EXTENDING USEFUL LIFE OF F-CLASS GAS TURBINE COMPONENTS

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ABSTRACT

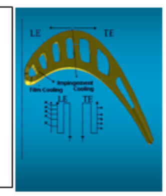
This paper addresses the engineering evaluation of F-Class hot section components from an owner/operator perspective, with the practical objective of extending their interval of useful service beyond the limits recommended by the OEM. Starting with the first stage, the initial aim is to extend operation from two to three intervals. A multi-disciplinary approach to hot section life management is described, which is used to assess the component condition and possible risks involved with extending the active service life. The assessment draws from many sources: design analysis (durability, weak points, material and coating limitations), inspection (when, where, limits and tolerances), service (base load versus cycling) and repair techniques (welding, brazing, heat treatments). Results of the modeling, damage tracking, NDT and destructive metallurgical and mechanical testing are summarized.

INTRODUCTION

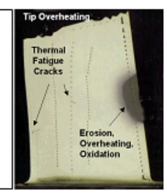
As the F-class generation of gas turbines amassed a historical record of field service it became increasingly apparent that some of the original designs within the hot section, particularly in the first stage, were unable to meet a basic target of starts, hours or equivalent operating hours. Since the introduction of the FA class, when firing temperatures were increased to the presently used 2420^{o}F (1327^{o}C), numerous issues have manifested themselves as premature damage. Systematically corrected by the respective OEMs with repairs and upgrades, it also prompted EPRI to take a proactive role on behalf of the operators/owners by focusing on the critical components in the hot section whose operating life controls the inspection cycle of the turbine and often dominates the expenditures involved to keep them in active service. On the other hand, increasing the repairability and operating life of components with a minimal risk, will result in significant amount of financial savings for gas turbine owners. In parallel with the rapid expansion of the F-class as a major source of power, EPRI organized a multi-disciplined engineering approach (**Figure 1**) which has ultimately involved the integration of several related disciplines. These have been organized to allow the independent assessment of the mechanical condition of a hot section component (relative to its original design state) and project the potential risks of operating it for a given period of time and/or type of duty.

Figure 1: Engineering Approach to Life Extension

Durability Modeling
- •Calculate Temp & Stress
- •ID Critical Locations
- •Estimate Damage Rates



Damage Tracking
- •Document each s-s cycle
- •Estimate life consumed
- •Project repair life/interval



Inspection and Testing
- •Visual and advanced NDT
- •Metallurgical/mechanical testing
- •Repair and update life rates

The present EPRI approach to condition assessment draws from many sources:

Design analysis – Advanced aerothermal modeling of several major F-class hot sections has been ongoing to evaluate their structural response under simulated conditions of service. The baseline analysis of original components has routinely been updated with the assessment of design modifications or repairs introduced throughout the last 10 years. [1, 2,3,4,5]

Durability modeling – Temperatures and stresses obtained from the analyses are reflected as estimated hours of coating oxidation or spallation, cycles for TMF cracks to form and hours for cracks to form from material creep. These are practical measures, which can be directly related against the hot gas path inspection interval (HGPI) requirements of starts and hours and for tracking damage between inspections.

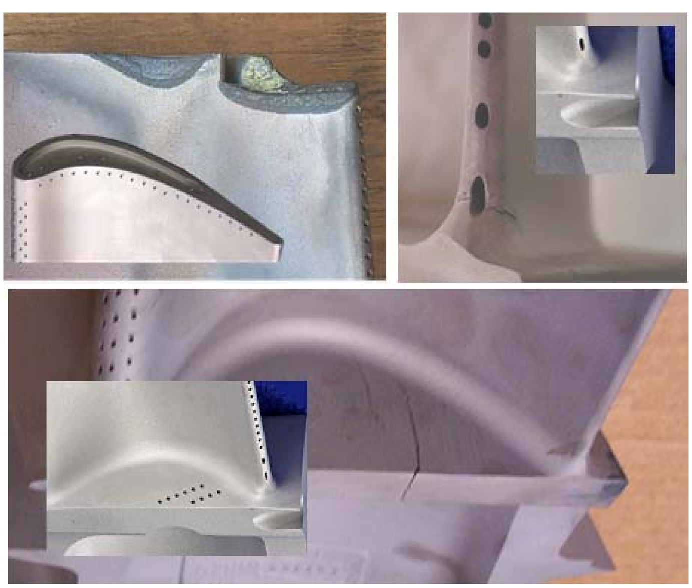
Inspection guidelines – Tolerance and sensitivity studies and their impact on life predictions are correlated with actual field serviced parts to more firmly establish when observed damage is likely to have started, what was its principal source, whether it is more or less severe than expected and how certain tolerances might influence the rate at which coating is lost or cracks are formed.

