18TH SYMPOSIUM OF THE INDUSTRIAL APPLICATION OF GAS TURBINES COMMITTEE
BANFF, ALBERTA, CANADA
OCTOBER 19-21, 2009

2009-IAGT-3.02

LIFE EXTENSION OF SIEMENS INDUSTRIAL-SIZED GAS TURBINES

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Keywords: *life time assessment, life time extension*

Abstract

Gas turbines are typically designed for a service life of 100 000 – 160 000 hours of operation, or 12 – 20 years of operation. During the design phase, plenty of assumptions are needed, e.g. worst case or near-worst case operation conditions are assumed throughout the operational life even though it is known that only very few gas turbines will operate at such conditions for more than a fraction of their service life. This means that in almost every case, most components in the gas turbine have plenty of life left. On the other hand, during the service life of a gas turbine, new failure modes tend to be identified, and components are redesigned to improve the degradation resistance. Further, corrosion and material ageing may influence the serviceability of parts more than intended. Therefore, while there is always a potential to extend the service life of every gas turbine, the exact limits of the life extension and the necessary procedures to verify the condition of each gas turbine needs careful consideration.

In order to come up with the best possible judgment of the turbine condition, investigations of maintenance history as well as current condition is needed. For optimized cost and down time, the life extension activities are divided into a Life Time Assessment, where life times of main structural components are evaluated, and a Life Time Extension, where required actions are implemented and some of the evaluations are repeated. The final scope can be anything from only replacement of standard parts up to the replacement of the entire gas turbine with a new unit.
As part of the Life Time Extension, upgrades in power output, efficiency, low-emissions capability and various reliability improvements can be implemented, achieving almost the characteristics of a new engine at lowest possible cost.

The paper explains the various reasons why and when life times can be extended, and also typical stoppers. Siemens methodology to assess the status of light industrial gas turbines is described with examples from available life extension products. It is concluded that in order to reduce risks to humans, surrounding equipment and the environment, life extension is always beneficial compared to run-to-failure, and from a cost perspective life extension can be very advantageous compared to replacement with new equipment.

The IAGT Committee is sponsored by the Canadian Gas Association and supported by the National Research Council Canada. The IAGT Committee is not responsible for statements or opinions advanced in the technical papers or at the Symposium or meeting discussions.

Definitions and nomenclature

Overhaul

Maintenance event where all major parts of the gas turbine are disassembled for inspection and/or repair/replacement.

Overhaul interval

Maximum allowable adjusted time between overhauls.

Adjusted time

Measure used to determine outage intervals for a gas turbine. Dependent on design and manufacturer it could be calendar hours, running hours, equivalent running hours, starts, equivalent starts or similar, or a combination of the above.

Original design life

The life time that was the original design target of the equipment, defined in units of adjusted time.

Package

The gas turbine system, including all surrounding equipment that is part of the gas turbine installation that requires rebuild or replacement if the gas turbine is replaced with a different type of gas turbine. Driven equipment is excluded, if possible.

FM

Failure mode – manner in which an equipment or machine failure can occur.

HFM

Health critical failure mode – a failure mode that has the potential to cause injuries to humans.

Functional component

A functional component is one of the main building blocks of the gas turbine that adds one of its main abilities needed to perform its mission – compressor, combustor, rotor and turbine. In order to make the gas turbine package complete, the functional components air inlet, exhaust parts and auxiliary system should be added. From a maintenance point of view, driven equipment is also a functional component. While extremely important, this paper does not cover maintenance of driven equipment.

1 Introduction

Industrial gas turbines are typically designed for a service life of 100 000 – 160 000 hours, or 12 – 20 years, of continuous operation, expressed in adjusted time. These life time requirements may be determined based upon international or national standards like [1] or from customer requests. In order to fulfill this, a number of assumptions are required regarding typical load, number of fired hours per start, with sufficient margins to take into account worst-case of near-worst case operation conditions. Additionally, especially for major structural parts like casings and rotors where a failure could cause the total breakdown of the package and the risk of loss of human lives, adequate safety margins are required to ensure that the probability of such a failure is sufficiently low.

In many cases when the gas turbine is approaching the end of its design life, there is an interest in continued operation of the equipment if the cost is reasonable. Typical options are: Continued operation with existing equipment, replacement of the gas turbine with a similar unit with more remaining life and possibly better performance, upgrading the existing equipment, and replacing the package. The best choice depends on, among other things: Current condition of the gas turbine and other parts of the package, how long into the future the package is expected to be needed, current and expected future operation costs including fuel costs, environmental and other regulations, available upgrade options, available replacement options, owners risk willingness. It can therefore be concluded that decisions on whether life extension is worthwhile or not has to be determined on a case by case basis.

