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INTEGRATED APPROACH TO GAS TURBINE ROTOR CONDITION ASSESSMENT AND LIFE MANAGEMENT

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ABSTRACT

Turbine manufacturers (OEM's) place limits on the service life of aging gas turbine (GT) rotors/discs based on either the number of hours of operation or the number of start-up cycles. These limits are based on design calculations and maintenance conventions, but and seldom fully factor in actual operational history of the individual turbines. A significant number of gas turbine rotors are either condemned or slated for replacement during a future outage. Some turbines experience premature damage resulting in the selective component replacements. EPRI conducted metallurgical evaluation of retired discs to understand the crack initiation and propagation mechanisms as well as detailed structural engineering analysis to understand damage root cause. Examples of rotor condition and remaining life assessment studies conducted are presented in this paper.

INTRODUCTION AND BACKGROUND

Historically, GT rotor life was considered to have many decades of useful life, consistent with a major structural component of the unit. Unlike the routine repair and replacement cycle for gas path and combustion components, the rotor presents significant maintenance issues for owners to ship large, heavy rotors to the limited facilities capable of disassembly.

OEM's have now defined significantly shorter than the original design life expectations or mandated periodic major disassembly inspections for the rotor structure. Premature rotor damage can result in large unplanned costs associated with extended outages where spare rotors are unavailable. OEM's have issued several directives to turbine owners about these problems and recommendations. The full cost of an unexpected serious rotor damage can exceed \$10M with considerable interruption to plant availability.

Since the rotor contains significant kinetic energy, sudden failure of rotating components represents various safety risks to personnel and equipment. An example of the substantial shortfall in expected rotor lives is the GE F-Class Stage 1 and stage 2 turbine wheel rim dovetail post cracking shown by Figure 1. These failures can happen in less than 50,000 hours and can cause additional millions of dollars in collateral damage to the gas path components. Other recent examples are the GE aft compressor rotor dovetail cracking on both the E-Class and F-Class turbines, resulting in a number of replacement Stage 17 compressor wheels. The Siemens V-X4.X Class turbines have similarly been identified to have significantly shorter lives due to premature embrittlement of the 12Cr turbine wheels. A failure incident related to compressor tie bolts on the Siemens-Westinghouse 501F resulted in extensive flowpath and rotor damage. The Alstom 11N's are also experiencing early retirement or shop rework due to turbine rotor life limiting design issues, such as the cracking in the turbine L-bore cooling channel. However, to date rotor damage has not resulted in outright catastrophic failure and safety impacts.

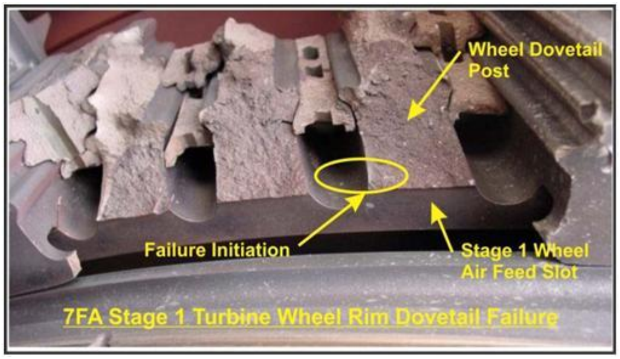

Figure 1. Frame 7FA First Stage Rim Failure

Many utilities recognize the need for proactive actions in life management of their fleet with safety, reliability and cost benefit as their main concerns. Balancing these aspects of the power plant management requires consideration of the OEM recommendations as well as the knowledge, expertise and technology available from independent engineering service providers. The EPRI rotor program has developed technology and methods to offer an integrated approach to gas turbine rotor condition assessment and life management. These methods provide turbine owners with an independent evaluation of remaining life with a defined rotor-specific technical basis

ROTOR DAMAGE MECHANISMS AND END OF LIFE

A significant level of variations exists in the conditions between the compressor inlet to the turbine outlet. The important variables that affect the damage mechanisms are temperature, stress, humidity, other external environmental variables such as the introduction of steam or water for NOx control and power augmentation, washing practices, use of chemicals, variations in the fuel compositions, rotor internal cooling configurations, stress concentration regions such as sharp corners, the severity of start-stop practices and unexpected trips. The potential and historically observed damage mechanisms for the GT rotor are many There are several categories of damage. The table below identifies the escalating damage categories in gas turbine rotors.