Repair techniques – A test based approach has been used to assess the effectiveness of repair techniques and heat treatments in terms of how much original design life is reasonably restored. The current program relies on creep and mechanical fatigue tests of specimens taken from components of a known service history at first and second intervals (eventually third) for comparison with each other and correlation with the durability model projections.

CURRENT PROGRAM GOALS

As noted, many of the original F-class components experienced durability issues, which are well known to operators. Examples of corrective strategies that have been introduced over the last 10 years are illustrated in **Figure 2.** Relative to the first row of the 7FA and 9FA designs, original buckets with a metallic coating oxidized prematurely on the leading edge. This was corrected with the addition of cooling holes and later with the addition of a thermal barrier coating (TBC). Cracks forming in the lowermost hole of the trailing edge were addressed by the application of a platform undercut and adjustment of the holes to more effectively cool the surrounding material. Cracks and coating spallation on the platform were addressed by directing more cooling flow through the platform.

Figure 2: Examples of Modifications and Repairs to F-Class Buckets



As these durability problems have been systematically resolved, they brought with it a growing awareness that many of the criteria originally used to inspect and retire components might now be overly conservative. Assessment of the most recent modifications applied as repairs or retrofits to earlier designs has further supported this opinion. Ultimately this raised a couple of questions. Firstly, can conventional techniques of repair and retrofit actually restore a significant proportion of the original component life. Secondly, is it possible to repair these serviced components to run them at minimum risk for at least an additional cycle, possibly more.

This then became the focus of the current life cycle extension program. With the direct cooperation and involvement of an operator with a large 7FA fleet, the goal was to operate parts at least one hot gas path cycle beyond that recommended by the original equipment manufacturer (OEM). The scope of effort which was specifically tailored to address the host 7FA fleet involved:

- Defining the 7FA stage 1 behavior to different operating cycles starting service as either an original FA+e design and/or with the latest modifications previously noted.
- Assessing the buckets taken after the 1st, 2nd and eventually 3rd operational cycle, before and after refurbishment.
- Tracking the damage accumulated before and after each service interval.

The remainder of this paper addresses each aspect of the technical scope of work and how it fits into serving the stated goal. It should be emphasized that the individual pieces of engineering technology highlighted in this paper are only considered a means to this end. The success of this program is not being measured by the sophistication of the design analysis or authenticity drawn from testing actual serviced parts. The measure of success relies on saving millions of dollars by avoiding the premature scrapping of these critical hot section parts.

INITIAL CONSIDERATIONS

As many operators note when they open up a unit for its periodic maintenance, most components have managed to withstand service without significant damage, or with superficial damage that could be corrected. When the question of why scrap good parts was posed to EPRI's GT engineering team, it was determined that to minimize the risk of adding service intervals, the original question needed to be sufficiently addressed from four different perspectives:

- *How durable is the design?* Where are the weak points and what are the predicted life limits for material and coating if general tolerances are assumed to be met?

- *How soon should an inspection be performed and where should it focus?* In essence the question seeks to define how conservative the OEM limits are and which tolerances are actually the most critical in terms of affecting the overall life of the component.

- *How does the duty of the cycle impact on the accumulated damage?* Is there an advantage to shifting sets which have primarily seen base load duty to units that are frequently peaked?

- *Could service be extended?* Since many original buckets of an older design often exist in a large fleet, was it possible to bring them up to the standards of the modernized designs by repair and retrofit.