A key feature for such parts is their long term stability versus exposure to loads in the low-temperature creep regime. Unfortunately, since this is a long-term property that requires extensive test times for analysis, it is very difficult to make a sufficiently accurate assessment of this property at the design stage. Next, gas turbine life times are typically stated assuming operation in a reasonably clean environment with clean fuel and assuming that all maintenance instructions are always followed to 100%. An especially difficult subject is airborne gas-phase pollutants which can cause corrosion but are very difficult to remove even using best possible filtration systems.
In addition to the major structural parts there are often a number of parts along the gas path that are normally not replaced during the gas turbines original design life. At the time of life extension, an assessment of their condition is necessary. A failure to do so may result in an engine failure that, while normally not critical to human safety, will damage a large number of hot gas parts beyond repair and cause a major outage.

In order to come up with an estimate of the current condition of the gas turbine, and the best possible way to ensure the gas turbines future operability, all these factors – and a number of others – need to be assessed. The outcome is a condition assessment of the engine parts that can be turned into a repair, replacement and future maintenance recommendation for the engine.

2 Benefits and feasibility of life extension

The main reason why gas turbine life extension is an interesting topic is obvious: If you can run the equipment longer with a reasonable increase in maintenance cost you can postpone or avoid an investment in new equipment. However as the equipment gets older, more parts may come close to their life limit. In order to identify these parts and in order to identify correct maintenance strategies for each of them, their failure consequences, damage evolution pattern and inspection possibilities need to be understood. Special attention is required for failures that have the potential to put human safety at risk. For gas turbines this means that rotors, casings and fuel system need special attention. By developing a risk management strategy for each failure mode, an inspection and replacement strategy for life extension can be established.
At a certain stage the cost of life extension compared to replacement may become too large. The optimum choice depends on the expected cost and time required to restore the gas turbine to a sufficiently good condition, expected cost and time requirements for replacement with new equipment, and expected future power demands including the time of decommissioning of the plant, if known. Available

upgrade solutions, legal requirements, tax systems and environmental pollution fees further complicate the feasibility evaluation.

It can be concluded that continued operation of a gas turbine without life extension inspections imposes the gas turbine itself and its surroundings to unknown risks. Therefore, before a gas turbine is operated beyond its original design life it should always be the subject of a life extension investigation.
It can also be concluded that in order to make the right choice between replacement and life extension, the technical condition of the gas turbine, the total costs of the different restoration options and the commercial boundary conditions of the operator have to be well understood. Further, in order to maximize the value of the life extension, in order to support decision making and to give time for delivery of necessary replacement parts, it is preferable to assess the condition of the gas turbine well before the decision about extending the life or not has to be made.

3 Risks, degradation and failure

Gas turbines can fail in different ways, and the failures may have very different consequences from minor failures that may cause very long term damage or result in minor loss of performance up to rotor failures where the gas turbine and surrounding equipment can be expected to suffer extensive damage and the loss of human lives cannot be excluded. In this context failure is interpreted as any event that reduces the economical value of further operation, or prevents further operation, to a "significant" extent, including unrecoverable degradation due to e.g. compressor fouling that cannot be reversed using normal washing procedures as well as increasing emissions due to wear or malfunction of combustion system or related auxiliary parts. From a life extension perspective, the scope can be reduced to *long term damage effects that are not covered by the normal maintenance plan*. A possible approach is to use known gas turbine damage mechanisms as a starting point, to analyze which mechanisms that can possibly be active in the functional components air inlet, compressor, rotor, combustor, turbine, exhaust parts and auxiliary system, and to further detail the work for each functional component using a structured risk assessment methods like Failure Mode and Effects Analysis, FMEA, and HAZOP, Hazard and Operability. The major inputs to the risk analyses are theoretical calculations results, fleet experience of the current and similar gas turbine types and a general analysis of which failure modes that can realistically be expected to occur within each functional component.

Dependent on the situation damage mechanisms may sometimes interact, accelerating the rate of damage accumulation. A solid understanding of expected damage evolution and how degree of damage can be measured for each failure mode is vital in order to correctly judge the risks in allowing further operation with the parts. A number of damage mechanisms of importance for life extensions are described briefly in Appendix 1.

3.1 Failure mode properties

When the risk analysis has been completed the result should be transformed into maintenance strategies for each failure mode, taking into account failure consequences.

