health monitoring with failure detection and actual measurement of degradation to increase availability and reduce maintenance cost as well as to reduce required design margins and hence life cycle associated costs.

Structural health monitoring technologies require to be validated based on historical service data records, dedicated sub-assembly test rigs or full engine tests.

Some of the developed tools, especially in the aero engine industry, include:

- algorithms (software) based on pattern recognition and model-based analysis for engine failure and degradation diagnosis.

- algorithms (performance diagnosis software) for short- and medium-term performance prognosis

- hardware for structural health monitoring embedded in the system (e.g., in correspondence of the main bearings) including sensors, wireless power supply and data transmission and central data acquisition.

Such technologies have proved to be effective for the reduction of maintenance costs and for improved reliability [15]. The difficulty in inspecting rotating parts during the service life of gas turbines makes the detection of potential damage much more difficult in these structures than in static (non-rotating) structures. Therefore, suitable symptoms are needed that can be measured (typically vibrations) and that are able to clearly indicate the presence of damage in rotating parts. If these symptoms arise in an engine, the engine may be stopped, the affected part may be uninstalled and inspected with standard procedures and the catastrophic failure of the complete unit may be avoided [16].

Frameworks like the one presented in reference [17] are increasingly used to estimate cycle-dependent and creep-dependent damage based on actual unit operation data in land-based aero-derivative gas turbines. However, a definite determination of the amount of life extension cannot be provided purely based on creep and fatigue alone. Rotor conditions for fretting/wear, corrosion, FOD damage, and other stochastic failure modes have to be performed as well. Life cycle management and extension of the rotors are contingent upon periodic inspection guidelines and implementation of relevant repair schemes, as mentioned in reference [18].

3. Potential learnings from aero engine LTA procedures

3.1. Aero engine LTA procedures: Safe life and damage tolerance

Commercial aircraft spend approximately 30 years in operational service. During this time maximising performance and minimising costs while also contributing to the overall sustainability of air transportation are major efforts. The aircraft's engine (named afterwards aero engine) lifetime is not necessarily coupled with an aircraft's lifetime: engines be switched from one aircraft to another, temporarily dismounted from for maintenance, or simply having different lifetime than other aircraft life limiting components.

An aero engine is made of different components having each their individual lifetime. The overall engine lifetime is usually defined as the lifetime of its large structural components, essentially rotor parts, while smaller parts (i.e. blades) are typically replaced several times. Rotor parts main damage mechanism being Low Cycle Fatigue or Thermo-Mechanical Fatigue (LCF/TMF), their lifetime is typically only limited by a maximum number of equivalent cycles, integrating start/stop (highest load variations) and thrust variations (secondary but non neglectable load variations).

Being critical elements for safety, this limitation is often a legal requirement and limits the total engine life. For other parts, both a start and an hour limitation can exist but the latter one is often a performance limitation (exceeding it will not compromise the engine safety).

The "safe life" design was (as for land-based turbines) the traditional lifing methodology. Essentially a minimal number of cycles (before crack initiation) is estimated based on empirical (material and component testing) and analytical (modelling, statistics) inputs. This estimation integrates the various manufacturing tolerances and safety factors. The actual maximum allowed service life is then expressed as a fraction of this theoretical minimum.

While this conventional methodology showed great general success, it failed to predict component failure due to undetectable anomalies. To accommodate these anomalies and improve safety, a refinement of the lifing methodology was proposed by addition of a "damage tolerance" approach based on probabilistic fracture mechanics. It should be noted that it doesn't aim to replace the safe life method but to improve it.

