The Future of Gas Turbine Technology
9th International Gas Turbine Conference
10-11 October 2018, Brussels, Belgium

Paper ID Number: 52-IGTC18

EXTENDING THE LIFE OF F-CLASS GAS TURBINE ROTORS FOR IMPROVED OPERATIONAL & MAINTENANCE LIFE CYCLE COSTS

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ABSTRACT

F-Class heavy-duty gas turbines have been in commercial operation in excess of 25 years. While being a workhorse in the power generation market during that time, the market has evolved dramatically, resulting in the change of operational modes of these units. Switching form baseload to cyclic operations, failure mechanisms unforeseen on earlier E-Class units are starting to emerge. Furthermore, larger components such as the rotor, are fast approaching, or have reached, the OEM recommended lifetime from either a starts or hours-based perspective. As such, the reliability and maintenance of such capital components are on the forefront of many operators minds. To address this issue, operators are turning to OEMs and third party service providers to replace or evaluate the continued operation beyond that of the original recommended service life. While limited end of life (EOL) inspections have been sufficient on older technology, recent comprehensive inspections on multiple OEM F-Class units have revealed significant drawbacks of limited inspections. Utilizing a comprehensive set of inspections, multiple life-limiting indications have recently been discovered at various locations throughout F-Class rotors. These indications will be detailed, as well as the repair and/or replacement solutions provided to successfully return the units to service beyond that of the OEM recommendation.

INTRODUCTION

The fleet of F-class gas turbines has become mature technology with successful operation of thousands of units around the world from multiple OEMs. These units have been designed to provide safe and reliable means of producing power for industrial purposes, all the while surviving some of the harshest environments possible. While there are significant differences between the different units, all units undergo various levels of overhaul during the operational lifetime as a result of degradation in those environments. Many of the components, e.g. airfoils and combustion systems, are readily interchangeable in the field at the exhaustion of their prescribed interval and can be inspected and/or replaced during normally scheduled outages. Larger components, such as the rotor, are designed to last multiple intervals with little-to-no degradation over the lifetime. Now that the F-class fleet has reached mature status, these capital components are in need of overhaul and replacement. Considering the cost of a replacement rotor can exceed €10M, Operations and Maintenance (O&M) budgets are forcing operators to explore alternative solutions to rotor replacement.

Building on the success of end of life (EOL) inspections of older units, several third party vendors are preforming lifetime evaluation (LTE) inspections that interrogate select components within the rotor, e.g. aft stages of the compressor section and turbine rotor. In doing so, such inspections turn a blind eye to the possibility of damage accrued in other locations as a result of several factors, e.g. assembly practices or original manufacturing non-conformances. Coupled with the more detrimental duty cycles and stresses that are inherent in the F-Class fleet, limited inspections have the catastrophic possibility of missing potential life limiting flaws in the components that were not inspected. As such, a myriad of inspections on all components should be the backbone of any rotor LTE program.

Over the last several years, a robust and comprehensive rotor LTE program has been developed in which all components are inspected and analyzed for continued operational usage. The goal of this paper is to highlight the core pillars of such an evaluation program and detail the specific requirements of evaluating multiple OEM rotors. While there are key differences, the framework and inspection techniques are similar, enabling a cross-fleet knowledge base that enables a more enlightened recommendation. Additionally, recent inspection findings and repairs will be detailed that reaffirm the necessity to inspect all components for continued reliable operation.

NOMENCLATURE

DOF	Degrees of Freedom
EC	Eddy Current Testing
EOL	End-of-Life
FCG	Fatigue Crack Growth
FE	Finite Element
FEA	Finite Element Analysis
FM	Fracture Mechanics
FPI	Fluorescent Penetrant Inspection
HCF	High Cycle Fatigue
LCF	Low Cycle Fatigue
LEFM	Linear Elastic Fracture Mechanics
LTE	Lifetime Evaluation
MT	Magnetic Particle Testing
NDT	Nondestructive Testing
O&M	Operations and Maintenance
OEM	Original Equipment Manufacturer
UT	Ultrasonic Testing

END OF LIFE ROTOR INSPECTIONS

Rotor inspections are typically executed after having developed inspection criteria and allowable defect maps based on advanced finite element modeling (FEA). Such analyses includes the use of super computers to model the complete transient behavior of rotors, e.g. Das, 2014. By capturing the assembly loads, start-up, steady-state, and shut down regimes, stress ranges are calculated for a complete cycle. When utilizing elastic-plastic properties, and running the simulations over multiple start-stop cycles, the true shaken-down stress range is calculated. Additional mechanical integrity calculations are then performed to determine the inspection criteria.