The strategy can be formulated as a list that includes at least the following:

- Maximum allowable time to first inspection
- Maximum allowable inspection interval after the first inspection if no damage is observed
- Maximum allowable life time independent on inspection results
- Criteria for further operation/repair/replacement decisions if damage is observed

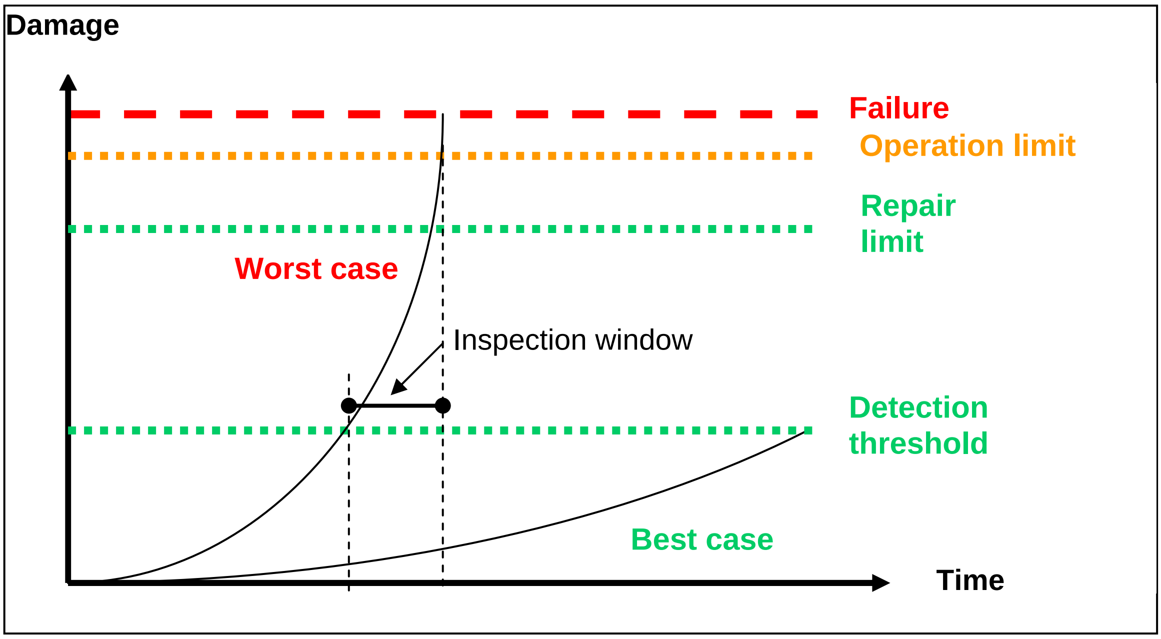

Figure 1: Characteristic properties for maintenance planning. Inspection window

These parameters, in turn, require that a number of characteristic properties are known for each failure mode:

- *Worst case degradation*
  The degradation pattern that can be expected under worst possible, yet realistic, conditions for the specific failure mode, resulting in minimum life.
- *Best case degradation*
  The degradation pattern that can be expected under best possible, yet realistic, conditions for the specific failure mode, resulting in maximum life.
- *Operation limit*
  The worst condition that is allowed for the component in service – "The line that must not be crossed"
- *Worst case and best case degradation life, WCDL and BCDL*
  Operation limit if the worst and best case degradation curves are followed
- *Repair limit*

The worst condition that is allowed for the component in order to be possible to repair

- *Detection threshold*

  The minimum damage that can be detected with acceptable probability AND where the degree of damage can be quantified with reasonable accuracy

- *Measurement accuracy*

  Measure of the accuracy at which, when the detection threshold has been passed, the degree of damage can be stated. In this context the measurement accuracy is given in per cent of damage. E.g. a measurement accuracy of 2% means that when the detection threshold has been passed the difference between measured and actual damage is less or equal than 2%.

- *Life variability LV*

$$LV = \frac{BCDL}{WCDL} \tag{1}$$

  The quota between best case degradation life and worst case degradation life. The purpose of inspections and prognostics methods is to reduce LV for specific failure modes. LV can sometimes exceed 100. Typical values for turbine blades and vanes range between 4 and 30.

- *Inspection window*

  The fraction of the life time between worst case detection threshold and worst case degradation life - refer to Figure 1

- *Ideal inspection window*

  The fraction of the life time between best case detection threshold and WCDL, if applicable - refer to Figure 2