The Advisory Circular AC33.14-1 "Damage Tolerance for High Energy Turbine Engine Rotors" by the U.S. Department of Transportation [19] describes the above summarized lifing methodology and provides guidelines to build a probabilistic life management tool. Its main concepts are the following:

- Some OEMs use the probabilistic approach. This probabilistic approach tries to estimate a component event rate, expressed as the theoretical number of failures per cycle. This event rate is then compared to the Design Target Rate (DTR) for acceptability.
- The events considered are only the ones relevant for safety i.e., "uncontained rotor" event. It means other failure, affecting the performance for instance, might occur before a safety critical failure.
- The combined or integrated event rate for all the components from an engine is calculated using a systems reliability approach resulting in an engine event rate which is also compared to a specific DTR for acceptability: even if all component DTR are reached individually, the integrated risk for the engine might be not acceptable.
- The event rate is calculated first for a given anomaly based on its "natural" occurrence. Defects are assumed to be initially present in the material and their statistical size distribution should be known (from modelling and confirmed empirically).

- The defects are considered as growing, sharp cracks: the number of cycles before they reach a critical size (causing failure) can be calculated using crack growth rate from material testing (fracture toughness and Paris law).

- The stress levels within a component during a representative operational cycle are calculated. The component volume is then split into areas with similar stress level (mesh).

- Within each volume, the probability of failure as a function of the number of cycles is calculated (based on the defect distribution probability).

- The overall component event rate is obtained by the integration of each volume failure probability.

- While multiple design parameters (material specification, geometry, operation limits) might impact the actual event rate, the AC33.14-1 focus solely on the effect of inspection (frequency and criteria) to bring event rates within DTR acceptability.

- A second layer of probability is introduced as each inspection is associated with a Probability Of Detection (POD) of existing defects. Obviously, the POD depends on the inspection technique and criteria.

- A third layer of probability is introduced with the "part exposure" concept. Essentially it considers that within a normal operation, a component will at some point be "naturally" accessible for inspection, meaning without having to impose downtime specifically to inspect it. The probability for this component to become accessible increases along the life cycle and must be estimated (so called "part exposure distribution").

- The concept of "opportunity" inspections and "soft interval" are introduced, as opposed to "mandatory inspection" after reaching a "hard interval" (a "do not exceed limit"). Basically, a component should be inspected after it reaches its "soft interval" at the next "naturally" occurring opportunity (see "part exposure" concept above). The setting of the "soft interval" is then integrating the probability of the "part exposure distribution".

- The analysis can be further refined by adding "module exposure" or "engine exposure" distributions: the component is not directly accessible but its mother part (the module) or the whole engine is accessible: some downtime is caused as the component needs to be dismantled from the module (or from the engine) but less than if operation had to be stopped solely for this component inspection.

As a summary, this document provides notable inputs that could be of use (possibly with some adaptations) for land-based engines LTA:

- A description of a fracture mechanic probabilistic approach, relying on event rate estimation and comparison with DTR
- A test case to use to calibrate a user probabilistic calculation tool
- The concept of POD for inspection
- POD curves for different NDT techniques and calibrations levels
- The concept of "part exposure", "module exposure" and "engine exposure" distributions within a lifetime
- The concept of "opportunity" inspection and "soft time" inspection intervals
- An illustration of the impact of inspection (and of criteria severity) on the final event rate

In addition to the Advisory Circular AC33.14-1, reference [20] provides a recent overview of probabilistic lifing approaches for aero engines and land-based gas turbines for energy production, as discussed here. Some applications of probabilistic approaches for land-based gas turbines can be found in reference [21].

Next to LTA, life optimization of areo-engines within a fleet is another practise of possible interest for land-based engines. Engines might indeed be switched to different use cases/aircraft models to maximise lifetime reaching the sweet spot between cycles and hours. Power generation users with multiple engines likely already try to optimize their lifetime by switching their operation profile, however, physically swapping engines with opposite operation history might be beneficial for mechanical drive GT or for isolated power generation GT (depending on the transport costs, availability).

Another potential practise of interest relies on the build-up of large data bases (Skywise, AVIATAR, Honeywell Forge, ...) thanks to widespread data-collection to optimize maintenance, leveraging on the large fleet size and on increasing digitalization. For land-based GT, such fleet wise data base is typically only accessible to the OEM (reducing the possibility of independent evaluation) and typically less extensive.