Surface-induced issues can arise due low cycle fatigue (LCF) and high cycle fatigue (HCF). The cyclic operational modes gas turbines are transitioning towards result in LCF issues in high stress locations, whereas prolonged operation can lead to HCF issues, e.g. rotating-bending. While lifetime prediction methodologies of both LCF and HCF have been around decades, e.g. Basquin, 1910, Manson, 1953, Coffin, 1954, implementation on FE models that contain >10M degrees of freedom (DOF) requires the development of sophisticated LCF/HCF tools. Further, accounting for the major contributing factors that credit or debit the life is a requisite for robust life tools, e.g. Day, 2011. Once LCF and HCF lifetimes are calculated, crack growth analyses are required to understand the behavior of flaws beyond initiation lifetimes.

Fracture mechanics (FM) methods are used to understand the growth of flaws and cracks, whether the flaws are service-induced surface indications or manufacturing defects from original material processing. Crack growth analyses follow the LCF and HCF calculations to determine the critical flaw size in all locations through the rotor. Sophisticated software tool suites are commercially available that account for influences on the behavior of cracks, e.g. threshold, stress ratio, load redistribution, etc., NASGRO, 2015. These tools have been used in the study of heavy duty gas turbine rotors and have the ability to simulate the growth of flaws , Keller, 2015. In addition to predicting the growth behavior, back-calculations are possible in which minimum flaw sizes to achieve a safe operational interval are readily calculated. Utilizing this calculation mode, flaw size zone maps and detection limits can be develop for nondestructive testing (NDT).

The remaining analyses include the use of sophisticated creep equations to predict the long-term exposure effects on the rotor. A significant portion of the rotor is subjected to sufficient stress and temperature that warrant the investigation of creep behavior over several hundred thousands of hours. Creep rupture is not necessarily a concern for common rotor materials, but creep deformation has the potential to be a failure mode after sufficient operational time. Similar to the LCF/HCF calculations, such routines to analyze creep deformation must be sufficient to work on large FE models. Methods have been developed capable of working on such models, e.g. Day and Gordon 2014, Day and Gordon 2017, which are suitable for analyzing multiple materials within a single user subroutine. The added benefit of these routines is that design margin, based on the material, is able to be estimated, providing analysts with understanding of the limits of the OEM rotor design.

Through the use of advanced FEA and multifaceted lifetime analyses, inspections required to perform rotor LTE analyses are developed. By coupling the operational history of the unit and the analytical methods highlighted, comprehensive NDT inspection plans are required to understand the current state of the rotor. These inspections serve as the basis for all life calculations on the rotor and any potential extension of life.

