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Life Cycle Management Strategies for Aging Engines

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ABSTRACT
Diminishing budgets for new weapon systems are creating pressure within NATO nations to keep legacy aero engines in operation well beyond their service life expectancy. Techniques for safely extracting maximum usage out of aging components in these engines, to reduce maintenance costs, are discussed. The mechanisms responsible for the aging of components are described. The different strategies that fleet managers may adopt for extending component lives economically and safely are identified and discussed from an operator's perspective. The paper borrows from recent NATO activities in this area and shares related Canadian experience. It presents and discusses a qualification methodology for component life extension developed in Canada for the Canadian Forces. The methodology incorporates an Engine Repair Structural Integrity Program (ERSIP), which is used to identify structural performance requirements and the qualification tests required to ensure component airworthiness throughout the extended life. Examples of life extension technologies applied to gas path components and critical rotating parts are described, including the use of protective coatings and repairs to increase component durability. The application of damage tolerance concepts that allow safety-critical components to be used beyond their conventional safe-life limit is also addressed.

1. INTRODUCTION

This paper offers an operator's perspective of the problem of aging in gas turbine engines. It is aimed at NATO engine fleet managers and provides suggestions and advice for the cost-effective management of equipment through judicious use of component life extension technologies. The work presented is based on a fifteen-year Canadian team effort involving the development and implementation of a variety of component life extension technologies for Canadian Forces (CF) aero engines. This development program has involved extensive collaboration between CF engines life cycle managers (LCM), the NRC, the Chief Research and Development of the Canadian Department of National Defense (DND), Canadian industry (Orenda Aerospace Corporation and others) and universities. The paper raises a number of questions for the benefit of NATO engine LCMs. What does aging of engines mean and what does it entail? Why is aging of engines an on-going concern to NATO operators? What are the challenges faced by operators, overhaulers and the NATO research community to address aging engine problems? It also suggests what LCM can do to cost-effectively manage NATO aging engine fleets, while ensuring engine reliability and safety.

2. AGING OF ENGINES – CAUSES, EFFECTS AND MANAGEMENT

Besides gradually falling prey to obsolescence, engines age in service due to the gradual deterioration of many structural and functional components. This deterioration is due to damage incurred in service as a result of the highly demanding operating conditions. The aging of components is the cumulative effect of service time, quality of maintenance and the nature and conditions of operation. The rates of damage accumulation are difficult to predict due to uncertainties in operating conditions and, occasionally, changing requirements. Aging damage reduces component structural integrity and is therefore detrimental to engine reliability and safety. It may also reduce engine performance [1]. When damage exceeds allowable limits, or when lives dictated by design are reached, the components should be replaced with new ones. Replacing service-damaged or life-expired parts, is costly and is a significant contributing factor in life cycle costs. [2].

Paper presented at the RTO AVT Specialists' Meeting on "Life Management Techniques for Ageing Air Vehicles", held in Manchester, United Kingdom, 8-11 October 2001, and published in RTO-MP-079(II).

2.1. Aging Damage Modes

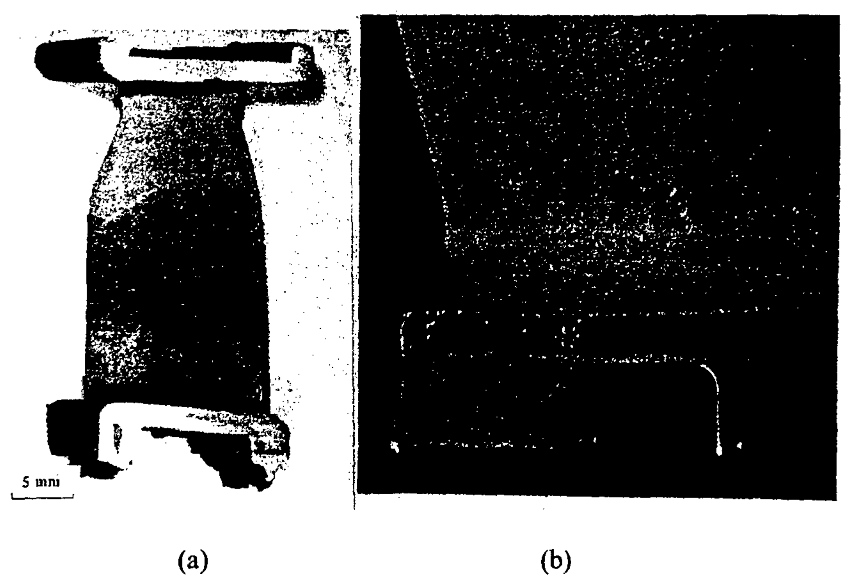
Aging of engine components may take many forms depending on component, engine type and operating conditions. The damage may be external affecting dimensions and surface finish, as a result, for instance, of erosion, wear, corrosion or oxidation. This form of damage affects the aerodynamic performance and load bearing capacity of gas path components. Surface cracks and notches induced by low cycle fatigue (LCF), fretting-wear or foreign object damage (FOD) may also lead to high cycle fatigue (HCF) failures. The damage may also be internal, affecting the microstructure of highly stressed and hot parts, as a result of metallurgical aging reactions, creep or fatigue. This form of damage may reduce component strength and lead to component distortion. Its accumulation may cause the initiation of flaws, which may lead to cracking and component failure [1,2]. Table 1 summarizes the generic forms of damage known to affect engine components by type.