Table 1. Damage Categories in Rotors

Damage Category	Example	Consequences	Discovery Period
Repairable	Local Damage / Rabbet Oversize	Variable Maintenance Cost	Early
Non-Repairable	Deep Cracking	Early Replacement Cost Outage Delay	Mid-Life
Liberation Contained	Dovetail Post Failure	Extensive Collateral Damage Extensive Outage Duration	Mid-Life
Liberation Non-Contained	Wheel Fracture / Casing Rupture	Plant & Personnel Injury Loss of CT, Injury Litigation	Late

Various damage mechanisms are operative at the different parts of the turbine as listed below:

- Material property variations and service degradation
- Low cycle fatigue crack initiation in critical locations
- Creep damage in the higher temperature regions
- Fretting and fretting fatigue damage at the rim locations
- High-cycle fatigue at the rim due to abnormal vibration
- Oxidation, wear and corrosion of sections and key interfaces
- Crack growth during service from initiation or original defects
- Reduced fracture tolerance due to material embrittlement
- Abnormal loading which exceed the design parameters
- Other effects such as damage by adjacent structure or maintenance practices
- Progressive mechanical damage due to improper repair and assembly

A generalized map of some of the more common damage mechanisms in gas turbine components are shown in Figure 2. Depending on the location and the service conditions, rotor and disc crack initiation and propagation mechanisms may vary. On the compressor discs, corrosion pitting, stress corrosion cracking, low-cycle fatigue (LCF) crack initiation and growth, high-cycle fatigue (HCF) cracking of the blade attachments may limit the useable life. On the hot section turbine side the damage mechanisms are creep crack initiation and growth, low-cycle fatigue and thermal-fatigue (TMF) damage, embrittlement, etc. Other damage mechanisms include rim dovetail cracking due to excessive staking, flange cracking due to both HCF and LCF, vibration due to rabbet / bolt face slip, premature rabbet cracking, etc.

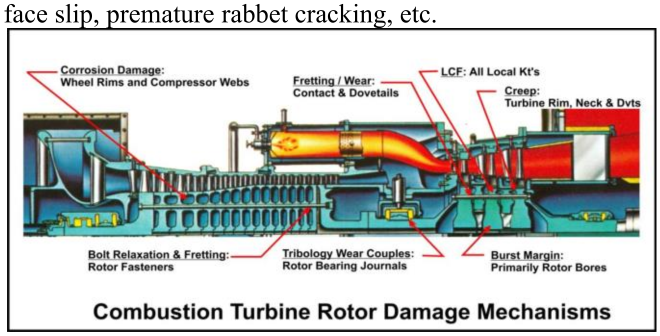

Figure 2. Some of the common damage mechanisms in GT rotors

Within the same wheel/disc, the damage mechanisms differ depending on the location. For example in a compressor wheel, the near bore area is subjected to high tangential and circumferential stresses. Even a relatively small flaw located in the near bore region could theoretically grow to critical crack size leading to rapid brittle fracture during a cold start condition. At the periphery blade attachment locations the failure mechanisms could be high-cycle fatigue crack initiation and propagation, corrosion pitting, crevice corrosion and stress corrosion cracking. Examples of corrosion pitting on a compressor disc and dovetail cracking is shown in Figure 3.

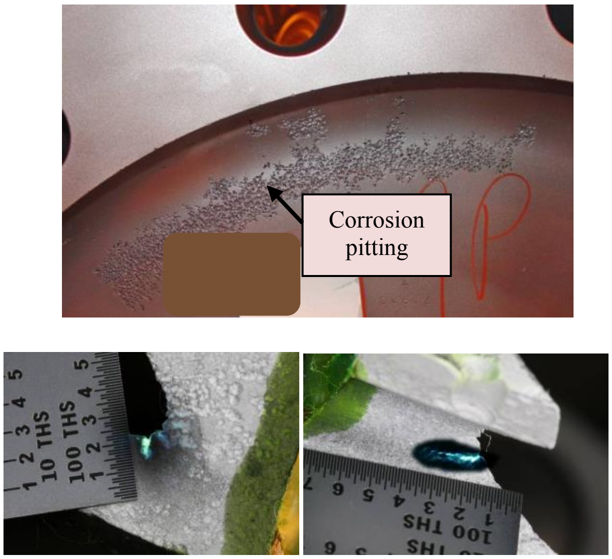

Figure 3. Corrosion pitting of an IGT compressor disc (top) and fluorescent particle indication of a crack at blade attachment dovetail (bottom)

Cracking at the inlet air feed slot of a Frame FA turbine is shown in Figure 4.

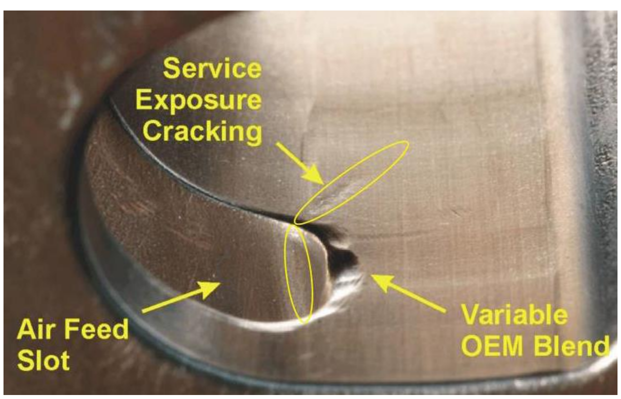

Figure 4. Air-feed slot crack at the first stage disc of a Frame FA rotor

In the case of turbine discs, the failure mechanisms may be crack initiation and growth from the bore area due to thermal fatigue stresses:creep crack initiation and growth from the rim, neck and dovetail locations (Figure 1) Locations where assembled discs interface with an adjacent spacer or connecting shaft, such as rabbet fits, are prime locations for fatigue induced cracking. Thus a condition and remaining life assessment study of a gas turbine rotor should take into account these numerous locations and respective failure mechanisms. NDE inspection methods, in-situ condition assessment steps material sampling, property selection and life assessment models, structural analysis require careful consideration of the various failure mechanisms for the integrity and remaining life assessment. Of course, the past operational history and future duty cycles of the turbine are required in this integrated life assessment procedure.