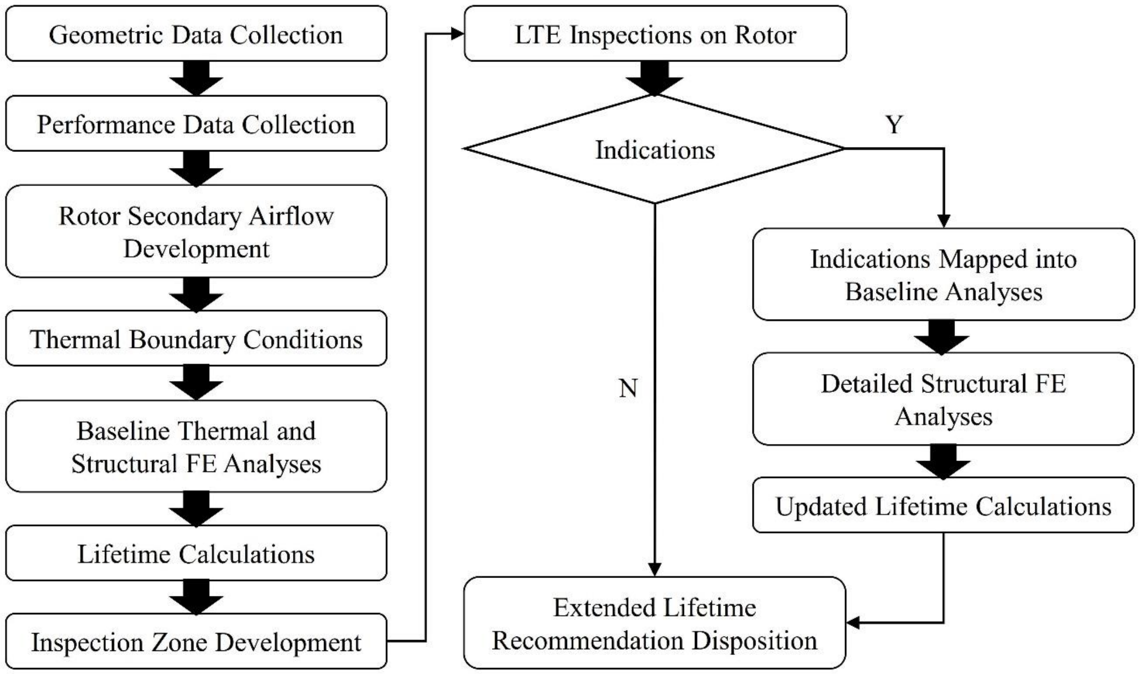

Figure 1: Rotor lifetime evaluation flow chart.

Rotor EOL investigations should be conducted on all components of disassembled rotors, ensuring complete and overlapping coverage of multiple NDT methods. While analytical models can drive the exact inspections and techniques used, NDT technicians should be "blind" from critical flaw sizes to prevent potential skewing of results and ensure the probability of detection is sufficiently high for all indications. Inspections should include the use of visual, dimensional, metallurgical, hardness, penetrant, eddy current, and ultrasonic testing techniques to ensure all detrimental indications can be found.

Standard rotor repair procedures include the destack of the compressor and turbine modules. Upon cleaning of the individual components, all parts should be visually inspected for gross flaws. Depending on the composition of the components, fluorescent penetrant inspection (FPI) or magnetic particle testing (MT) shall be conducted on all parts. Provided the criticality of the rotor, all relevant linear indications shall be reported and dispositioned regarding the residual life estimate.

Tracking and trending of the material is essential to understanding the continued load carrying capability of the components. At various locations throughout the rotor, microstructural evaluation and hardness testing should be conducted. Both hot and cold locations should be reviewed, as the cold locations will serve as comparators for the hot section results. Degradation can easily be captured through microstructural review and macro/microscopic hardness testing. Care should be given to the locations, such that re-inspection could be carried out in either assembled or disassembled configurations, enabling additional sampling points outside of rotor-out events.

In areas of high stress and/or poor line-of-sight, eddy current probes should be utilized to inspect for surface defects. Common locations include disk attachments, bolt holes, cooling holes, and central bores. With some features of F-Class rotors having cooling holes that are >12 in (>300 mm) in depth, eddy current probes have the ability to provide sufficient coverage while maintaining a high probability of detection. Linear array systems exist that can be form fit to custom probes and output digital records of scanning for archival purposes. With the small flaw sizing resolution of these systems, all critical areas are able to be inspected while maintaining a high probability of detection.

With individual components accessible from all sides, ultrasonic inspections (UT) can scan the entire volume of a disk for anomalies. Utilizing the latest in phased array UT equipment, large volumes can be inspected with resolution sizing down to <0.030 in (<0.763 mm). By scanning the components from multiple faces, overlapping inspections are readily obtained, reducing the amount of time that is consumed via smaller conventional UT probes. Whether anomalies are present as a result of original forging process or through service-induced growth, all components should be UT inspected regardless of location within the rotor.

Upon completion of the NDT efforts, the results should be fed back into the analytical models to evaluate the current status of the rotor and evaluate the possibility of continued operation. While inspection-only will provide a “snapshot” in time of the status quo, the complete LTE process map, Figure 1, with the analytical models is paramount to the evaluation and extension process. While an extension of life is not guaranteed, a sound engineering approach has been implemented to asses the true lifetime of the components.

INSPECTION FINDINGS

Implementing the EOL inspection, recent assessments of F-Class rotors have revealed several failure modes across multiple fleets. As the subject rotors were compromised of several disks in a bolted configuration, any one issue had the potential to be the life-limiting feature within the entire rotor. While some indications could potentially be discovered through visual inspection, others required the use of multiple NDT techniques to identify and confirm the indications. The following are some recent examples of NDT discoveries on a number of F-Class rotors.