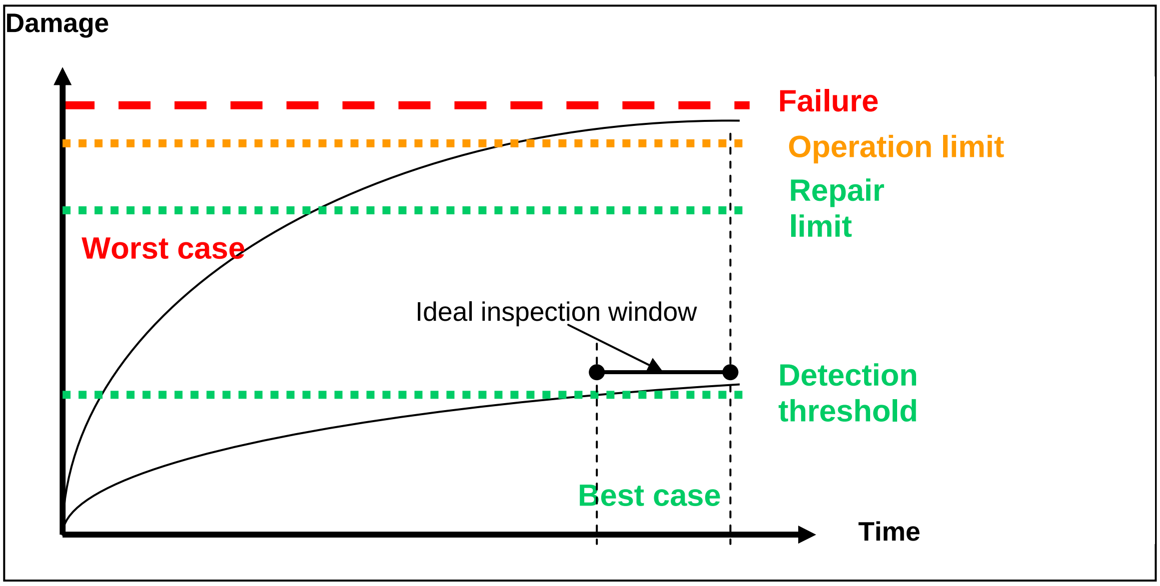

Figure 2: Characteristic properties for maintenance planning. Ideal inspection window

3.2 Example – maintenance strategies for three failure modes

Now, consider the following example: In a gas turbine, three failure modes are determining the maintenance interval. The first one is a sharp notch in a structural, non-rotating part with LV = 30 that is reasonably easy to access during a turbine inspection. The second failure mode is a creep loaded structural non-rotating part made out of steel with LV = 4 that can be inspected only during overhauls. The third one is an uncooled rotating turbine blade with LV = 20 that can be accessed during turbine inspections and can be borescope inspected during any outage. We will assume that if any of these parts fail, most of the turbine blades and vanes will be destroyed, and if one of the structural parts fails, the turbine stator will also need extensive repair. Therefore the consequences of failure modes 1 and 2 are slightly larger than the consequences of the blade failure. Finally, for simplicity, WCDL and measurement accuracy are assumed to be approximately the same for all three failure modes.

Figure 3 shows how the damage is expected to develop. As can be seen, for failure mode 1 the degree of damage can be observed and measured with sufficient accuracy already when 10% of the life time is consumed. However due to the magnitude of LV, the best case detection threshold occurs later than WCDL. Therefore no ideal inspection window exists. The first inspection should be scheduled before, but as closely as possible to, the WCDL. The outcome of the first inspection will govern the future inspection interval taking into account observable damage, if any, the minimum acceptable time to next inspection and possible countermeasures. If damage is observed and the expected remaining life is insufficient to postpone maintenance actions until next outage, actions will have to be taken now. On the other hand, if actions can be postponed beyond next outage, the condition of the other critical parts will also be taken into account. An optimization between minimizing the number of replaced parts and a minimum number of outages should be carried out where the preferred maintenance strategies and observed condition of all the failure modes are taken into account.