The definitions of 'end of useful life' vary depending on the users' perspective and priorities in their overall philosophy of rotor life management. The three main factors considered to arrive at end of life are the plant history, performance and inspection. Engineering analysis (NDE, materials and structural analysis), turbine operational variables, safety concerns, economic analysis and justification, etc. play critical role in deciding the end of useful life. A detailed discussion of this subject is outside of the scope of this paper. The reader is referred to Reference 1 for the various definitions of failure and end of life criteria.

Design Based End-of-Life Criteria by the OEM's

Rotor design life is specific to a turbine model and the OEM as shown in Table 2. For example, GE's TIL 1576 states that the end of life of an E-class rotor is when 5000 factored starts or 200,000 factored hours are reached. Other OEMs do not actually declare an upfront end of life leaving open such determinations to the scheduled inspections. End of life may be limited to only certain rotor components such as bolts or discs particularly where the design has been upgraded. The uncertainties in the design and statistical distribution of life calculations tend to be under accounted. Life limits are based on proprietary design information, material data, and fleet history retained by the OEM's and not openly shared with the turbine users.

Table 2. End of life criteria used by the major OEM's - Update

GE - E and F class:	Siemens - V Machines E and F class:	Siemens - (Westinghouse 501) D/E and F:	MHI G-Class:
(starts / hours) E-Class 5,000 / 200,000 F-Class 5,000 / 144,000 No Extension	2^{nd} major Insp.: 3000 starts /100,000 h Extension: 3000 /100,000 h	Major Insp.: 3600 starts/100,000 h Extension: 3600 starts/ 100,000 h	2^{nd} major Insp. 3200 starts/100,000 h Extension: 3200 starts/ 100,000 h

A typical OEM approach is to apply the minimum values for the entire fleet size and therefore protect the worst case unit. Based on expected scatter for the engineering variables, the average unit should expect a significantly longer useful life. This is shown by the Figure 5 and is the basis for most engineered life extension programs.

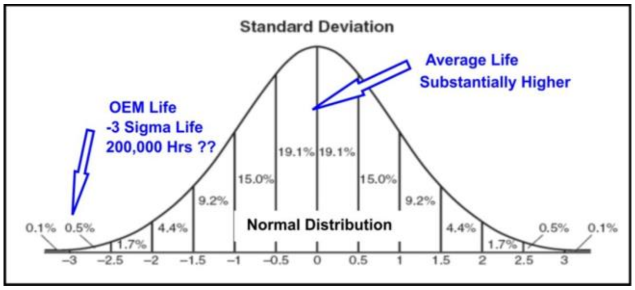

Figure 5. Normal life distribution curve and OEM's end of life definitions

For example, for the GE MS5001 class industrial gas turbine has declared the useful life to be 5,000 factored starts and 200,000 factored hours with up to one additional 50,000 factored hours interval based on disassembly and inspection. These criteria are established for the E-class rotors by GER-3620, TIL-1576 and ETC-068. GE provides no additional service life beyond 5,000 factored starts. The restrictions apply to both the compressor and turbine rotors. Further, no starts based maintenance factors is provided for rotors other than the F-Class. The situation leaves turbine owners with the inability to calculate factored starts. Consequently several GT owners of E-class turbines confronting the 5,000 starts life limit have taken it upon themselves to re-qualify the rotor for extended service using independent resources.

MATERIAL DEGRADATION MECHANISMS AND THEIR EFFECT ON ROTOR LIFE

There are several alloys used in the manufacturing of gas turbines. Depending on the operating temperature and environment various chemical compositions, heat treatments and strengths are selected. Low alloy steels such as 2-3.5NiCrMoV and 1CMoV steels are generally applied to the compressor discs. For the hot end turbine discs and built-up rotors, 1CrMoV, 12Cr alloys and in some cases INCO alloys (IN-706 and IN-718) with varying compositions are used by the US and European manufacturers. When the rotor is exposed to the operating environment and high-temperatures for a long time, the rotor material properties will eventually degrade. It is important to take into account such property degradation in performing the remaining life assessment calculations. Material vintage and cleanliness can have an influence on the material properties and aging characteristics. The extent of residual elements such as phosphorus, sulfur, antimony and tin play important role in the embrittlement susceptibility of the steels. Old vintage alloys (pre 1980) are more susceptible due to higher impurity content. More recent vintage rotor materials are cleaner and less susceptible to this problem. Some of the material degradation mechanisms as a result of service exposure are listed below.