Table 1. Life-limiting damage modes for turbine engine components

Section	Component	Failure Mode
Fan	Blades	FOD
Compressor	Blades	FOD, ER, COR, HCF
	Vanes	FOD, ER, COR, HCF
	Discs	LCF, C, HCF
	Spacer	LCF, C, HCF
Turbine	Blades	TMF, C, HC, LCF, HCF
	Vanes	TF, HC, C, HCF
	Discs	LCF, C, HCF
	Torque Ring	LCF
Combustor Case		LCF, TF, C, HC
Shaft		LCF, WR
Compressor discharge case		LCF, COR
Rotating seal		LCF, C, HCF

Abbreviations:

FOD: Foreign Object Damage
HCF: High Cycle Fatigue
LCF: Low Cycle Fatigue
TMF: Thermo-mechanical Fatigue
TF: Thermal Fatigue
ER: Erosion
COR: Corrosion
C: Creep
HC: Hot Corrosion
WR: Wear



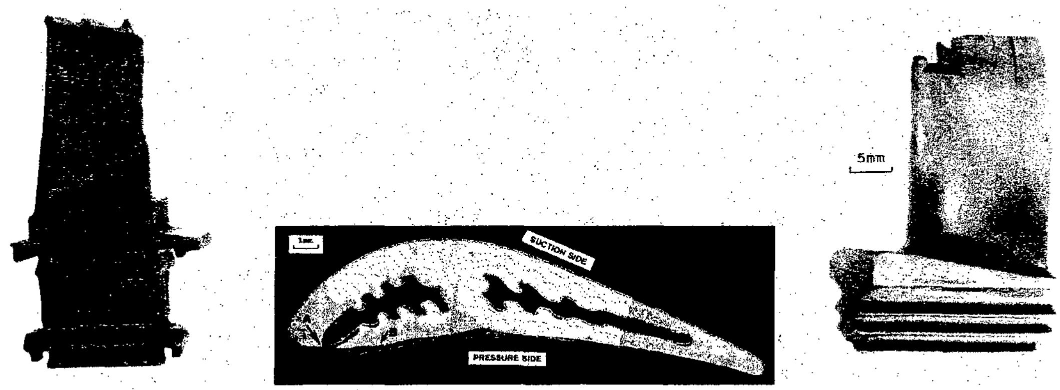
(a) (b)

Figure 1. (a) Erosion damaged compressor vane airfoil from a CF transport aircraft after approximately 5000 hrs of service (b) Corrosion pits close to the root of a compressor blade from a transport aircraft engine exceeding damage allowable limits.

2.1.1. Surface Damage

The eroded T56 vane segment shown in **Fig 1a** illustrates how erosion by ingested sand and other hard particulate matter can significantly alter compressor airfoils shape and surface finish. Such changes, in addition to reducing compressor efficiency, may lead to resonant excitation and HCF failures of airfoils [3]. Pitting corrosion may develop in marine environments. Both steels and titanium alloys are particularly susceptible to this form of damage. Corrosion pits provide sites for crack initiation and have been known to be responsible for HCF failures. The corrosion pits in the root section of a T56 compressor blade, **Fig 1b,** exceed allowable limits and would be cause for rejection at overhaul [4]. Corrosion pits in discs may also reduce LCF life.