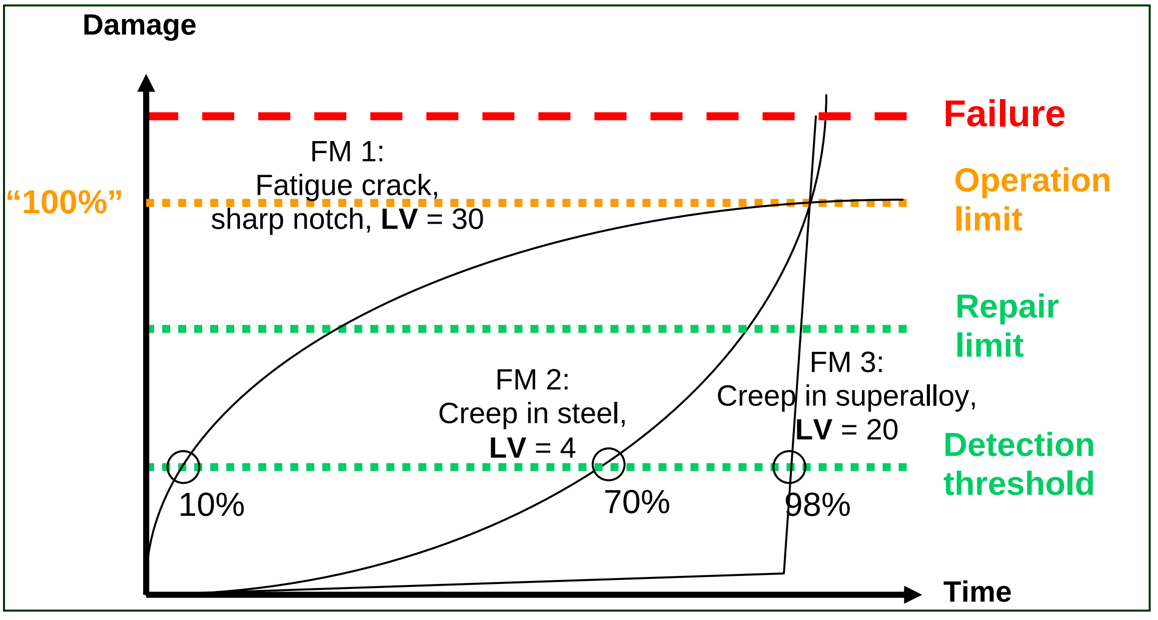

Figure 3: Degradation patterns for different gas turbine failure modes

The case where no damage is observed for failure mode 1 deserves additional afterthought. While this information cannot be used to determine a specific degradation curve for this unit, it can nevertheless be used to reduce the LV IF it can be assumed that the gas turbine will continue to be operated in the same way in the future. In this case, if no damage is observed, LV for this specific case can be reduced to 20.

If on the other hand some damage is observed, this means that the degradation curve is known, save only the measurement uncertainty. By adding measurement uncertainty to the measured degradation, a degradation curve can be defined. If e.g. the measurement uncertainty of the method is 2% and a damage of 27% is measured, the future degradation should be planned along a degradation curve assuming 29% damage in the diagram at the time in question. Actions should be taken when approaching the repair limit or the operation limit dependent on what is considered most feasible for the failure mode in question.

Like failure mode 1, failure mode 2 has no ideal inspection window. Furthermore LV is smaller than that of FM 1. The first inspection will determine whether action should be taken immediately or whether a reduced inspection interval will be needed in the future. Due to the degradation pattern and the relatively small LV, the maintenance needs for this FM are much easier to predict.

The situation with FM 3, an (uncooled) turbine blade, is quite different. Due to the extremely short inspection window, unless a better inspection method can be developed, preventive replacement is the only feasible maintenance action.

It can be concluded that the maintenance strategies for the three failure modes will not be the same. The difficulty to inspect for failure mode 3 means that preventive replacements of that blade are needed at WCDL intervals. The actions required for FM 2 will depend on the cost of down time versus the cost for corrective actions. If the repair or replacement cost is relatively high, it may be reasonable to accept additional inspections to extend the life of FM 2. Actions for FM 1 will depend on the findings. Since FM 1 is relatively easy to inspect, it should normally be possible to extend its life significantly compared to its worst case life time.

Testing of scrapped parts may provide useful information especially in cases where destructive testing may reveal actual condition at end of service life. Tests of samples from e.g. a set of turbine blades or vanes may allow a new condition evaluation of the set that may result in approval for further use of the remaining parts as described in [2].

4 Development of a life time extension product

In previous sections it was concluded that: feasibility of life extension has to be determined on a case by case basis, that the condition assessment of the specific gas turbine should be carried out as early as possible and that disregarding to carry out a life extension evaluation means unnecessary risks not only to the gas turbine and its reliability but also to surrounding equipment including humans. In order to meet these requirements, a condition assessment of the specific engine should be executed as a separate event, followed by an implementation of actions at a later stage, if desired. In order to minimize risks to humans and equipment, the risks involved in continued operation without life extension should be communicated by OEM's and other maintenance providers to customers.

4.1 Theoretical life times and general fleet experience

The best sources of information about possible failure locations are: Design life time specifications, fleet experience and general experiences of similar materials in similar applications. Experience from gas turbines in general can be of value – however each gas turbine model tends to have its own strengths and weaknesses that need to be taken into account especially when the engine is operated beyond original design limits. Risk analyses of expected failure modes incorporating relevant damage mechanisms should allow the definition of a reasonably short list of long term degradation activities that need special attention from a life time extension point of view.