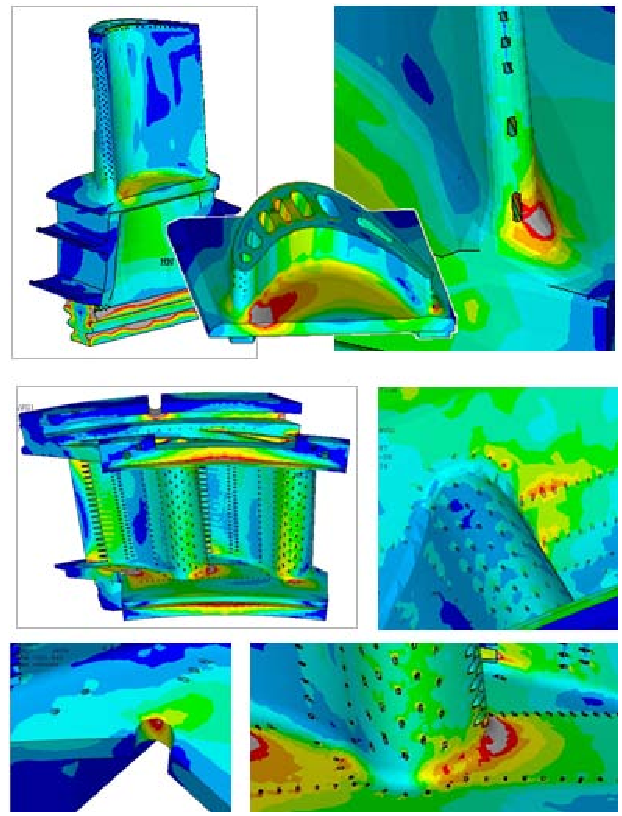
EPRI LIFE MANAGEMENT TECHNOLOGY

The first concerns or considerations had already been addressed using technology developed by EPRI in 2001-2002 referred to as the Hot Section Life Management Platform (HSLMP). [6] The platform is a compilation of aerothermal modeling, durability modeling and test results which was developed explicitly to handle the advanced design techniques and systems found on all F-class hot section components. These include advanced cooling schemes (serpentine passages, impingement cooling holes etc,), advanced coating systems (thermal barrier coatings) and new materials (directionally solidified and single crystal). To obtain critical temperatures and stresses for any given design, the platform relies on commercially licensed finite element analysis (FEA) and computational fluid dynamics (CFD) programs. The durability models unique to EPRI are based on metallurgical and material tests of different alloys to relate temperatures and stresses to estimate coating degradation (in hours until base metal is exposed) and thermo-mechanical fatigue (in cycles) until there is a high probability for cracks to form. Creep damage is assessed (in hours) as a calculation using the original FEA model and CFD results.

The purpose for all of this simulation is to establish an understanding of how the weak points of the design might be affected under different operating scenarios and whether the root cause of a type of damage apparent at one location was different or compounded by another mechanism. The platform was also designed to handle damage on F-class components which operate beyond the thermal limits of their base metal.

In the course of 10 years of applications (buckets/blades and stationary nozzles/vanes), the platform has revealed several items that supported the concept feasibility for extending service life of these parts, which eventually coalesced into the goals of the current program. Firstly, as documented by the aerothermal models, damage caused to these parts under normal operation conditions (base load or peaking duty), is typically localized and superficial (**Figure 3**). This is consistent with the general impression given when the operator sees relatively undamaged serviced parts. For the interval extension program it inferred that it should be possible to effectively repair the relatively confined damage, so that the component can survive another cycle intact.

Figure 3: Examples of Concentrated Stress in Row 1 Components



Secondly, different mechanisms often attack these concentrated sites irrespective of one another, or to a degree where one mechanism dominates as the root cause of cracks. This explains why operators of base load units often see more aggressive damage to locations affected by creep or coating spallation which is different from parts taken from peaking units where TMF is dominant. In terms of further extending service intervals, this implies a management aspect to the strategy, whereby sets of parts that have seen extended peaking service in their first and/or second HGPI should be swapped into base load units and vice versa. Through actual tracking of damage on a cycle by cycle basis, the durability estimates produced from the baseline examination could further refine the selection and management process to optimize the trading of sets between different units.

Finally, the most recent assessments of modifications introduced to the original designs by the OEM and as retrofits offered by qualified third parties, have clearly identified a margin of durability that these changes can provide or restore. To the host utility, this offered the possibility to include older, original designs, rather than excluding them from the program and scrapping them completely after the completion of second interval.

ROLE OF TESTING AND INSPECTION

As discussed, the HSLMP provided a wealth of critical information on the design engineering, which would have normally not been available to the operator of the host fleet. The durability projections established a basis for how original and modified designs present in the fleet should behave for a given operating scenarios and to define critical tolerances so that they could be checked to show consistency with those assumed in the analysis. Together, these provided a technical yardstick by which the condition of any given set of components could be initially calibrated.

However, it is recognized that even when a sophisticated process of simulation is applied, projected estimates of life consumption should never be taken as absolute. Material test data always exhibits a degree of variability even when obtained under controlled laboratory conditions. Rupture and fatigue data also involves working on a nonlinear scale. All this makes projections based on test data sensitive to nominal differences in temperatures, tolerances and strains. Regarding tolerances, it is also known that suppliers to the OEM may adhere to different tolerances, which they individually select from within the allowable acceptance range proscribed by the OEM.