- Metallurgical microstructural changes
- Material softening and hardness decrease
- Yield and tensile strength reduction
- Creep strength decrease
- Low-cycle fatigue strength reduction
- Increase in crack growth rates leads to lower life
- Increase in the ductile to brittle transition temperature (fracture appearance transition temperature, FATT)
- Decrease in fracture toughness which results in increased risk of brittle failure

One of the most reliable methods of obtaining material properties is to conduct destructive sectioning of retired rotors and discs and perform the various metallurgical and mechanical tests to obtain the critical properties. EPRI has acquired many such rotor discs after retirement and is conducting various metallurgical and mechanical tests to obtain the necessary data to apply in our life assessment programs.

Properties obtained are tensile, Charpy impact (FATT), fracture toughness, crack growth, low-cycle and creep properties. Material tests from highly stressed locations such as the fir tree posts were conducted to investigate the presence or absence of local damage due to long term service. Disc materials covering the full service operating regime range from low hours/starts to high hours (exceeding 300,000 hours) and high starts (exceeding 5,000 starts) are evaluated and tested to obtain material properties.

INTEGRATED ROTOR CONDITION AND LIFE ASSESSMENT

An integrated approach which combines critical engineering disciplines and plant operational history is essential to conduct a pragmatic condition and remaining life assessment of rotors. These four areas are illustrated in Figure 6. All these four components are critical and play equal importance in any rotor life assessment program.

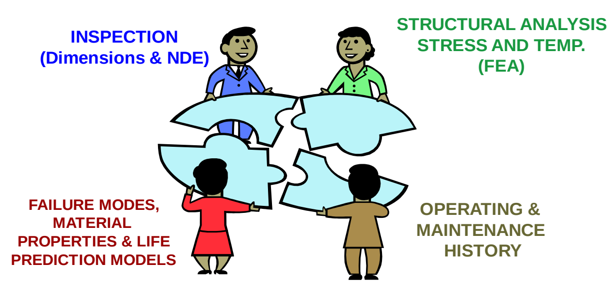

Figure 6. Four critical disciplines of an integrated condition and remaining life assessment program

Dimensions and Nondestructive Inspection

The dimensions of the rotor components undergo changes during the life cycle of turbines. There are many reasons both metallurgical and mechanical in nature contributing to these changes over time. The dimensional features of each component are characterized and models prepared by computer aided design (CAD). The measured dimensional features help to verify whether the critical dimensional tolerances have deviated over time due to the thermal stresses of the gas turbine that may operate in a cyclic load. The dimensional measurements are performed using coordinate measurement machines (CMM) and then converted to CAD models. The accuracy with which this activity is performed will affect the precision of the subsequent structural integrity and remaining life assessment evaluations. Some of these critical dimensions are listed below.

A. **Turbine Wheels** – all stages – diameters, run-outs and flatness are the critical dimensions
    1. Rabbet fits
    2. Bores
    3. Bolt circle faces
    4. Bolts and bolt holes
    5. Bucket dovetail fit – measure and assess stock loss from wear/corrosion

B. Turbine Spacers
    1. Rabbet fits
    2. Bores
    3. Bolt circle faces
    4. Bolt holes
    5. Outer diameter seal features

Proper tooling with high accuracy and sensitivity are used to measure these dimensions either in the field or at an overhaul facility. Both contact and non contact systems are used for this purpose.

Nondestructive Evaluation (NDE)

NDE is an integral part of any condition and remaining life assessment program. We follow the general outline below:

Disc/wheel NDE Methods

1. Central Bore – Ultrasonic and Magnetic Particle
2. Web and Disc – Ultrasonic, Liquid Penetrant, Magnetic Particle
3. Bolt Holes – Eddy Current, Ultrasonic
4. Rim - Ultrasonic, Liquid Penetrant
5. Blade Attachment Posts (dovetails) - Eddy Current, Liquid Penetrant,

Figure 7. NDE methods used to evaluate the various regions of a turbine disc

A. Turbine Wheels/Discs
    1. Visual and fluorescent magnetic particle (MT) inspection of all surfaces
    2. Ultrasonic (UT) inspection of the bore, web and rim areas
    3. Eddy current (ET) of the through-bolt holes and rim dovetail serrations

B. Turbine Spacers
    1. Visual and fluorescent MT inspection of all surfaces
    2. UT of the bore
    3. ET inspection of the through-bolt holes

Metallurgical Assessment

A. Turbine Wheels/Discs
    1. Bore area – replicas for microstructural assessment, hardness tests
    2. Rim/dovetail area – replicas for microstructural change and material damage assessment and hardness tests

B. Turbine Spacers
    1. Bore area - replicas for microstructural assessment, hardness tests
    2. Rim/seal area - replicas for microstructural assessment, hardness tests

Using the results of the NDE solely to make a disposition on the wheel/rotor is not prudent since some internal quality conditions and defects which may be missed detection during inspections will adversely affect the integrity and remaining life of the rotors.