3.2. Aero engines LTE procedures: Legal procedures

As introduced, life limits of aero engines, being critical for aircraft safety, are often legal requirements. The process of extending the service of a part beyond its original designed lifetime is therefore a complicated process requiring the approval from authorities.

Basically a Life Time Extension (LTE) of an already existing part requires to repeat the same methodology as for LTA, with enough supporting data to convince the authority that an LTE is possible. This could be based on either additional input (material testing, modelling and investigation of ex-service parts), on change of the cycle definition (different operation profile) or on the risk management aspect (changes of inspection technique, criteria, frequency).

It should be noted that the initial LTA is not necessarily aiming to determine the maximum life of a component, but to demonstrate that reaching a given number of cycles has a low risk. As such, some component might be suited for LTE even without significant new input.

Overall, an LTE requires an extensive re-certification effort that is typically only worthwhile when a large extension is targeted (such as doubling the lifetime of a whole ageing fleet). This is a major difference with land-based engines, where relative short LTE (10-20%) relying mostly on condition-based assessment can be considered, keeping effort/benefit/risk ratios acceptable.

3.3. Limits of aero engine LTA/LTE procedures portability for land-based engines

While the aero engine LTA/LTE methodology was proven reliable, its applicability for land-based engines is not straightforward:

- Aero-engines fleets are significantly bigger than land-based ones (ex: around 1700 engines for a flight operator versus for approx. 180 for an energy company), leading to have more field data to fuel models and to obtain in turn more realistic output. In addition, while aero-engines receive upgrades, they are more comparable within upgrade versions. Land-based GTs however, seem to be more tailored to customer/user specifications making them more unique individually.

- Due to the bigger fleet size and the individual lower cost, the sacrifice of an engine (or of some engine parts) to validate a model can be economically considered while it is usually out of the question for a heavy-duty gas turbine.

- Dismantling of an engine (or of a module) to allow a direct observation of internal components is easier for aero-engines, leading to more confidence in the condition of aged parts.

- Likewise, the opportunity for inspection of an areo-engine (part exposure) is typically greater than for a land-based turbine, especially for heavy duty GT due to the significant cooling time (1 to 2 days for land-based GTs versus 1/2 hour to a few hours for aero-engines) after a stop before inspection.

- Even for engines having both aero and land versions, the thermal and stress level during a cycle might be too different to extrapolate data.

- Likewise, fuel contaminants and environments are different for aero and land-based engines, leading possibly to different corrosion behaviour.

- Existing procedures, notably the AC33.14-1, have a limited scope excluding for instance surface anomaly related to manufacturing or maintenance and alloys other than titanium (while most land-based turbines have steel rotors)

3.4. Comparison of engines having both aero and land-based version

While keeping the limits in comparability in mind, some engines exist in both aero and land-based versions, that share many similarities and sometimes even the same components. The maintenance philosophy of both engines follows overall a similar process: Critical components, essentially rotor parts, have a total start limit and mandatory inspection are prescribed at different operational milestones.

Surprisingly, discrepancies are found between the cycle limits, which are in some cases higher for the aero version, even for the exact same part number. One could have indeed expected a lower maximum cycle limit for the flight engine due to higher safety margins. These discrepancies are not well understood but suggest that an industrial operational cycle is considered more severe than a typical flight cycle. This difference could also result from corrosion considerations: Jet-A1 kerosine is significantly cleaner than land-based GT fuel. However, depending on the location and/or on the filtration system used, air contaminant and moisture levels could be lower for land-based GT. Investigation of land-based and aero ex-service parts coupled with operational data analysis could validate these considerations.