Paramount to the final decision of the operator to extend the interval of service for a row 1 bucket is that the risk of a catastrophic failure is minimized. To this end, the F-class studies have consistently demonstrated that damage accumulated by any given set of buckets is very much service dependent. The host fleet, which is the object of the interval extension program, represents a mixture of base load and peaking units. In order to account for this variability, specific features of individual cycles as well as the number and their duration are being "tracked" on a unit by unit basis. This is done using a spreadsheet based process referred to as the Damage Tracking Module (DTM). The DTM was developed using results obtained from the Life Management Platform to characterize each completed start-stop cycle. DTM analysis provides the damage accumulated by the components over the service interval. The advantages of using a DTM are to accurately predict the damage for each and every start at its weak link depending on the design, and also offering credit for the lower operating temperature profile if any, similar to the approach used by OEM but in a more detailed and less conservative approach. For example, a fast start as considered by OEM will be considered as 14 starts, whereas, DTM provides a more accurate number based on the design revision, which might end up as a lower number. In turn, this record is used to more precisely tally the actual life consumed by each of the individual sets of FA parts presently in service and identify the prime candidates to operate for a third interval.

To further minimize the risks to the host fleet part of the current plan evaluates their condition at each successive HGPI. In conjunction with a more definitive record of their cycle by cycle record of service, the actual magnitude and location of damage is correlated against the original projected estimates of life consumption made from the durability models of the HSLMP, using the refined history of the DTM. In this way the factors used to track the accumulation of TMF, creep or coating loss are verified, refined and revised as required, facilitating the smooth transition from design simulation to the real world of the turbine operating environment. Such condition evaluation relies on visual inspection, non destructive testing (NDT), a full report of fall out rates and what repairs were made.

As this is one of the first applications of the interval extension plan, a feature of the condition assessment included detailed metallurgical and mechanical testing of parts. These tests serve several basic purposes. They extend the material test databases originally developed by EPRI when it first embarked on the hot section initiative. In doing so they provide the opportunity to review and revisit the key parameters which feed into the life consumption algorithms that form the basis of the durability models and the projections of life that are produced. Since they are performed after successive operating intervals, they allow the benefits of traditional repairs to be registered in order to judge their effectiveness of restoring life relative to the part which starts out brand new. As a consequence of this comparison, the factors used to assess and track life consumption can be reasonably adjusted to reflect the portion of life that is non-restorable in successive intervals.

DETAILS OF CONDITION EVALUATION

The ongoing process of condition evaluation consist of several different levels of assessment: (1) visual inspection, (2) non-destructive measurements of internal and external coating thickness and PT cracks, (3) metallurgical analysis, and (4) mechanical tests of fatigue and creep rupture. A key feature of this aggressive plan is to undertake each of these inspections at successive intervals in order to establish a baseline which can be applied to other sets of buckets, stationary vanes and/or stages two and three of the turbine.

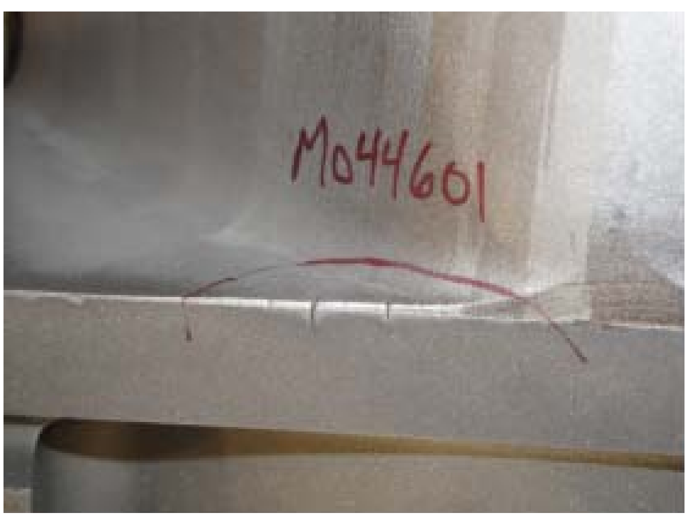
1st and 2nd operation cycle buckets and buckets after 2 operation cycles and repair buckets were visually inspected: Eddy current Tested (ET) for Thermal Barrier Coating (TBC) coating thickness, and Ultrasonic Tested (UT) for wall thickness. The TBC coating thickness of the 1st and 2nd cycle buckets was average 15 mils. The coating thickness of the repaired buckets differed from vendor and especially at the platform. If the TBC coating does not delaminate, this will reduce the metal temperature and increase the material strength during starts and stops. In some cases local delamination of the TBC top coat was observed.