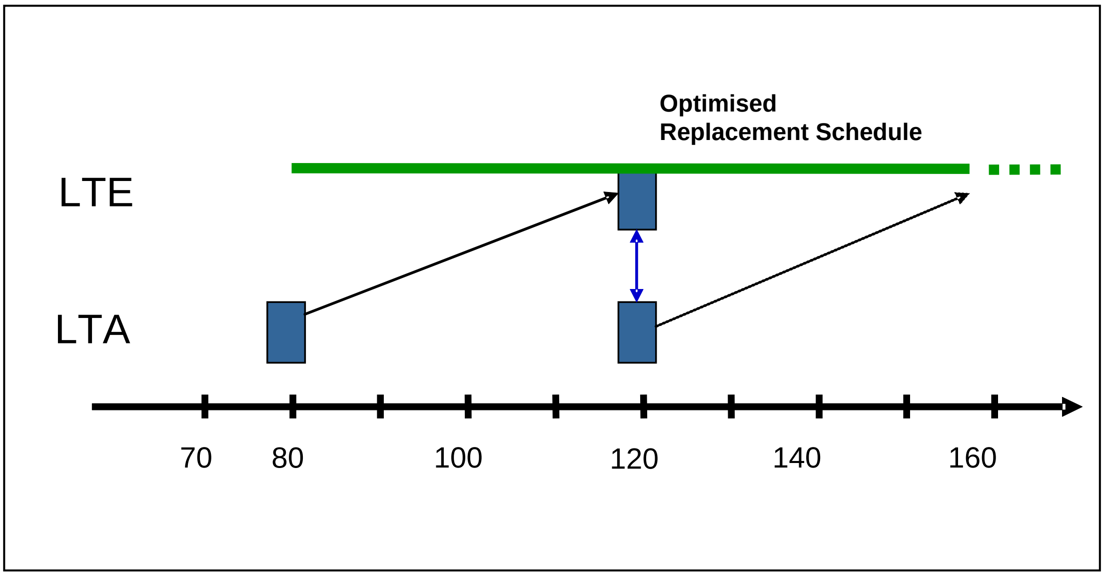

Figure 4: Example life time extension product structure

4.2 Life extension product structure

Once the expected life times and inspection requirements are known for the long term degradation effects not covered by standard maintenance, an overall product structure can be defined. As stated above, in order to make the right decision between gas turbine replacement and life time extension, the condition of the gas turbine needs to be known at the earliest possible stage. However since many degradation mechanisms are difficult to observe until much of their life has expired, too early inspections, although carried out using best available methods, may not be able to observe the state of damage. Therefore the maintenance strategies for different parts will be quite different. The proposed solution to get the most cost beneficial balance between the different requirements is to split the life time extension activities into: An inspection event, or Life Time Assessment (LTA), where inspections to determine the condition of critical parts is carried out; An implementation event, Life Time Extension (LTE), where replacements and package modifications are carried out; and an optimized inspection and replacement schedule for future operation that should be updated after each future inspection. This means that while the inspections and some of the replacements are predetermined for every LTA for the gas turbine model, the outcome of the LTA inspections determine the extent of replacements and future inspections needed.

Figure 4 shows an example of a life time extension product with a LTA where a condition evaluation of the engine is performed, followed by a LTE where suitable replacements are carried out. During the remaining life of the gas turbine, an Optimized Replacement Schedule, specific for each engine, defines which actions that need to be carried out at each maintenance occasion.

By repeated inspection and replacement activities at suitable intervals it is theoretically possible to continue the life extension cycle indefinitely – however with time, it is likely that the inspection scope needs to be further extended. As soon as the cost of life extension exceeds the threshold where replacement becomes more favorable, the next inspection and replacement event is exchanged to a gas turbine replacement.

4.3 Engine operation and maintenance history

An essential part of the LTA is to investigate the service history of the package. By analysing previous events and the rate of degradation of the engine from standard reports, data acquisition systems, component test results and other available sources of data and adding this to the outcome of the package inspection, further conclusions can often be drawn that can be used to further optimise future maintenance activities. If the operation and maintenance history analysis can be carried out before the LTA site inspection it is possible to fine tune the inspection activities further.

4.4 Life time assessment inspection

As part of the life extension a set of inspections will be carried out with the purpose to capture as many as possible of the foreseeable long term degradation mechanisms that the gas turbine in question can be expected to be sensitive to. The inspections should target known failure modes with large LV and significant cost. For health critical failure modes, HFM, performed inspections should not only search for signs of damage but also to a reasonable extent confirm that they can safely be operated until next inspection. That is, the risk of continued operation should be equal to or less than the risk of replacement with new equipment. The inspection activities may include destructive testing of e.g. blade samples and may be carried out partly on site, partly in suitable workshops and partly in laboratories where special materials analyses can be carried out.

4.5 Analysis and future planning

Once the site inspection are finalised, the scope for LTE can be determined, and the maintenance strategies for all the analysed failure modes can be turned into a maintenance plan for the package. The maintenance plan needs to be updated after each inspection, and it tends to be increasingly customised as more and more parts are replaced and more and more parts become the subjects of inspections.

4.6 Case study – Siemens SGT-600

Originally developed by Swiss company Sulzer, Siemens SGT-600 is a light industrial gas turbine with an electrical power output of around 25 MW, efficiency around 34%, Time between overhaul, TBO of 40 000 Equivalent operation hours, EOH, a maintenance interval of 20 000 EOH between inspections and a design life of 120 000 EOH. Figure 5 shows the standard maintenance plan for SGT-600 with LTA and LTE events included.

