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Importance of Physics-Based Prognosis for Improving Turbine Reliability
Part 1 – A Turbine Blade Case Study

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ABSTRACT

Prognostics and health monitoring (PHM) technology needs to be developed to meet the challenges posed by aging gas and steam turbines in power plants, transportation systems, gas pipelines, nuclear, chemical and pulp and paper industries. It is necessary to use physics based residual life prediction and life extension techniques to take into account the state of damage due to prior service. This paper will focus on the requirements of the technology and the state of development to date.

The paper describes the results of a case study on the use physics based prognosis to deal with the uncertainty of turbine blade failures. A companion paper, Part 2, deals with the turbine disc problem. It is demonstrated that useful remaining life limits based on traditional empirical methods are very limited. In addition, expensive material databases need to be generated to make reliable life cycle management decisions on the basis of empirical approaches. Physics based crack initiation approach, on the other hand, yields substantially more accurate results. The case studies presented in Parts 1 and 2 clearly demonstrate the reliability of physics based prognosis in predicting the remaining useful life of aging engine components.

INTRODUCTION

The ability to forecast remaining life of equipment appears simple enough, particularly if a log of usage in hours is kept which can be compared to a ceiling number of hours, or if a graph of operating characteristics can be compared to threshold values. But this is simplistic, and invokes certain questionable assumptions. One assumption is that the components fail according to a wear-out schedule, e.g., at x hours of usage. This may not be the case. A ceiling usage based on hours does not factor in stresses that can prevent realization of these hours. The notion of stresses that significantly diminish mean time between failures (MTBF) is not new. Professional logistics, maintenance and manufacturing engineers are familiar with the distinction between calculated MTBF and operational MTBF (actual usage with real operating data), in which operational MTBF may be a factor of 20 different to the calculated MTBF.(1)

The determination of predicted MTBF requires the development of prognostics expert systems that consider the specific stress and temperature histories of each major component on an individual basis and factor them into the damage accumulation models formulated at the microstructural/nano-structural level. These expert systems should be capable of anticipating the risk of future failures, based on assumed operating conditions, and continually revise predictions based on actual operating experience as it is accumulated. Life Prediction Technologies Inc. (LPTi) has developed a prognostics for gas and steam turbine applications. A schematic of the prognostics system is presented in Figure 1. The solution integrates engine modeling, thermodynamic analysis, and finite element modeling including a non-linear finite element solver, operational data filter and microstructural damage models on a single platform. The system provides a choice of damage models, for steam as well as gas turbine applications such as creep, Low Cycle Fatigue (LCF), stress corrosion, corrosion fatigue, cyclic oxidation and Thermal Mechanical Fatigue (TMF) analysis.

This paper and the companion paper present the results of two case studies, one on T56-A7B turbine blade creep and another on W-101 turbine disc cracking, where the value proposition of using microstructure based damage analysis is clearly demonstrated. These case studies were carried out by LPTi in collaboration with the Canadian Department of National Defense (DND) and Venezuelan oil company Petroleos de Venezuela (PDVSA) respectively.