While stretching the maximum cycle limit for an aeroengine is a complex qualification process (legal requirements), doing the same exercise for a land-based engine may be less complex (but still needs to be discussed with the user, the OEM, the insurer and still needs to comply with legal requirements).

If the safety margins used for flight engines are significantly greater than the ones acceptable for industrial use, it is reasonable to imagine that some residual life is present in "end of life" flight engine.

A full condition assessment at the "end of flight life" condition, including destructive testing and a full metallurgical examination of the most critical section will provide valuable information and guidelines for life extension of industrial engines.

4. Identification of the gaps, additional requirements and development of a generic LTA procedure

The application of rotor life assessment is not entirely new and companies such as the OEM, independent engineering firms and service providers including some operators have already started carrying out assessments. However, there are gaps which need further attention to manage the uncertainty and improve the confidence in the rotor life analysis. The nature of some of these gaps or uncertainties depends on whether the assessment is being done by, or in conjunction with the OEM, or if it is being done independently. These are further discussed below.

Analytical: Temperatures

A rotor thermal model for the steady state operation of the turbine can be developed using available computational tools, as discussed earlier in the paper (section 2) by accessing the geometry of the rotor, developing the unit thermodynamic/performance model, and understanding the secondary cooling circuits. Some of this information can be relatively easily generated. However, whilst the OEM will have access to detailed information, an independent body will need to make their own estimates and evaluations, e.g., cooling flows in the machine as a whole.

For assessing transient operation, which would be an integral part of rotor lifing in a flexible market, past operational cycle of the turbine as well as future cyclic demands should be analysed. Uncertainty will arise from the model, depending on the boundary conditions and assumptions made. Again, the OEM and the independent body have access to differing levels of information.

Validation of the rotor thermal model is not a straightforward exercise. OEMs will have far more validation information. Independent bodies would need to carry out instrumented trials of some form. Validation can be sought via FAT performance data which Operators will have (in lieu of additional instrumented trials or reliance on on OEM-specific information) [22].

Analytical: Life calculation

For the discs used in aviation, a full geometry disc may be tested to destruction to validate the lifing model, i.e., in a spin pit test. However, no such process has been adapted when designing a rotor or reevaluating the rotor life later for the industrial turbines. In the absence of such robust validation process, it is suggested to perform thermo-mechanical testing of sample of discs, after developing the model based on the creep, LCF and oxidation/corrosion data to validate the overall model. This should be considered in line with the probabilistic analysis of the rotor integrity.

Another area is that of the appropriate safety factor to use. Each OEM will have their own set of safety factors (which will be used in their proprietary design methodology). These are not in the public domain. In assessing the potential for extending the life of discs and rotors one is essentially eating into these safety factors. On the aeroengine side methodologies and inspection regimes have been devised and researched (damage tolerance, retirement for cause etc). The transferability of these to industrial units, with suitable modifications, needs to be assessed.

Materials data

The availability of appropriate material's data, particularly around the material's toughness and crack growth behaviour for aged rotor material and operational cycle, is an essential part of an assessment. Most OEMs design the rotor based on creep, low cycle fatigue and oxidation data for the data obtained on the virgin alloy. A reasonable amount of these data is also available in public domain for some disc alloys. In contrast the amount of data on ex-service material is somewhat limited, particularly for large produce forms (reflecting manufacturing differences between small aeroengine discs and much larger industrial components). This situation will exist for both the OEMs and independent bodies, but it applies more to non-OEMs.

The situation is also complicated by the range of materials used, i.e., low alloy steels, 3NiCrMoV steel, 12 Cr steels, and several types of superalloys.

Generating ex-service disc/rotor material data is relatively expensive task. This can be more readily justified in a collaborative program involving the OEMs, service providers and operators. Some of these types of collaborative work were performed during 80s and 90s in Europe, e.g., COST programs.

Materials – additional damage processes and evaluations

As noted above, the OEM designs will consider a number of 'standard' damage processes (creep, LCF etc), as they have experience of the known properties of some of their materials. However, additional forms of damage which are not explicitly included in the design rules, but which may be catered for in the safety factors, can occur.