The development of a life time extension concept for SGT-600 was initiated in 2005 and was carried out according to the procedure described in this document. The investigations concluded that from a mechanical integrity point of view the power turbine blades and vanes that are not replaced during the design life, rotors and casings were the items that deserved the most attention. Further, wear of a number of components have been observed to cause performance losses and occasional other difficulties. Finally, over the years a number of improvements have been introduced into the SGT-600 fleet that have increased reliability and robustness of the gas turbine. Based upon these observations and thorough analysis of the expected degradation pattern of the expected failure modes, an inspection package was defined that is based upon the standard major overhaul but where investigations of the mentioned parts are more extensive that usual. Special tools were also developed to improve quality and time required for rotor requalification. Destructive testing of selected power turbine components was specified. Increased requirements on inspection documentation were also issued for a number of components in order to ensure that relevant information was documented in a quantifiable way.

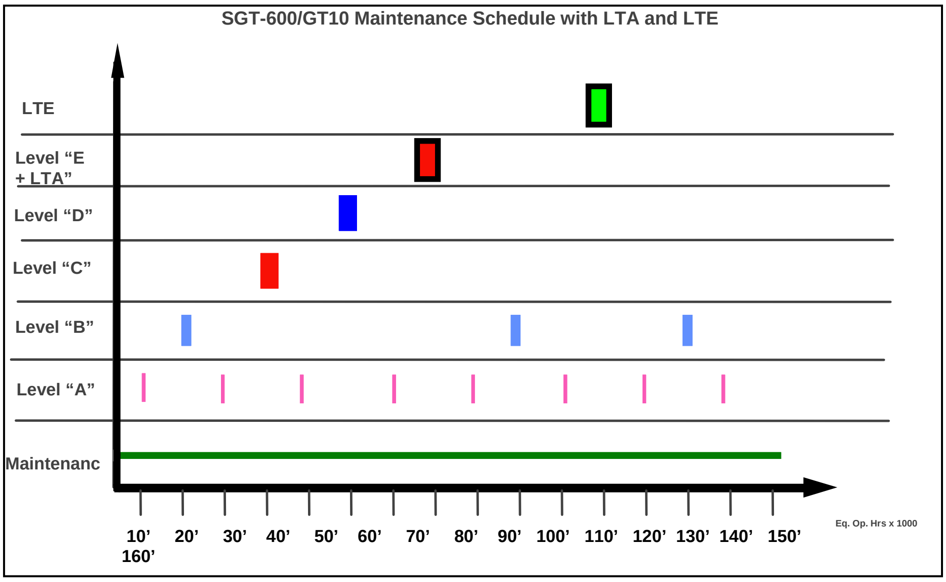

Figure 5: Example life time extension product structure (Siemens SGT-600)

In order to identify suitable improvements and to identify trends in e.g. compressor performance degradation the operation and maintenance history investigation was found to be very important. Check lists were developed and engineering and life prediction specialists were identified as required members of the investigation team. The final analysis and evaluation of the operation and maintenance history is carried out of a team of specialists from key areas with support from a network of Siemens specialists in various areas.

The LTA is recommended for execution together with the 80 000 EOH overhaul. It is possible to delay the LTA somewhat but that will increase down time and is reduces the available time to prepare for the LTE. Until June 2009 around 10 SGT-600 LTAs have been successfully delivered or are in various stages of execution, one of which has so far resulted in a LTE and continued operation. More units are expected to follow within the next years.

5 Modification options at time of life extension

In order to maximise the benefits of life extension it is often suitable to combine it with a selection of upgrades that are needed for the specific application. However in order to keep investment cost down, upgrades need to be carefully selected. Each upgrade should be motivated by itself or in combination with other upgrades at that time.
Upgrades that are easy to motivate and that are useful for almost every operator are: Safety and efficiency upgrades. The benefit of safety upgrades is obvious, and since fuel cost can exceed 70% of the operations cost of a gas turbine, any improvement in efficiency can be directly transferred into improved cash flow.
Dependent on situation, upgrades in power output, emissions, life times and maintainability can also be very useful, but the benefits tend to be applications specific and tax driven and therefore very operator specific.

6 Conclusion

Gas turbine life time assessment and life extension can be a useful tool to correctly analyse future operation potential but requires insight into the life time characteristics of the gas turbine type in question. Without performing necessary, non-standard, inspections, operation beyond original equipment design life may expose humans, the equipment itself and its surroundings and the environment to unacceptable risks. In order to allow proper cost comparison and evaluation of different options for continued operation, inspections should be carried out as early as technically possible. A necessary part of a life assessment is to analyse the previous package service history. A life time extension may be a very beneficial time point to introduce engine upgrades. It can be concluded that carefully performed life time assessments support correct decisions between available maintenance options, and that life time extension can be a valuable method to minimise power production costs under each operators specific conditions.