A total of 13 buckets have been sectioned, which can be split into three categories. The first category consisted of 5 buckets that completed their first service interval. The second category consisted of 4 buckets that completed their second service interval with a full repair performed after their first interval. The third category consisted of four buckets that completed their two intervals (repaired after first intervals per OEM recommendation). These four buckets in the third category were sent to different repair vendors and were tested to obtain an understanding of the general repair quality and the restoration of the mechanical properties after repair. The buckets were selected from peaking units, with a starts based operating profile.

Figure 4, F7FA 1st stage bucket platform cracking

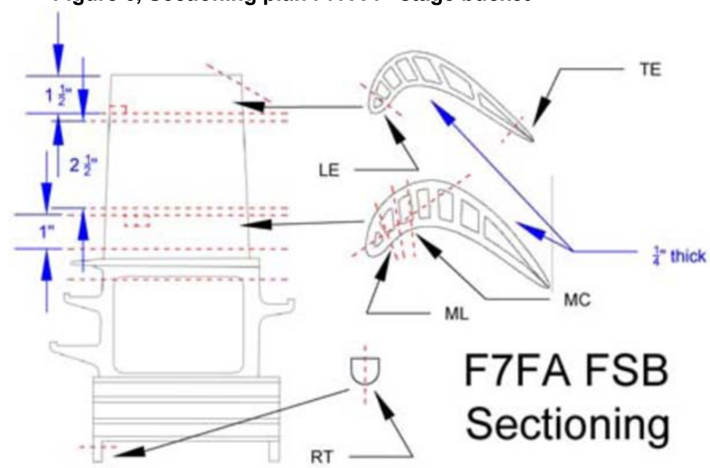
The bucket that completed 1st cycle and 2nd cycle were also Non Destructive Tested (NDT) including Penetrant Testing (PT) and visual after stripping of the coating – see figures 4 and 5. The results were compared to the simulations and confirmed the earlier results in most cases, the simulation was further defined in other cases as shown in figure 3.

Figure 5, Bucket platform cracking after stripping



After sectioning the buckets the internal and external coating and surface condition was metallurgically evaluated at 2 airfoil cross sections 1½” from the tip and 1” above the platform (figure 6.) From this large cold mounts were created in vacuum, ground and polished.

Figure 6, Sectioning plan F7FA 1st stage bucket



The external coating was mostly Dense Vertical Cracked coating, however some of the repaired buckets showed high porosity TBC coating, figure 8. Delamination of the top coat just above the bond coat interface seen in the microscope was mostly of buckets with the spallation observed during incoming visual inspection. The bond coat was generally in good condition and limited or no oxidation or porosity was seen with exception of the “flash-coat”. Note flash-coat is a coating that is Air Plasma Sprayed (APS) between the original bond coat, which is typically sprayed with High Velocity Thermal Spray (HVOF) process, and the APS sprayed TBC to enhance the bonding of the top coat, see figure 7.