Recent Finding #1 – Surface Indication in Blade Slot of a Row 2 Compressor Disk.

A non-planar surface breaking crack was discovered on the pressure face of a blade slot in a Row 2 Compressor Disk, as shown in Figure 2. The total length of the indication was approximately ~1.5 in (~38 mm) and the depth of the crack was measured via ultrasonic testing to be ~0.500 in (~13 mm). While initially the crack was missed on the visual inspections, the crack was discovered using MT, EC, and UT inspections. The importance of overlapping inspections was highlighted with the visual “miss,” as the additional methods were able to detect and size the flaw.

The result of this finding was the retirement of the particular component. Upon structural model review, the remaining useful life of this surface-breaking crack was not sufficient to achieve the customer desired extension interval. As such, a replacement Row 2 Compressor Disk was matched to fit the remaining disks within the rotor. At one point in time, a request was made to leave the disk bladed and to perform as complete of an assessment as possible. Although detectable via UT, by being able to confirm with EC and MT inspections, the probability of detection was never in doubt.

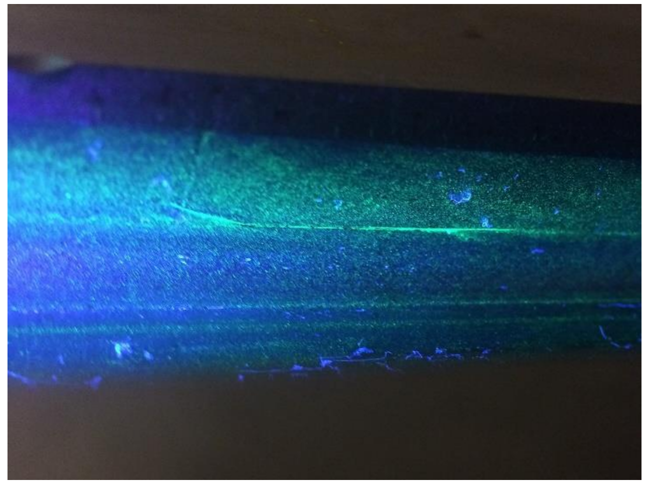

Figure 2: Surface-exposed crack discovered in a disk attachment near the edge of contact with the blade.

Recent Finding #2 – Forging Defects in Row 9 Compressor Disk

During the phased array UT inspection of a Row 9 Compressor Disk, over 60 indications were discovered, as shown in Figure 3. While a majority of these indications were individual findings, a cluster was discovered that exhibited a linking up of multiple indications resulting in a total length of ~0.750 in (~19 mm), as shown in Figure 4.

Figure 3: Over 60 UT indications discovered in a row 9 compressor disk.

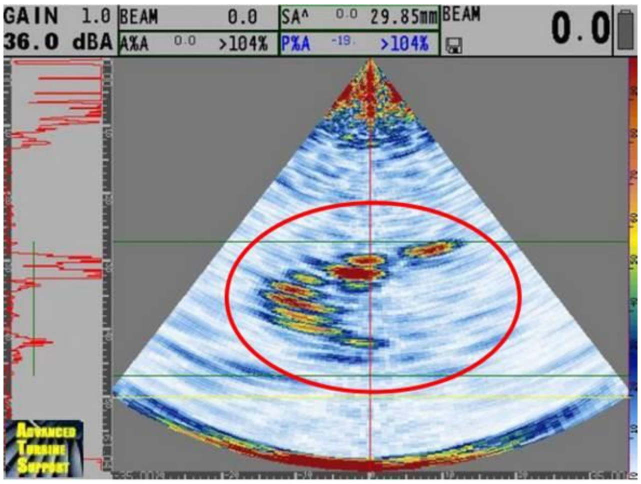

Figure 4: Large UT indication in the middle of a compressor disk web with a length of ~0.750 in (~19 mm).

A comprehensive fracture analysis was completed on the disk and all inclusions. The mode of calculation included the backwards calculation to estimate the original size of the defects. It was predicted that relatively small growth had grown up to the current size. Additionally, through the forward calculation of instability, the OEM-recommended EOL for the rotor would have been successfully met on the current operational profile. The issue arose in regards to an extension of life, as the customer required interval could not be successfully met based on the operational demands on the plant. As such, the single component was replaced, while the remainder of the rotor was recommended for continued operation beyond the OEM-recommended EOL.