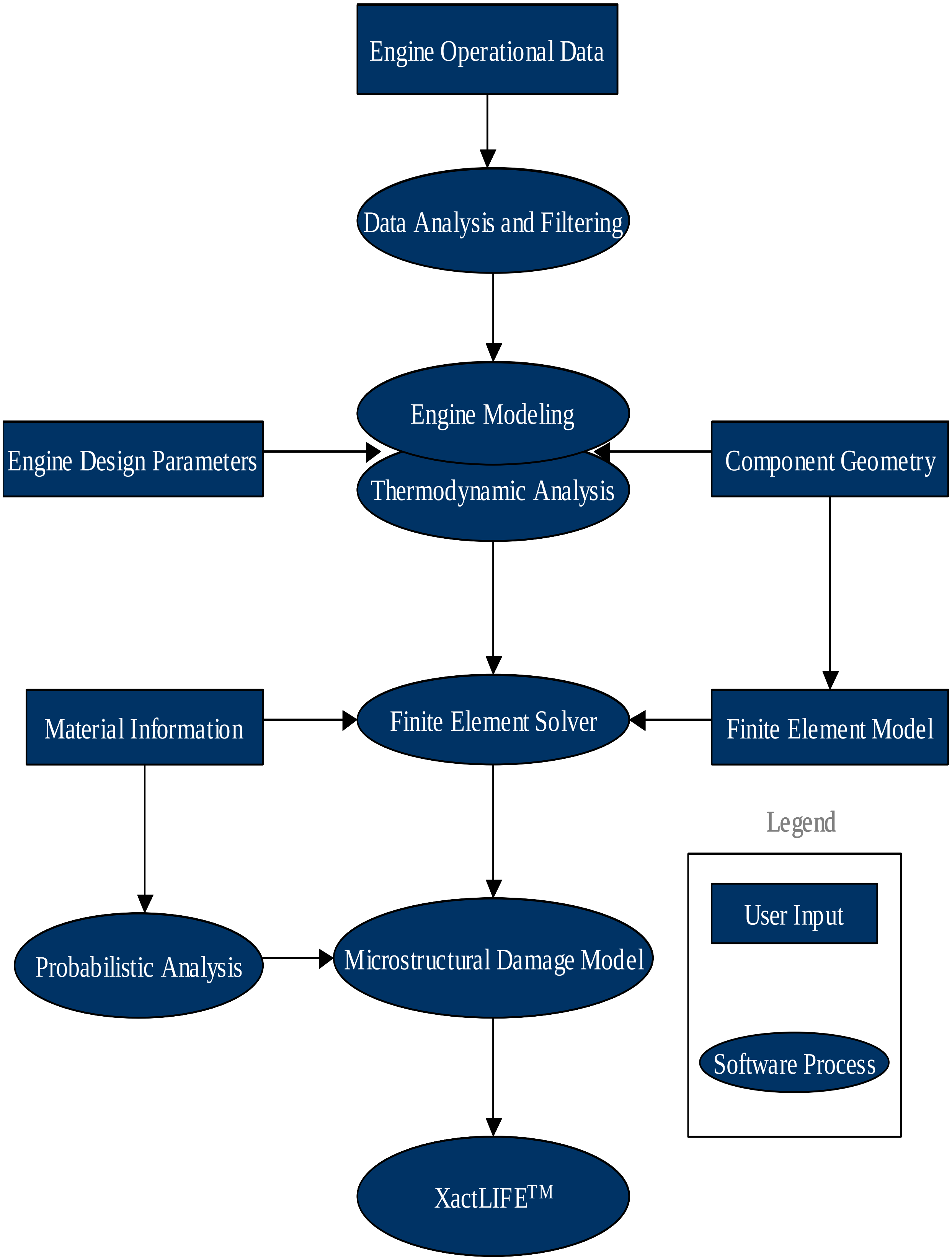


Figure 1. Engineering flow diagram for the prognostics system designed and implemented by Life Prediction Technologies Inc.

TURBINE BLADE CASE STUDY

In this study, the prognostics software tool was used to analyze the blade creep problem in T56 A7B first stage turbine blades, Figure 2, using typical engine operating data from the field in terms of engine speed and average turbine inlet temperature (TIT), Figure 3. The T56 blade is known to suffer airfoil untwist and lengthening during service and this is obviously followed by stress rupture failure (2). The primary objectives of the case study are to show why the original equipment manufacturer (OEM) was unable to predict the blade behavior upfront during the design stages of the engine and how the prognostics system can allow a user to avoid unforeseen catastrophic failures.

The first step involved in using the prognostics software requires the creation of the blade geometry using the geometry analyzer feature of the software and this is followed by the creation of a fully meshed finite element model of the blade, Figure 4. The temperature dependent material properties data such as elastic modulus, Poisson ratio, yield strength and work hardening coefficients required for non-linear finite element analysis were also collected to perform the thermal-mechanical stress analysis of the Alloy 713C blade (3). The software uses the average TIT or exit gas temperature (EGT) or power and known on-design engine parameters to compute the pitch line airfoil temperatures at different stages of the turbine under off-design (changing ambient temperature and pressure) engine operating conditions. This input along with a computed TIT profile is used by the advanced thermodynamic module to calculate the blade temperatures in both the radial as well as the chord-wise airfoil directions, Figure 5. The metal surface temperatures are then estimated along each cross section of the blade including the leading and trailing edges and this output of the thermodynamic module defines the temperature boundary conditions for thermal-mechanical stress analysis. The nodal temperature distributions along the convex (suction) and concave (pressure) sides of the blade airfoil are shown in Figures 6 and 7 respectively. It is evident that the blade mid-airfoil section is the hottest location in the blade.