Figure 7, DVC or DVM TBC coating after 2nd cycle

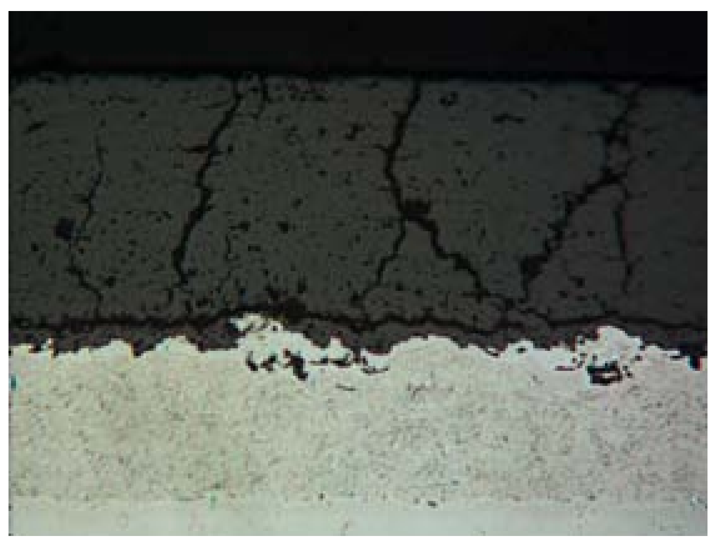
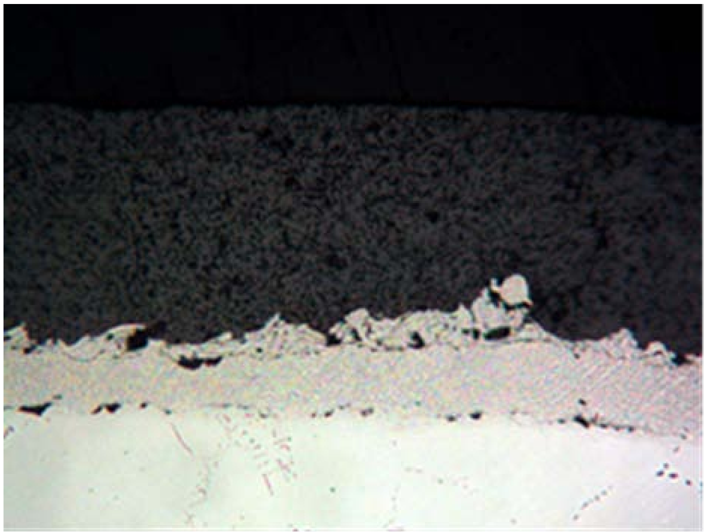
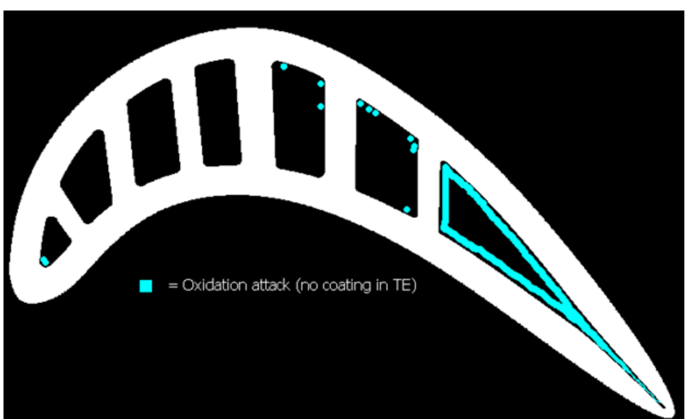


Figure 8, Repaired bucket with non DVC TBC coating



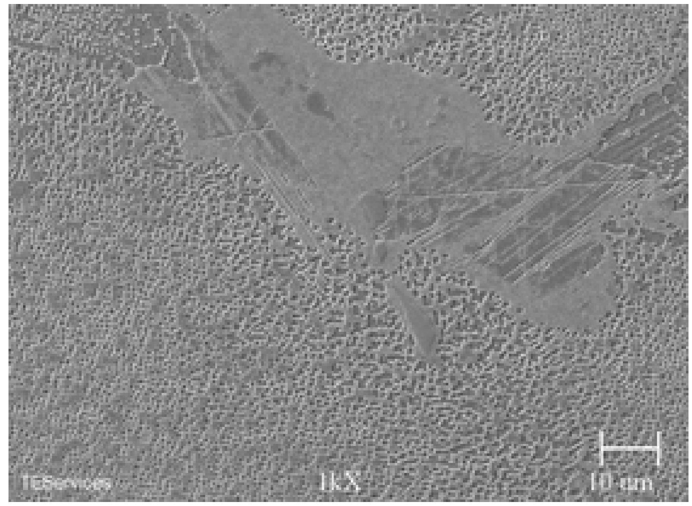
The internal coating and surface condition was evaluated using the same mounts and in general the Al-diffusion coating (2 -3 mils typically) was still in good condition although some coating was missing especially at the airfoil Trailing Edge (TE) locations possibly from original manufacture. At those un-coated locations some oxidation attack was observed, figure 8. More severe oxidation attack was found on the 2nd cycle buckets and some coating cracks. Note: While some alternative repair vendors advise to replace the internal coating with each repair, most do not strip and recoat the internal surface.

Figure 9, Mapping of internal surface observations



The condition of the buckets was further investigated using visual and Scanning Electron Microscopy (SEM) at 5 locations: TE tip, LE 1/3 from tip, cross and longitudinal mid sections 2/3 from tip, and root, figure 6. Some large secondary metallic phases were observed at all buckets and at all locations and these were titanium and tantalum carbides that were formed during the original casting manufacture- see figure 10.

Figure 10, SEM 1000X 2nd Cycle bucket



The metallurgical structure was defined for each specimen, especially the carbide and gamma prime condition (primary, secondary and area fraction). Most of the aging of the material was observed at the tip (figure 11) while the condition at other locations, even mid airfoil, did not show significant change of carbides and gamma prime compared to the root. The 2nd cycle repair buckets showed significant differences in metallurgical structure, especially the gamma prime. The metallurgical evaluation and mechanical testing is still underway for 2nd cycle repaired buckets.