Recent Finding #3 – Large Through Crack in Intermediate Hollow Shaft (Torque Tube).

Magnetic particle inspections (MT) were utilized in discovery of a through crack nearly 24 in (610 mm) in length, Figure 5. The crack was somewhat shielded during visual inspections, due to the corrosion pitting present on the outer surface. Upon MT testing, the crack was observed from both sides of the intermediate shaft, and crack tips were identified with subsequent UT inspections.

This particular failure mechanism was unexpected, as transient operating stresses in the location were sufficiently low enough to not warrant special attention. Regardless, the robust inspection plan ensured that all surfaces were inspected and the indication was discovered. A root cause analysis was started to more fully understand this failure and is on-going. To aide in future EOL inspections, dedicated EC probes have been developed, increasing the probability of detection of a flaw prior to reaching critical lengths. Similar to the previous example, the component was retired and replaced with an EOL-inspected torque tube that was match-machined to the existing rotor components.

Figure 5: Large through-wall crack discovered in an intermediate shaft.

Recent Finding #4 – Crack in Cooling Slot of Turbine Disk Attachment

Form-fit eddy current probes were used in the inspection of an Inconel turbine disk fir tree. During the inspection of several slots, cracks were observed to extend from the forward radius of the cooling slot with lengths >1.1 inch (>27.9 mm), as shown in Figure 6. Upon discovery of several small cracks, all were confirmed via directed visual and FPI tests.

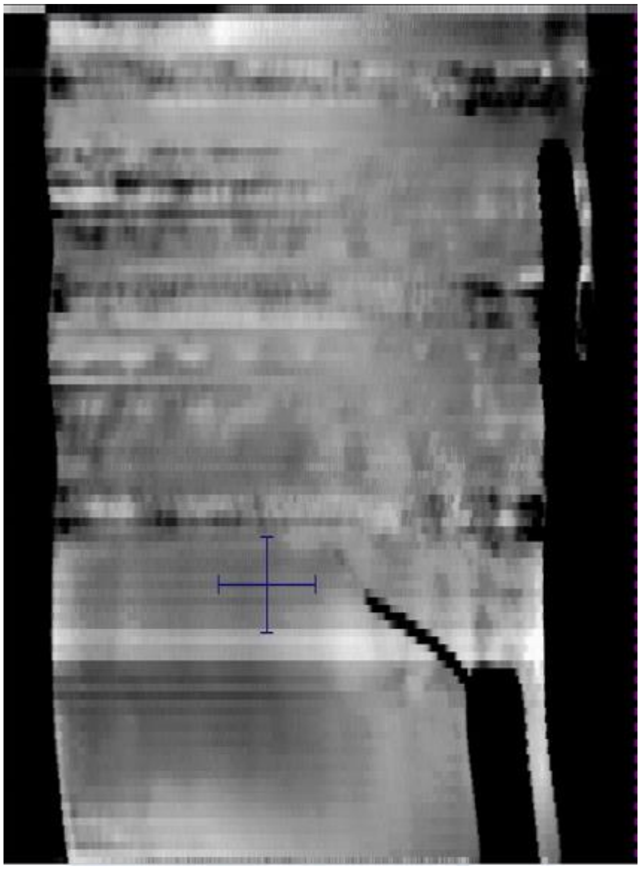

Figure 6: Eddy current response of a large crack in an IN706 turbine disk emanating from the aft cooling slot.

In this particular instance, a replacement of the component was necessary, as the crack was sufficiently long enough to be nearing the critical length for that location. While smaller cracks that are detectable with EC inspections have the possibility of being repaired, the length of this crack was sufficiently outside of the repair envelope and the component retired.

RETURN TO SERVICE

The examples presented in the previous section highlight some of the potential issues that exist in an F-Class gas turbine rotor. While all of the recent findings were analyzed against remaining life, only *Recent Finding #2* was found to have residual useful life. Ultimately, the residual life was not sufficient enough to warrant reassembly back into the rotor, rending the component scrap. Regardless, the significance of these inspection findings is the fact that the majority of the rotor was discovered to be in sound shape and had passed the EOL inspection. The outcome is that targeted replacement of failed components can be pursued, either through the implementation of new or used hardware.