The prognostics software automatically carried out the thermal-mechanical stress analysis using the nodal temperature distributions and the maximum engine rotational speed as boundary conditions for FEA. It is noteworthy that the T56 A7B blade is shrouded and the mass of the blade shroud was taken into consideration while calculating the centrifugal loads on the blade airfoil. The computed thermal-mechanical stress distributions along the suction and pressure sides of the blade are shown in Figures 8 and 9 respectively. The non-linear FEA revealed that none of the blade airfoil regions had undergone any plastic deformation under the influence of the loading conditions examined. This is significant, because only time dependent deformation would thus be expected to occur during service. The stress distribution was generally quite uniform along the airfoil although, as expected, higher stresses were prevalent in the blade root section.

The creep deformation model together with the oxidation damage accumulation model was used to take the FEA solver input to compute the creep lives at all nodes and to establish the primary fracture critical location of the blade. The fracture critical location of the blade was defined as the lowest creep life location in the airfoil. The quantitative microstructural information required to execute the damage analysis was collected up-front and input in the appropriate window within the overall prognostics system. This included microstructural variables such as the grain size, grain boundary microstructural parameters, intragranular microstructural parameters etc. A combination of deformation mechanisms such as the intragranular dislocation movement and multiplication, grain boundary sliding accommodated by a number of deformation processes, creep cavitation and a variety of dislocation-precipitate interactions are considered in the overall creep deformation processes. In the case of the T56 A7B blade, the airfoil fracture critical location was established to be in the vicinity of node number 7645 in Figure 4. This location is consistent with the blade necking location observed in service-exposed blades. It should be mentioned that occasionally the microstructural parameters may not be readily available for all gas turbine engine materials. However, LPTi works with the engine operators to determine the relevant quantities for the specific materials used in their machines.

The untwist data available for T56 A7B turbine blades, as a function of service life, indicates that the blades start necking at approximately 7000 operating hours which is obviously followed by stress rupture failure. Blade necking is indicative of bulk creep deformation in the blade substrate. In keeping with the bulk material deformation rationale, the blade creep crack initiation life was computed using microstructure models embedded in the prognostics algorithms and using temperature and stress profile inputs shown in Figs 6 to 9. Blade creep crack initiation life was defined on the basis of a small volume of material accumulating a maximum allowable creep strain at failure. A failure strain in the case of cast alloys is dependent on the soundness and the size of a casting. For good quality small castings, the fracture strain may vary between 6 to 8% whereas in the case of poor quality large castings the fracture strain may be as low as 3 % (4). In the case of forgings the creep fracture strain would be expected to be higher than that observed in castings. For this specific analysis, the failure strain was set at 7%, due to the consistency in the high quality of the blades and, at which point, it is assumed that there is little creep life remaining in that region. The average creep life of the small volume of material in the vicinity of node number 7645 was computed to be 8,120 hours. This compares favorably with the observed average life of 7000 to 8000 hours to blade necking for a variety of blade sets from different engines in the field.

To compare the accuracy of the microstructural modeling based creep life with predictions based on empirical (Larson-Miller parameter) modeling, the creep life at a typical node on the convex part of the blade in the vicinity of the fracture critical location was assessed using the two techniques, Table 1. The Larson-Miller parameter based empirical methodology was chosen for comparison purposes because it is a standard life prediction methodology used by many OEMs and consulting houses. The Alloy 713C material data that was used to define the microstructural creep model also contained the Larson-Miller parameter data for the blade alloy and this data is presented in Figure 10 (5). Upon using the rupture life data for the smooth test samples in Figure 10 and the stress level of 110MPa for the chosen blade node (Table 1), a Larson-Miller parameter value of 50 is obtained. At an operating temperature of 1095K, the Larson-Miller parameter based calculation yields a rupture life of 184,000 hours. Assuming that the rupture life of a node also depicts the localized creep crack initiation life, these results can be compared with the microstructure modeling based life predictions for the same node using a creep rupture strain of 7%, Table 1. The creep life using microstructure modeling yields a life of about 5,900 hours. Therefore, the Larson-Miller parameter based life is over 30 times greater than that predicted by the microstructure models. Given that the field data indicate a life of 7000-8000 hrs, the error in the Larson-miller prediction is apparent. This reinforces the need to use the microstructure based damage models for prognostics based life cycle management of gas turbine engines.