Critical Material Properties and Testing

Some of the material properties and life assessment methodology developed for steam turbine rotors over several decades under various EPRI programs are also applicable to GT turbine rotors. These alloys are similar but there are also differences in the chemical compositions and heat treatments applied to manufacture GT rotor discs. Thus, one must exercise caution in the judicious selection of appropriate properties to apply in the life prediction models. TurboMet International has extensive experience in steam and gas turbine alloys – manufacturing, chemical composition, heat treatment, property degradation, etc.

The critical material properties used in rotor integrity and remaining life assessment are as follows：

- Chemistry
- Hardness variation at different regions
- Tensile (Yield & Tensile Strengths, %El and %RA)
- Charpy Impact Properties (FATT shift)
- Fracture Toughness, K_{Ic} and J_{Ic}
- Crack Growth (da/dN and da/dt)
- Low-cycle Fatigue (with and without hold times)
- Creep deformation, creep strength and Ductility

A good material database is essential to carry out such projects and being developed under this program from retired discs as well as using miniature samples obtained from discs in service

An example of miniature sample removal from a MS 5001 disc is shown in Figure 8.

Figure 8. Miniature surface scoop sampling from MS5001 turbine discs for material condition and property assessment

In the absence of such data, one assumes very conservative properties which could lead to erroneous recommendations. Many of these properties are a strong function of temperature. Small specimen versus large specimen property correlations are being established to facilitate the extraction and use of miniature specimen to obtain the necessary material properties from the actual rotor being evaluated.

Life Prediction Methods and Algorithm

Since the rotors and discs have relatively large section sizes, the total life of these components is determined by both crack initiation and crack propagation lives. As discussed previously, cracks may initiate under creep or creep-fatigue, low-cycle fatigue or high-cycle fatigue conditions in the turbine discs. Corrosion pitting, stress corrosion, low-cycle fatigue and high-cycle fatigue mechanisms may be operative in compressor rotors and discs. In spite of all the technological advances, it is very difficult to predict exactly when a crack will initiate and propagate to an engineering size crack before it may be detected by NDE methods. An important factor to be taken into consideration is the capability of the inspection systems used. Crack/flaw detection sensitivity and flaw sizing capabilities of these inspection systems vary widely. One of the major goals of conducting integrity and remaining life assessment of rotors and discs is to establish safe reinspection intervals to prevent potential catastrophic failures. The re-inspection intervals need to be established in order to detect cracks, which may form and grow during service before reaching a critical crack size where catastrophic failure may become imminent. Figure 9 illustrate this concept as a plot of crack size versus operating time or cycles.

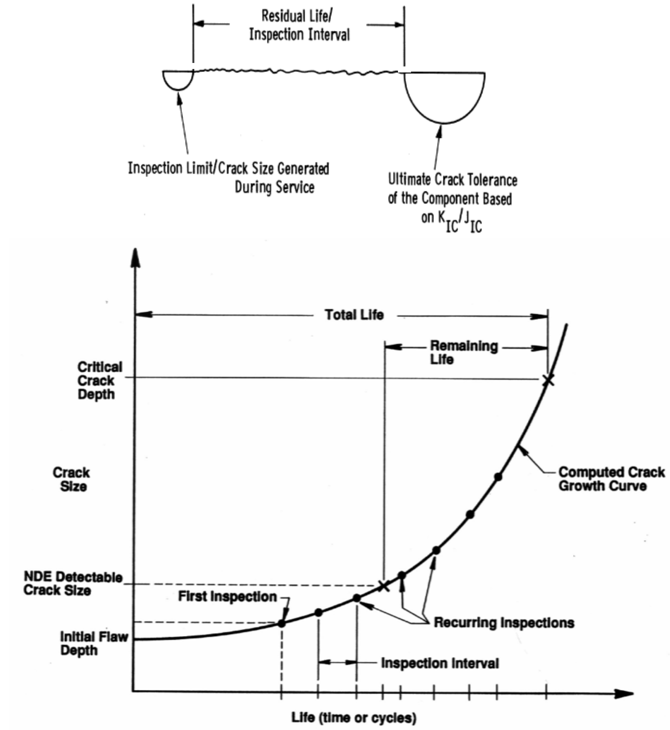

Figure 9. Schematic diagrams showing the relationship between NDE detectable crack size, life of the rotor and reinspection intervals

A general logic flow chart for the remaining life analysis of rotors and discs, using linear elastic fracture mechanics (LEFM) and time dependent (creep conditions) fracture mechanics (TDFM) methods for the GT rotors is shown in the Figure 10. Such methodology has been well developed under several EPRI programs and in use for over three decades in the steam turbine industry.