- **Interaction of creep and fatigue**. The interaction of the accumulated deformation by creep during the hold time to the LCF cracking during the start cycle need to be further explored to cover the range of alloys critical to the rotor section, covering the expected ramp rate and hold time for future operation of the turbine. The model could be verified by designing a TMF test reflecting the engine cycle of the gas turbine for future operation.

- **Alloy embrittlement**. Embrittlement is either the result of micro segregation of trace elements such as P, S etc. in the rotor steel or secondary hardening of some rotor alloys during service. The micro segregation of trace elements mainly affects the rotor steels which are manufactured with a relatively high level of impurities (without two step refinement of the steel). This type of segregation cannot be easily inspected by conventional NDE techniques (including hardness, or replica) or analytically assessed unless samples of the ex-service rotors are tested. Embrittlement caused by secondary hardening of the alloy can, however, be inspected by replication of the rotor microstructure. A certain amount of information can be transferred from previous work on low alloy steels used in steam turbines. However, as noted previously, other very different materials are also used in turbines.

- **Stress assisted environmental cracking**. Stress assisted grain boundary oxidations (or environmental cracking) can cause cracking of Ni-base disc alloys when the local stresses in the disc attachment area is high. Several mechanisms have been discussed for this type of cracking. The phenomena occur by the oxidation of the grain boundary at the crack tip at intermediate temperatures. This issue should be considered when lifing the rotor. However, there are no analytical techniques which is readily used to predict the time and rate of the cracking. Nevertheless, it is known that the cracking can be prevented by reducing the local stress level, combined with improving the alloy heat treatment.

- **Surface degradation from fretting or corrosion**. Localised damage such as fretting, corrosion pitting on the discs or blade fixings, or bad contact surface after exchange of components, can potentially lead to fatigue cracking. The consequences of fretting or pitting is linked to the stress field, type and condition of the material, environment, temperature, and ramp rate. However, exactly how one would analytically incorporate these into an assessment on real components is not straightforward.

- **Miniature sampling**. Miniature sampling like small punch test is one of the limited way to understand the level of material embrittlement and rate of cracking of the ex-service discs. There are a few issues which to be considered when utilizing the method; starting with obtaining the correct extracts from the locations of the disc/rotor which reflect the highest level service degradation, then the sampling and testing of each small punch extract for the required materials properties, and finally correlating the test data to the materials properties available from the standard test pieces which are used for the lifing and design. There is no protocol and standard to address the issues around the small punch sampling and testing for an aged rotor. This is an important area which need to be discussed further as part of the rotor lifing project.

Rotor inspections

The quality and interval of rotor inspections provide important input when lifing a rotor or disc. There are limitations on the method of inspection like penetrant testing, ultrasonic (including phased array) or eddy current, as well as the interval of inspections, e.g., as reflected in the probability of detection (POD). Some rotors can be destacked on site during every major inspection, however, some other rotors can only be destacked in a qualified workshop. In addition, for the welded rotors, the inspection of the weld will also be an important part of the assessment.