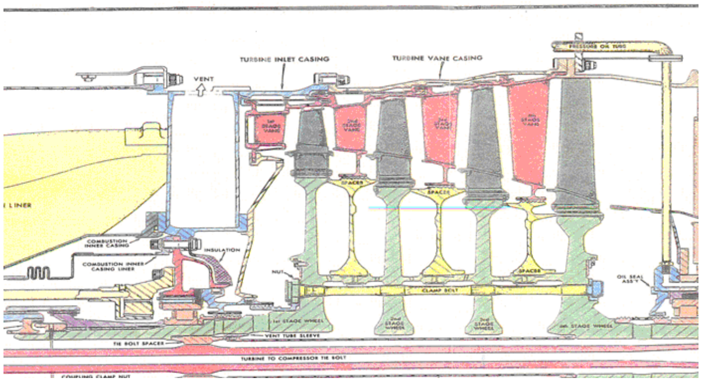


Figure 2 Schematic of the T56 A7B hot section

time, sec		incremental, dd/mm/yyyy h:mm:ss	rpm	Temp., oC	Altitude, m	Forward Speed, m/s	
cumulative	incremental	time	rpm	temperature	altitude	forward speed	Comments
0:00:00	0:00:00	05/01/2004 0:00:00	0	25	0	0	shut down
0:00:10	0:00:10	05/01/2004 0:00:10	13810	971	9144	172	t/o
3:00:10	3:00:00	05/01/2004 3:00:10	13810	971	9144	172	cruise
3:05:10	0:05:00	05/01/2004 3:05:10	0	25	0	0	shut down

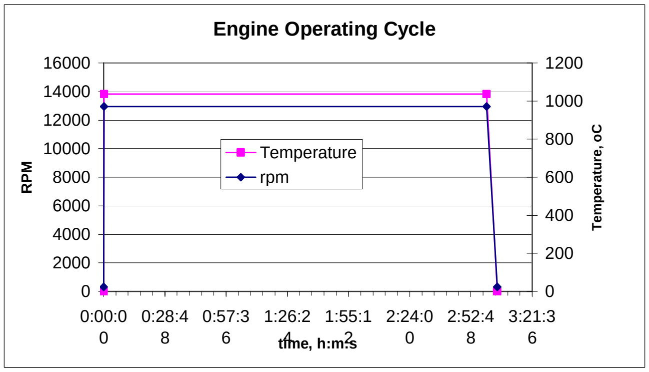


Figure 3. Typical engine mission profile in terms of turbine inlet temperature and speed

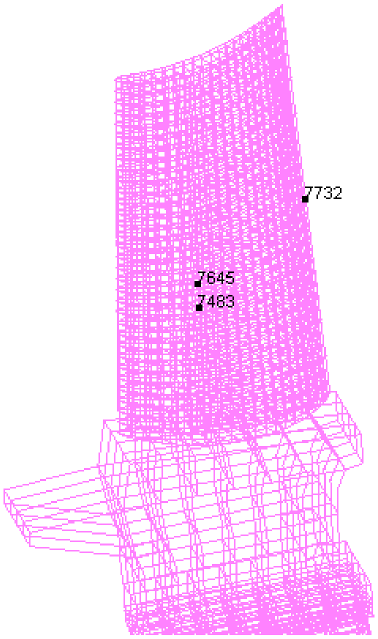


Fig. 4 A detailed finite element model of the T56 A7B blade containing 65 elemental cross sections along the blade airfoil and the location of three finite element nodes 7483,7645 and 7732.