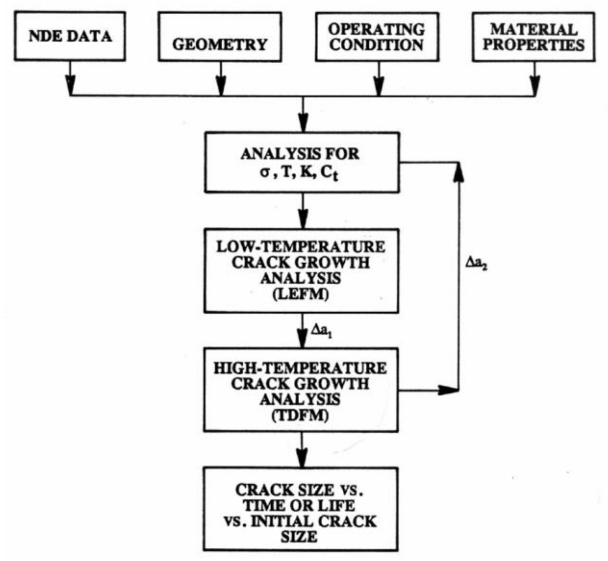

Figure 10. A logic flow chart for the remaining life analysis of GT rotors and discs follows similar proven approach used for steam turbine evaluation

A full description of the EPRI approach to rotor life assessment is covered in Reference 2. Several GT disc condition and life assessment projects have been conducted under EPRI contracted projects on turbine models such as 7FA/9FA (Reference 3), Frame 7EA, W-501B, Frame 5001, Siemens V 84.2, Frame 6B, SW501F Details of a specific case study on a MS 5001 disc are presented in the next section.

A CASE STUDY – FRAME 5001 ROTOR LIFE ASSESSMENT

An example of the applied use of the methods described is the investigation of the GE Frame 5 rotor life. This project involved EPRI acquiring a high serviced hours (312,000 hours of base load service) scrap turbine rotor from a petroleum refinery. The GE Frame 5 (MS5001) single shaft gas turbine model has been in continuous production since the late 1950's with thousands of units sold by both GE and many international licensees. Both material and design changes were introduced over several decades. The unit consists of a base mounted, rear shaft drive, 17 stage compressor (16 stages early units) with a two stage turbine and a synchronous speed of 5100 RPM (4860 RPM early units). These units have served many industrial applications ranging from power generation, chemical processing, petroleum pumping, and pipeline compression. The Frame 5 is normally installed with a load coupling reduction gear system to match the intended drive speed requirements. The Frame 5 has an extensive history of model revisions and upgrade offerings ranging from 10,750 kW to 26,820 kW.

Rotor Disassembly and NDE

The rotor was removed from the power plant and shipped to a facility in Texas. Rotor disassembly procedures were prepared and the rotor disassembly performed as shown by Figure 11. Standard methods of thermal disengagement were applied with field tooling used to facilitate the rotor disassembly.

Figure 11. Disassembly of MS 5001 rotor using heating/cooling to disengage shrunk on rabbet fits

The program involved extensive NDE inspection to establish the surface and internal quality condition of the turbine wheels. As previously discussed, flaws can both initiate during service and could originate from initial forgings at manufacture. These defects can grow in service and become an important aspect of defining the remaining life limit of the discs. It is important to note that even if defects are below the reported inspection sensitivity, they could grow during service and should be considered in the remaining life assessment study.

The inspection methods described previously were used to inspect the disc. Ultrasonic inspection using straight and angle beams and phased array units were performed. Figure 12 shows the inspection of the MS-5001 first stage disc.

Figure 12. Ultrasonic inspection of the MS 5001 first stage disc

No detectable indications were reported by the various inspection techniques utilized to inspect this disc. However, minimum detectable crack size was used in the life assessment of the wheel by the fracture mechanics methodology described above.

Metallographic and Materials Properties Evaluation

Initially, material properties available from other similar CrMoV disc material testing and material property database developed for the GT rotor assessment project were used in this analysis. Metallographic evaluation of the rim post serration samples did not reveal the presence of localized creep damage. Thus, creep crack initiation was not a concern in this case.

Chemistry testing revealed relativity high amounts of phosphorous and sulfur in the first stage disc. Given the pre-1980 steel vintage and long operating history, these impurities raised concerns that the material had embrittled. The rotor discs were subsequently sectioned and destructively tested. Figure 13 indicates the overall FATT results based on Charpy impact specimens and confirms embrittlement. The baseline FATT of 66C (150F) was established by testing de-embrittled heat treated material and colder rotor shaft end material. Small punch testing was independently performed. Figure 14 shows that the standard large specimen results correlated exceptionally well with miniature small punch samples. The difference in FATT (ΔFATT) from the de-embrittled condition is (365 -150 = 215F [119C]), This data shows that a significant degree of embrittlement occurred during service exposure in this disc and resulted in toughness loss (References 4,5).