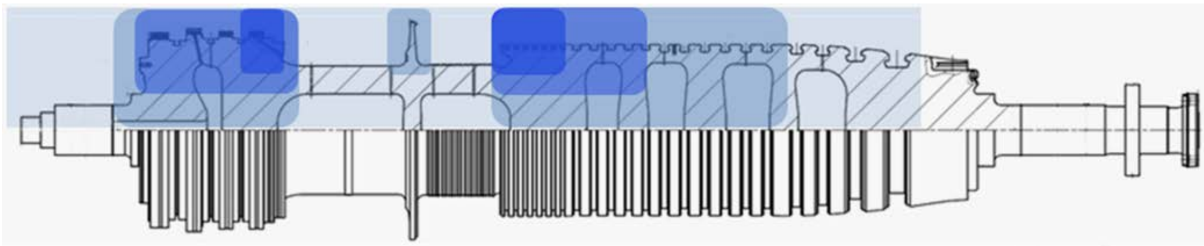


Figure 14: F-Class ALSTOM welded rotor / ©ALSTOM

Individual discs can be inspected for surface breaking and sub surface defects around the blade attachment area. However, this inspection may not address the level of material degradation and the stage of internal damage leading to cracking. Surface replica and hardness testing can provide some information on the level of material degradation of steel alloy discs. However, the ability of the method to detect the rotor alloy embrittlement by grain boundary segregation (by S or P) or damage evolution in the Ni-base alloy is rather limited.

Geometry checks of the blade root attachment have been used as an indication of localised material deformation due to creep. The absolute changes in the geometry of a fir-tree by creep deformation are relatively low and one can question the reliability of the measurements thus generated. Therefore, careful considerations need to be made when assessing the disc fir tree geometry.

The on-site and off-site inspection of the rotor could be further reviewed and updated to provide some common understanding of the limitations and complexity.

Uncertainty and probabilistic analysis

Uncertainty arises from several sources during the rotor lifing:

- Materials data and scatter (aged materials vs original material data)
- Manufacturing variability (causing macro or micro segregations)
- Uncertainty arising from the thermal boundary (specific to thermal transient for cyclic operation)
- Uncertainty from the lifing methodology, since no full-scale validation is performed for the given operational conditions

All the above points emphases the importance of running a probabilistic analysis to capture the major uncertainty and risks associated when extending the life of the rotor. Performing a probabilistic analysis preferably requires access to large quantities of reliable data. To what extent it is sensible or useful to carry it out depends on the quality of all the input data and the sensitivity of the results to uncertainties in certain key pieces of data. The more inspection, manufacturing, and material data we have, the more reliable predictions we obtain.

Integration of the rotor life

Finally, any rotor life assessment should consider two following issues:

- Localised level: by considering the localised damage developing in the "critical area" of the discs.
- Global level: considering the rotor as a complex structure and evaluating the interaction of different parts of the rotor, like fretting in the couplings due to frequent cycling, or crack initiation from the welded rotors, or cracking of the fretted bolt holes, combined with the cracking of the fir-trees.

It is easier to model a localised damage by understanding the thermal and stress profile of the area of interest. However, in a global level, some complexity may arise which need details assessment and risk evaluation.

Conclusions and suggestions

Any rotor life model should be able to provide clear recommendations to the plant operator to run, repair or replace a turbine rotor (or part of it). This can only be achieved by an in-depth knowledge of damage mechanisms, materials data, and thermal transient modelling of the rotor in a condition as close as possible to the expected operation of the turbine. A rotor is a complex structure, made of different stages of discs which are exposed to a range of temperature and stresses, with some unknown arising from the manufacturing, material and environment. Given the issues discussed in the previous sections, it is greatly beneficial to the turbine community to run a collaborative rotor lifing program to establish a generic lifing protocol for the rotors. This program does not need to address the life of a specific rotor type, rather it should be used to improve the awareness of the owner/operator (including the OEM and service providers) resulting in higher confidence in future operation. This more generic lifing model is a platform to reduce the risk and plan ahead when deciding on the condition of the most critical dynamic part of the gas turbine.