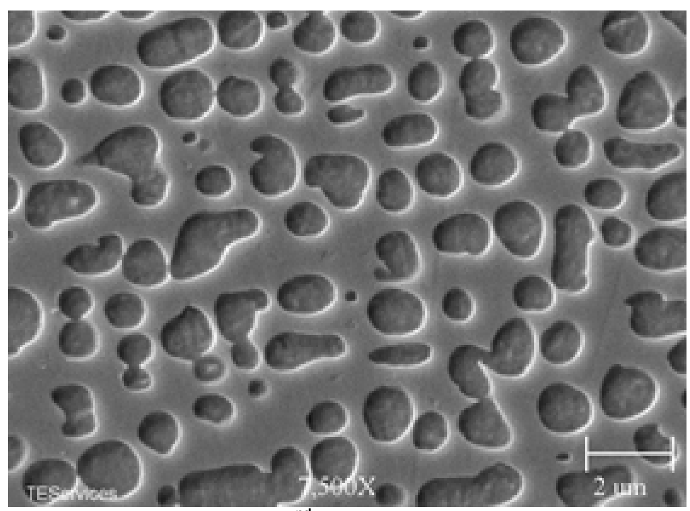
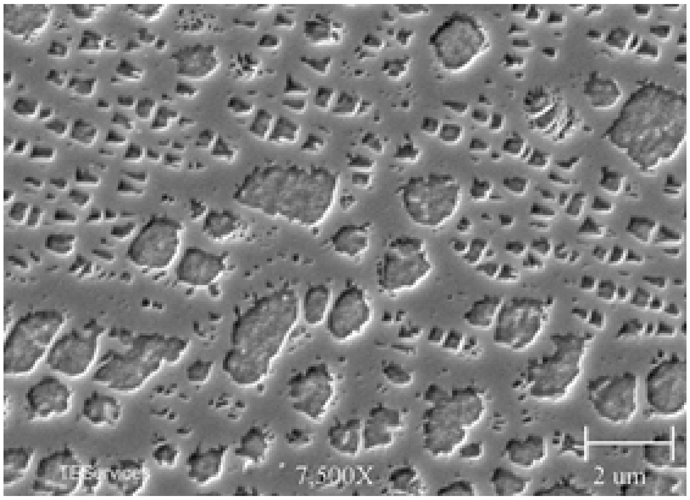


Figure 11, SEM 7500X 2nd cycle bucket at TE tip

Figure 12, SEM 7500X 2nd cycle bucket repaired at TE tip



To support the final aspect of mechanical testing, results of the aerothermal analysis were used to identify prime locations where specimens from used buckets could be physically machined, but which would also most likely register the most damage due to TMF or creep. For the first row of rotating buckets these proved to be specimens from material obtained in the transverse direction of the bucket platform and the longitudinal direction of the airfoil. Since new buckets could not be sacrificed, specimens from the shank were selected to act as a baseline. The aerothermal studies showed that because of the location and cooling flow available, these shank portions would experience little or no creep or TMF.

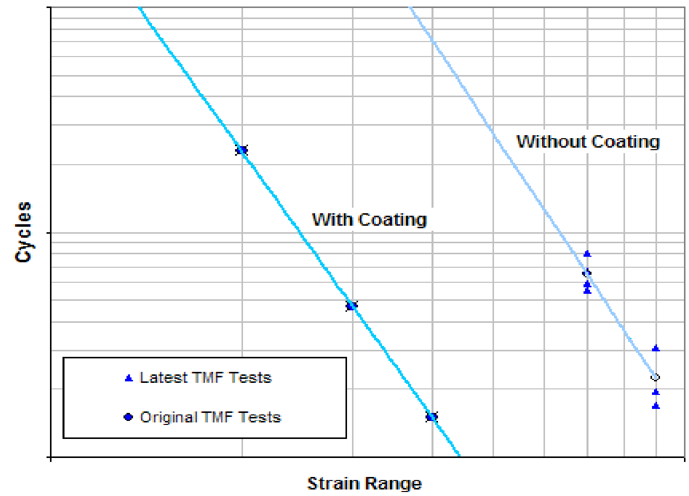
A large matrix of initial tests was initially performed to establish the procedure and focus the subsequent tests (after each HGPI) on locations that were most economically beneficial. These tests are not inexpensive as they require buckets to be sacrificed and need to cut out sufficient material in order to manufacture workable specimens. As results became available, TMF and creep rupture were plotted and first compared to the original data base developed by EPRI ten years earlier (**Figure 4**). [7]