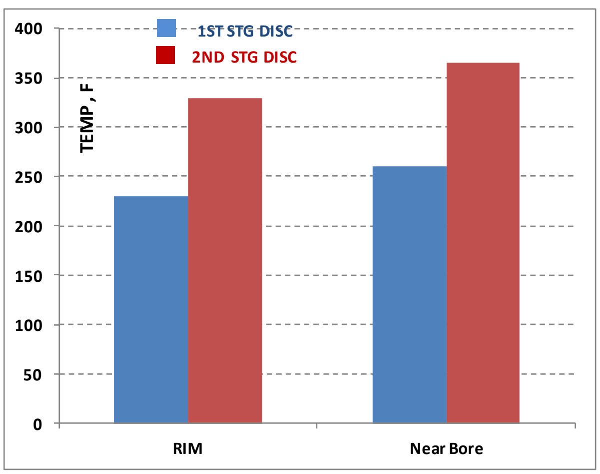

Figure 13 FATT of the two as-received discs measured by Charpy impact testing at the rim and near bore regions showing significant temper embrittlement (FATT Increase) during service

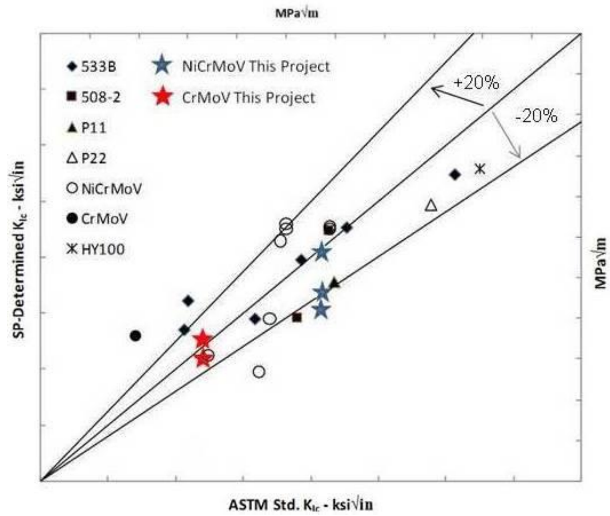

Figure 14 Comparison of various alloys using Small Punch and standard ASTM tests provides K_{Ic} toughness values within ±20% of full-scale specimens.

Dimensional Characterization

The dimensional characterization is an important part of the life assessment process. This step provides the geometric definition for the analysis, as well as describing abnormal wear, corrosion or other dimensional defects of the rotor components. Dimensional characterization was performed by AccTTech using laser scanning coordinate measurement machines (CMM) and other techniques. These results are used to produce a detailed 3-D CAD model of the turbine, shown by Figure 15.

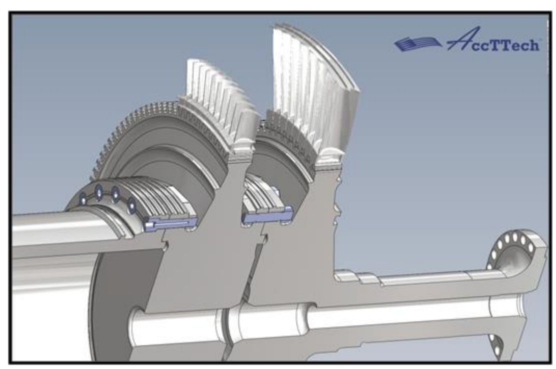

Figure 15. 3-D CAD model of the MS-5001 rotor showing the distance piece, Stage 1 and Stage 2 disc assembly

PLANT OPERATIONAL DATA

Turbine operating history was made available by the plant and is a critical input for this analysis. Various parameters recorded during a typical startup is shown in Figure 16. A worst case scenario for a typical cold start is used to establish the final fracture criterion. There is a significant concern that a sudden disc fracture would occur when the transient stresses are the highest and the fracture toughness of the material is relatively lower.

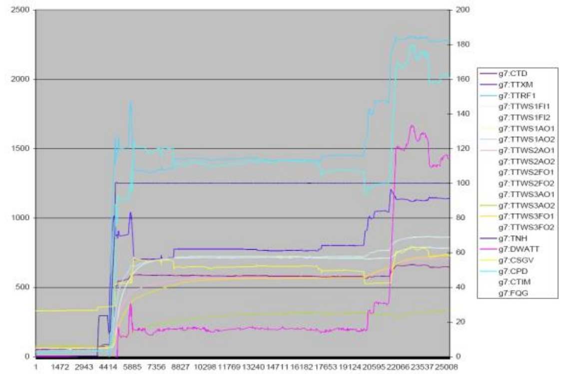

Figure 16. Example of turbine start-up data needed for structural analysis of rotors and discs

Structural Analysis

A finite element analysis is performed to assess the structural capability of the turbine rotor. The analysis identifies the critical regions for inspection and is the basis for the life assessment and reinspection interval definition. An ANSYS analysis was performed of the Frame 5 turbine rotor and is shown by Figure 17. A 2-D axisymmetric analysis is used to assess homogeneous sections of the rotor such as the bore and neck regions. The more complex regions such as the bolt holes and rim dovetail posts require advanced analysis treatments such as cyclic symmetry methods. Modern ANSYS analyses include the capability to model contact regions such as blade and disc attachment, friction, rabbet interference fit and other important local loading conditions. The advances in analysis methods have significantly improved the accuracy of the life assessment estimates from the original OEM calculations. These improvements, when correctly applied, can contribute to increased life of the rotor by reducing the original design uncertainties and excessively conservative design margins.