In some circumstances, operators have spares or retired assets still in the possession of the plant. Other scenarios exist such that parts are available on the third party market that may be of similar configuration to that of the failed component that have been retired for various other reasons. Nevertheless, the possibility then exists to perform the detailed inspections on the component and assess to the same level as the retired component.

To facilitate a potential swap, inspections require preliminary dimensional characterization. A robust and convenient method involves white light scanning of both components and overlay comparisons of two components, e.g. Figure 7. Once dimensions are confirmed to be identical, metallurgical and chemical analyses precede the NDT inspections outlined previously. If the material conforms to the existing material, with no signs of degradation, the option to re-stack the rotor with the used component exists, pending passing NDT inspections.

In the event the used component fails any of the mandated inspections, new make solutions exist that target individual components. The ability to produce a new disk, which requires access to capable engineering, materials, forging houses, and machining processes capable of producing compressor and turbine disks, has historically been reserved by the OEMs; however, a limited number of third parties have been able to develop new make solutions. Through re-engineering the component, new make drawings and material specifications are developed to produce either in-kind or improved components capable of achieving extended lifetime intervals, as shown in Figure 8.

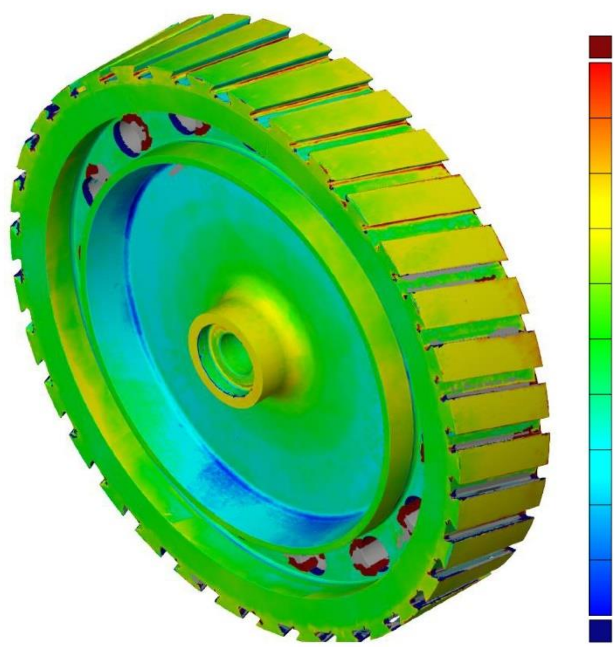

Figure 7: Overlay comparison of a retired and new compressor disk. Deviations are noted as highs (blue) and lows (red) in regards to nominal conformance (green).

Figure 8: New-make compressor disk used to replace a component in a rotor that had exhausted the useful operational lifetime.

Once a complete set of hardware is available to rebuild the rotor, the standard inspection, balancing, and assembly processes can commence. The result of the overhaul, comprehensive list of inspections, and targeted replacement is a significant reduction in the cost to obtain a rotor capable of continued operation beyond OEM recommended lifetimes. Through these types of detailed rotor repairs and assessments, operators can achieve additional operation up to 100,000 hours prior to re-inspection. In the event new make solutions are implemented, those particular components have the ability to continue beyond 100,000 hours, as the material condition and pedigree is known from the original processing. Together, the new and evaluated components are assembled to provide a rotor capable of continuing operation well into the future.

CONCLUSIONS

Heavy duty F-Class gas turbines are reaching mature frame status. As a result, several operators have exhausted the OEM recommended lifetime for the rotor. While complete replacement of the unit may be cost prohibitive or unaccounted for in O&M budgets, inspections and analyses have been developed to assess the condition and true lifetime of the critical components. Directed by advanced finite element analyses, a comprehensive set of nondestructive testing methods have been developed to fully inspect disassembled rotors. Through such inspections, multiple life-limiting indications have been discovered across multiple OEM rotors throughout the cold- and hot-sections. As such, analytical techniques and new-make solutions have been developed to replace targeted components as opposed to complete rotor replacement. The result of such evaluation and development programs is the extension of useful remaining life of F-Class rotors and the ability to return a majority of operators' assets to service.

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