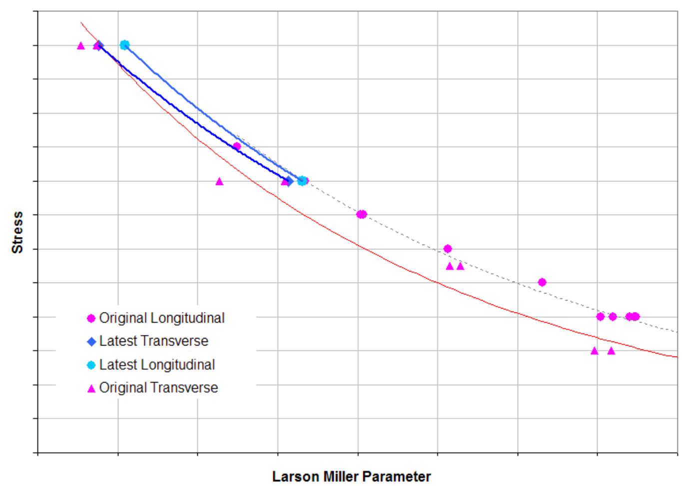
The consistency between results, particularly in the creep rupture data was notable, considering that the data represented three separate sources involved in making the specimens and performing the tests. After a more extensive review of the data the new results demonstrated that:

(1) Because of its consistency with the original EPRI data base, this meant that the factors and parameters applied in the ten years of aerothermal studies and damage tracking preceding the interval extension program remained valid in terms of furthering the objectives of the more current program.

(2) Differences between results obtained from parts after seeing an interval or two of service from were apparent enough to be used to make a relative assessment of the damage left after an interval and the residual damage that might remain after a repair.

Figure 4: Results of Original and Recent TMF and Creep Rupture Tests





It should be noted that by means of the aerothermal modeling, the results from the tests done on the first row could be extrapolated to any location throughout the component by using the local temperatures or stresses at the site of interest.

PRESENT STATUS OF PROGRAM

To date, the aerothermal modeling of the mixture of original and modified rotating buckets operating within the host fleet of 7FA turbines has been completed. A similar analysis of the first stage stationary vane segment was also finished at the end of 2011. An initial assessment of TMF and creep damage has been made for all of the sets of row 1 buckets currently in service. Damage tracking is ongoing. Inspections and metallurgical examinations have been completed for buckets that have seen a first and second interval. To date the results have been positive and promising. They indicate that through a combination of (1) possibly swapping sets between machines, (2) upgrading earlier designs with additional cooling and stress relief strategies, (3) conforming to critical tolerances and (4) undertaking proscribed repairs a third interval of service is feasible.

ADDITIONAL COMMENTS

It should be noted that the integrated process as described is not only intended to identify candidates that can be seriously considered for extended service, but also to also weed out the components which have a high risk of failure. This is a particular requirement when dealing with turbine components, since each stage and row is actually a system. Reliable operation is dictated by successfully maintaining the structural integrity of each individual part. A weak member within the set may be due to many causes: (1) residual damage caused by an earlier, improper repair, (2) extended damage caused by an inadequate tolerance margin before repair or (3) Un-repairable due to original manufacturing dimensions at the low end of the specification (Ex: platform wall thickness) (4) nonconformance after repair, (5) failure to remove enough residual damage after a repair or (6) an excessive history of duty cycling which consumed the available life at a much faster rate than projected. The checks and balances within the approach are meant to catch these particular weak links, whose individual limitations might inadvertently compromise the goal of the program.

In addition, component history tracking (original manufacture design, number of repair cycles, upgrades performed during repairs, and detailed repair reports) is crucial to successfully accomplish the goal of life extension.

As a final comment, the program focused on component life extension is also performing double duty. Refinement of durability projections based on tolerances, life consumption factors etc. provides a further level of confidence in the “baseline” projected condition that a set of components is expected to conform. This baseline can also provide interim assessments as to whether the observed condition (determined by bore scope) of different stages is deteriorating (1) more rapidly, (2) as expected or (3) better than expected. The interim inspection assessment again uses the aerothermal analysis to focus on critical locations where different types of damage are likely to first become apparent and to highlight noted damage on other locations that signifies a problem specific to the unit or the particular component. For example if unusual spallation is observed on a region that it should not occur (because of the higher than expected metal temperatures), this might highlight either a weak coating or local plugging of the cooling holes.

Used in this manner, the schedule for a HGPI could be updated at each inspection to establish whether it should be accelerated, performed as planned or possibly extended if the condition of the parts warrant this consideration.

ACKNOWLEDGMENTS
Put acknowledgments here.

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