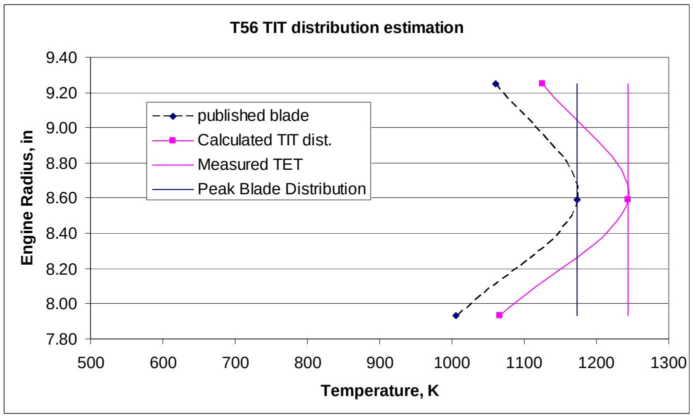


Figure 5. Computed TIT distribution and chord-wise blade temperatures.

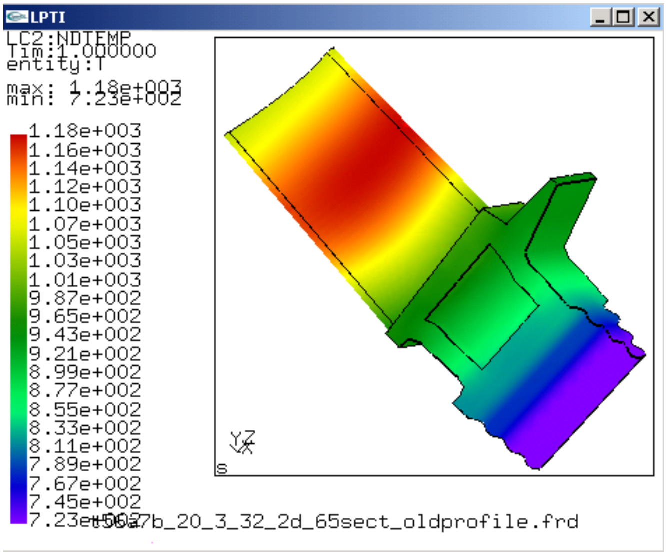
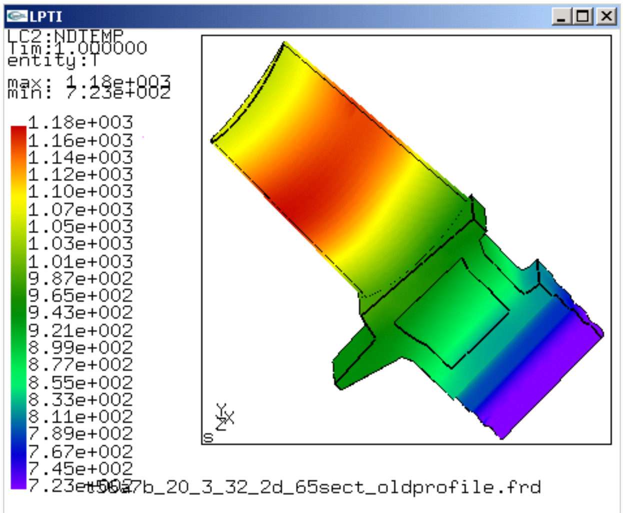

LC2:NDTEMP
Tim:1.000000
entity:T
max: 1.18e+003
min: 7.23e+002
t56a7b_20_3_32_2d_65sect_oldprofile.frd

Fig. 6 Temperature distribution along the pressure (concave) side of the T56 A7B blade.


LC2:NDTEMP
Tim:1.000000
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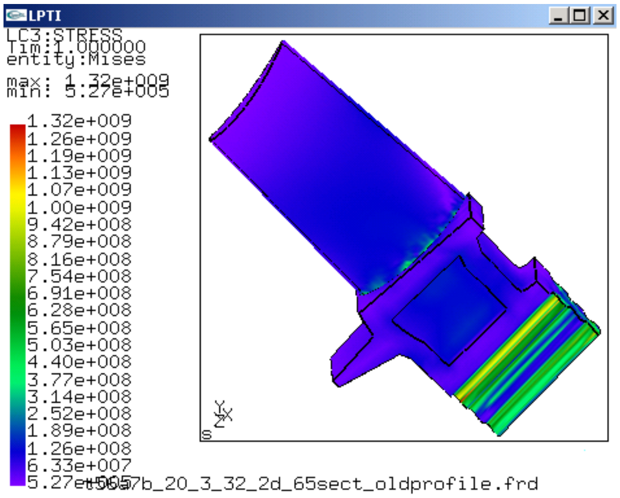
min: 7.23e+002
t56a7b_20_3_32_2d_65sect_oldprofile.frd