7 References

[1] Gas turbines — Procurement — Part 3: Design requirements, *ISO Standard 3977-3*, 2004.

[2] Slottner P and Wärja M, Maximum Utilisation of Parts Process – a method for increased precision of component lifetime estimations in medium sized gas turbines. *Proceedings of ASME Turbo Expo 2007*, Montreal, Canada, GT2007-27719, 2007.

Appendix 1. Gas turbine damage mechanisms

Corrosion and erosion

Corrosion is a chemically driven process and typically requires the presence of certain elements together with a liquid, normally water, to be present on component surfaces to occur. The elements normally enter either via fuel or inlet air. Protective measures are the use of anti corrosion coatings, inlet air filters and fuel treatment.

There are many different kinds of corrosion that will not be described in detail here. The various types of corrosion can cause a number of problems ranging from cosmetic damage to engine failure and need to be evaluated case by case. From a life extension point of view, it is important to observe signs of corrosion and corrosive elements before the resulting damage become non-recoverable. It is important to keep in mind that certain corrosion mechanisms can have a long incubation time and thereafter develop extremely fast. It is therefore in many cases not the corrosion itself but the prerequisites for corrosion to take place that need to be monitored.

Corrosion damage may appear anywhere in the gas turbine but due to the need for a liquid phase, compressors tend to be especially sensitive. Hot corrosion is a special case that is described below.

Erosion is the process of material loss due to impacting particles. The particles enter through the inlet air. Protective measures are the use of anti erosion coatings and inlet air filters.

Erosion damage may either cause damage directly by the removal of material from gas channel parts, and indirect damage by damaging protective coatings. Erosion damage in itself normally develops slowly but may accelerate corrosion attacks by the removal of protective coatings.

Both corrosion and erosion can cause performance degradation that may in itself require repair or replacement of parts.

Hot corrosion

Hot corrosion is a special case of corrosion damage that occurs in the turbine or combustor sections in the temperature range where the corrosive elements are present in liquid phase. This means that the corrosive reaction can take place without the presence of water. Hot corrosion can take place in the combustor, turbine and exhaust sections but is most common in the turbine section.

Fatigue

During starts and stops, the temperature and load changes in the gas turbine can cause huge stresses in certain parts of the gas turbine. With time, these stresses may cause fatigue cracking of various parts. Dependent on material, crack location and expected crack growth rate, preventive actions could be preventive replacement, on-condition replacement, repair or monitoring.

Creep

Components exposed to elevated temperatures and stresses tend to deform with time. This can result in cracks that can limit the serviceable life directly, or deformations that may cause indirect damage by causing rotor – stator interaction or closing / opening cooling air passages. Creep is strongly temperature dependent. Dependent on material, crack location and expected crack growth rate, preventive actions could be preventive replacement, on-condition replacement, repair or monitoring.

Oxidation

Oxidation is the chemical reaction between component alloys and the oxygen in the air. Oxidation is temperature dependent and typically develops slowly.
Similar to corrosion and erosion, oxidation can cause performance losses that may require repair or replacement.

Ageing

Over long periods of time, at elevated temperatures, the composition and structure of materials may change – so-called ageing. This results in changed material properties that can cause unexpected failures. While ageing in itself tends to be a slowly developing process, its consequences may come quickly due to the fact that a minor reduction in yield stress can cause a large increase in strain range, which in turn can cause a dramatic reduction in e.g. fatigue life. The ageing may also cause embrittlement that can make the part extremely sensitive to rotor – stator interference and foreign object damage.

Foreign object damage and wear

For various reasons, components are sometimes the victims of impact damage from pieces of material that are hard enough to cause plastic deformation, so-called foreign object damage, FOD. The source of the pieces can be: external objects entering through the air inlet, ice built up in the air inlet, objects forgotten or not positioned and locked correctly during maintenance outages or pieces coming loose from other components in the engine. It can also occur during maintenance or transportation of equipment. It can therefore occur anywhere in a gas turbine.
Minor FOD can sometimes be seen in gas turbines. While not critical to the integrity of the components themselves, a multitude of impacts may influence performance as well as compressor surge margin especially if combined with corrosion and erosion damage.
Long term use of components can cause wear of contact surfaces. Wear can also be caused by contact between rotating and non-rotating parts due to increased vibrations or unexpected load transients. Similar to FOD, wear can sometimes cause performance losses. Wear of contact surfaces can also result in leakages or misfits that may cause additional damage.
Wear can occur anywhere in a gas turbine.

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