The rotor structure is a complex environment with various cooling and heating effects driving the thermal response of the wheels. The large, massive wheels are subject to thermal transient stresses which can greatly exceed the steady state calculated values.

Figure 17. A 2-D axisymmetric ANSYS model of the MS 5001 rotor

An example of the transient response of a turbine wheel during a cold start transient is shown by Figure 18. The stress peaking, when combined with the cold metal temperatures, could create a life limiting combination. The peak thermal stress occurs internally at about 3 in radius from the bore surface. The material fracture toughness is a strong function of temperature, with lower temperature resulting in lower fracture toughness. The aging turbine rotor material could further reduce the fracture toughness due to embrittling phenomena, if present. The life analysis evaluates the time dependent stress and temperature to establish the volumetric distribution of allowable flaw sizes.

The embrittlement found in the disc is factored into the lifing analysis by relating the reduction in fracture toughness to critical crack size by the following relationship:

$K_{Ic} \sim \sigma\sqrt{(\pi\, ac)}$

Where K_{Ic} = the critical fracture toughness

σ= nominal stress

ac = the critical crack size.

Thus the critical crack size is proportional to the square of K_{Ic}.

$ac \sim \{K_{Ic}/\sigma\}^2$

K_{Ic} was found to be reduced by approximately ½ in the aged material. Thus the resulting critical crack size is significantly reduced by a factor of 1/4th during cold operating conditions.

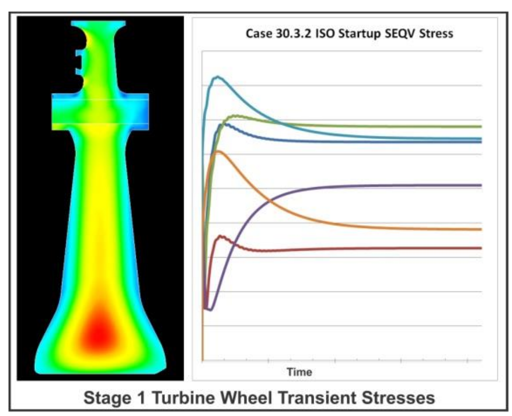

Figure 18. Example of transient stress versus time in a turbine disc during a cold start at a various distances from the bore surface

The final life assessment provides estimates of the creep life, LCF life and crack growth and final fracture life of the turbine rotor based on condition assessment of the components. All of the limiting locations of each component are evaluated to establish margin and life values against prudent design criteria. The process includes establishing the amount of life consumed and most importantly, the amount of life remaining. These values are reviewed with the turbine owner, along with operation and maintenance goals and risk tolerance levels to establish reasonable rotor life targets. A re-inspection program schedule is generally established unless the rotor life extension is intended as a onetime gap measure. An example of a crack propagation evaluation which was used as part of this life assessment strategy is shown Figure 19.

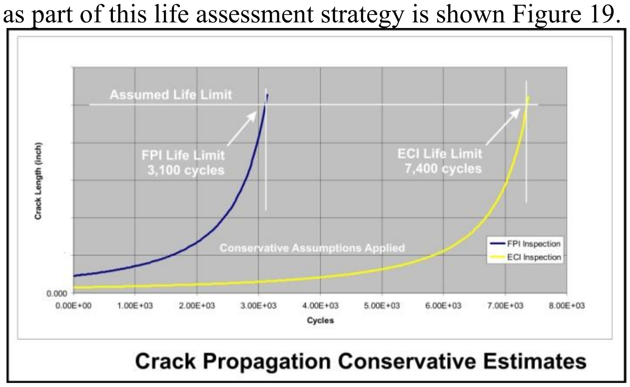

Figure 19. Results of crack propagation analysis

The assumed life limit is based on a critical crack size formation at the most life limiting location of the disc based on the structural analysis results. These curves are highly location and crack/defect orientation and local stress field dependent.

SUMMARY

Structural integrity and remaining life assessment of GT rotors requires a multidisciplinary and integrated approach to conduct a pragmatic engineering analysis by experts with extensive experience in this field. Qualified and reliable NDE methods, appropriate material properties representative of material chemistry and age, life prediction models to address the specific operating failure mechanisms, detailed turbine operational data and a comprehensive structural analysis are essential to arrive at reliable and safe remaining life estimate of rotors and discs. Understanding the weak links in a model-specific rotor design and relating to the site-specific operating history and inspections is key to moving beyond more generalized OEM life criteria. EPRI is developing the Small Punch Test and continues to develop material properties by acquiring and testing scrapped and retired GT discs. Structural analysis models are being developed for several turbine discs and rotor configurations to address the various complex geometries and cooling schemes used in the turbines. Recommendations resulting from these life assessment projects are applied by turbine users to effectively manage the life of their turbines.

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