References

1 Heavy-Duty Gas Turbine Operating and Maintenance Considerations, GER-3620P (01/21), GE POWER

2 A lifetime model for creep-fatigue interaction with applications to the creep resistant steel P92, Hermann Riedel, Gerhard Maier, Heiner Oesterlin, International Journal of Fatigue 150 (2021) 106308

3 Creep-Fatigue Failure Diagnosis , Stuart Holdsworth, Materials 2015, 8, 7757–7769

4 Creep-Fatigue Failure Diagnosis , Stuart Holdsworth, Materials 2015, 8, 7757–7769

5 Webinar on Rotor life extension (with Tom Freeman) | GE Power

6 World Energy Outlook 2022, IEA

7 ENERGY TRANSITION OUTLOOK 2021, DNV

8 Flexibility Needs and Options for Europes's Future Electricity System, Energy Brainpool 2017

9 Flexibility Needs and Options for Europes's Future Electricity System, Energy Brainpool 2017

10 B. R. Annigeri, Solution For Gas Turbine Rotor End Of Life, 17-IAGT-206, 2017.

11 Di Sisto, P. and Parodi, M., 2013, June. New Simulation Process for the Life Management of the Gas Turbine Rotors. In Turbo Expo: Power for Land, Sea, and Air (Vol. 55263, p. V07AT27A012). American Society of Mechanical Engineers.

12 Ding, S. et al. (2023) Review of the development of the probabilistic damage tolerance assessment of life-limited parts in compliance with the Airworthiness Regulations, Propulsion and Power

13 R.J. Lancaster, S.P. Jeffs, H.W. Illsley, C. Argyrakis, R.C. Hurst, G.J. Baxter, Development of a novel methodology to study fatigue properties using the small punch test, Materials Science and Engineering: A, Volume 748, 2019, Pages 21-29, ISSN 0921-5093, https://doi.org/10.1016/j.msea.2019.01.074. (https://www.sciencedirect.com/science/article/pii/S0921509319300917)

14 P. Slottner, LIFE EXTENSION OF SIEMENS INDUSTRIAL-SIZED GAS TURBINES, 2009-IAGT-3.02, 2009

15 E-BREAK (Engine Breakthrough Components and Subsystems) – Project Summary Handbook, 2017. Available at https://cordis.europa.eu/project/id/314366/reporting (retrieved on 25.09.2023).

16 N. Bachschmid, P. Pennacchi, E. Tanzi, Cracked Rotors – A Survey on Static and Dynamic Behaviour Including Modelling and Diagnosis, Springer-Verlag, 2010. https://doi.org/10.1007/978-3-642-01485-7

17 Dipankar Dua, Mohammad Khajavi, Matthew Hill, Life Extension Of Power Turbine Disks Exposed To In-Service Corrosion Damage, Proceedings of 2017 ASME Turbo Expo. GT2017-63366, June 26-30, 2017, Charlotte, USA.

18 Dipankar Dua, Quang Le, Anthony Saladino, Deepak Thirumurthy, Jaskirat Sing, Life Extension Of Power Turbine Disks Exposed To In-Service Corrosion Damage, Proceedings of 2021 ASME Turbo Expo. GT2021- 59390, June 7-11, 2021, Virtual Conference.

19 Damage Tolerance for High Energy Turbine Engine Rotors, Advisory Circular No.: AC 33.14-1, U.S. DoT FAA, 2017.

20 Kadau K., Enright M., Amann C. Probabilistic Lifing. In: Meyendorf N., Ida N., Singh R., Vrana J. (eds) Handbook of Nondestructive Evaluation 4.0. Springer, Cham. https://doi.org/10.1007/978-3-030-48200-8_11-1 (2021).

21 P. Engels, C. Amann, S. Schmitz, K.Kadau, Probabilistic Fracture Mechanics for Mature Service Frame Rotors, J. Eng. Gas Turbines Power 143, 071004 (2021)

22 Jin, H., Pistor, R., Lowden, P., Weber, B. and Grant, R., 2006, January. Prediction of gas turbine blade life: An interdisciplinary engineering approach for condition-based maintenance. In Turbo Expo: Power for Land, Sea, and Air (Vol. 42401, pp. 519-524).

ETN a.i.s.b.l.
Chaussée de Charleroi 146-148/20
1060 Brussels, Belgium
Tel: +32 (0)2 646 15 77
info@etn.global
www.etn.global

ETN Global