Fig. 7 Temperature distribution along the suction (convex) side of the T56 A7B blade.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max: 1.32e+009
min: 5.27e+005
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Figure 8 Stress distribution along the suction side of the T56 A7B blade.

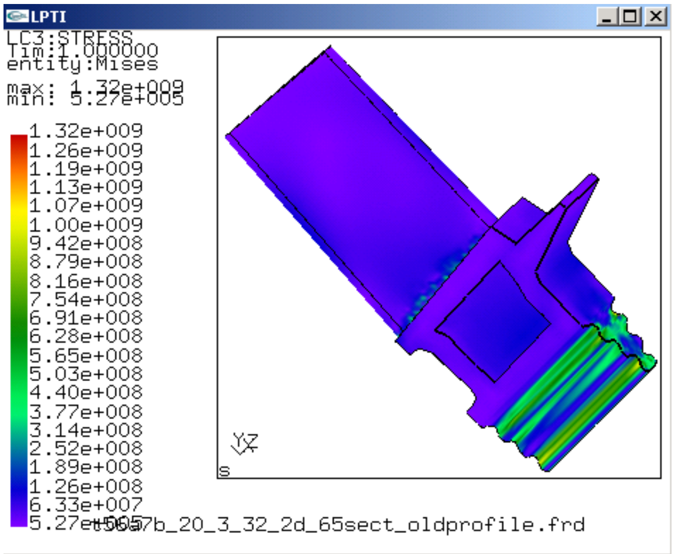

Figure 9 Stress distribution along the pressure side of the T56 A7B blade.

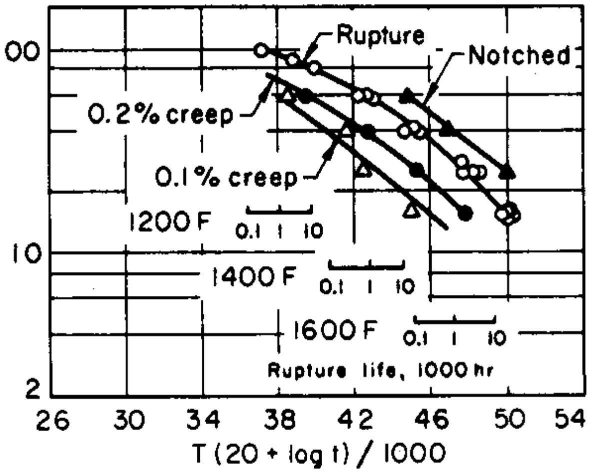

Fig. 10. Larson-Miller parameter data for Alloy 713C (T56 A7B) turbine blade material.

CONCLUSIONS

The LPTi prognostics system was successfully used to establish the creep fracture critical location of T56 A7B first stage turbine blades and to compute the average life to creep crack initiation in the blade airfoil. The results were compared with the service experience data from a number of blade sets in the field. The prognostics system based predictions matched with the field experience with remarkable accuracy. In contrast, the computations based on the Larson-Miller parameter method grossly overestimated the creep life in the vicinity of the fracture critical location by a factor of twenty five. Since all input data used in the computations were similar for both LPTi prognostics system and Larson-Miller parameter methods, the accuracy of the prognostics system based computations is attributed to the use of microstructural damage models in estimating the creep life.

Table 1. Comparison of L-M parameter and microstructure modeling based creep life prediction for Alloy 713 blade

Inputs:

Stress	110	MPa
	16.0	ksi
Temperature	1979	R
	1095	K

Results:

	Larson Miller	LPTi microsturctural creep model
Model input	50	7% failure strain
Creep Rupture life, hrs	184,198	5,932

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