Surface oxidation reduces the load bearing capacity of turbine blades and vanes. In marine environments, hot corrosion may rapidly destroy airfoils by surface melting, as evidenced by surface rippling, **Fig 2(a)** and metallography for a Mar-M246 T56 turbine blade, **Fig 2(b)** [5]. Turbine blades also often suffer tip oxidation, as protective coatings wear off rapidly at this location due to tip rub. In the case of directionally solidified (DS) blades, tip oxidation may lead to thermal fatigue cracking of the longitudinal grain boundaries that are embrittled as a result of boundary oxidation, **Fig 2(c)** [6].



(a) (b) (c)

Figure 2. (a) Evidence of hot corrosion damage on the pressure side of a Mar-M246 blade; (b) Metallographic section taken halfway across the airfoil of the blade showing evidence of hot corrosion damage penetrating the leading edge right through to the internal cooling passage; (c) Tip cracking of a DS blade caused by thermal fatigue of longitudinal grain boundaries embrittled as a result of grain boundary oxidation.

Fretting occurs where fan and compressor blades come in contact with discs. In CF F404 engines, the fretting occurs along the dovetails of fan and compressor blades as shown in **Fig 3**, which illustrates the various forms of damage incurred by this component in CF engines. Fretting scars may act as stress raisers, giving rise to fretting fatigue cracks. Fretting tends to reduce HCF life, but may also reduce LCF life. Another common form of damage affecting gas path components is foreign object damage (FOD), the result of impact by ingested foreign objects (e.g. rocks, ice pellets) with either static or rotating components. FOD is the predominant mode of damage for fan blades in CF F404 engines, and leads to their removal from service with considerable LCF life remaining. Most forms of external surface damage can be minimized through use of protective coatings or surface modification treatments [3,7-9], while FOD can be repaired within limits, as detailed below [10].

2.1.2. Internal (Microstructural) Damage

Internal microstructural damage is the result of metallurgical aging reactions and plastic strain accumulation. Time-dependent aging reactions occur primarily in hot parts, such as turbine blades and vanes. The reactions are varied and are invariably detrimental to mechanical properties, causing either loss of strength or embrittlement [11,12]. An example of coarsening of the strengthening precipitates in an alloy 713 blade arising from service exposure is shown in **Fig. 4.** Such coarsening causes loss of creep strength in nickel base superalloys. Loss of strength caused by service induced metallurgical aging reactions may lead to

distortion of hot parts. Vane airfoils may bow while blades may lengthen or untwist. Extreme distortion may lead to HCF failures.

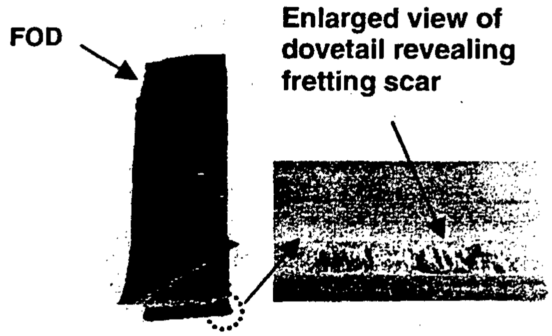
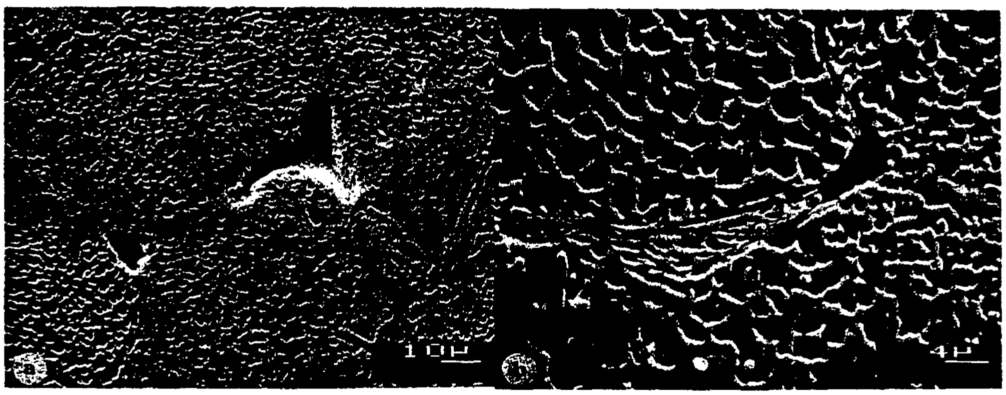


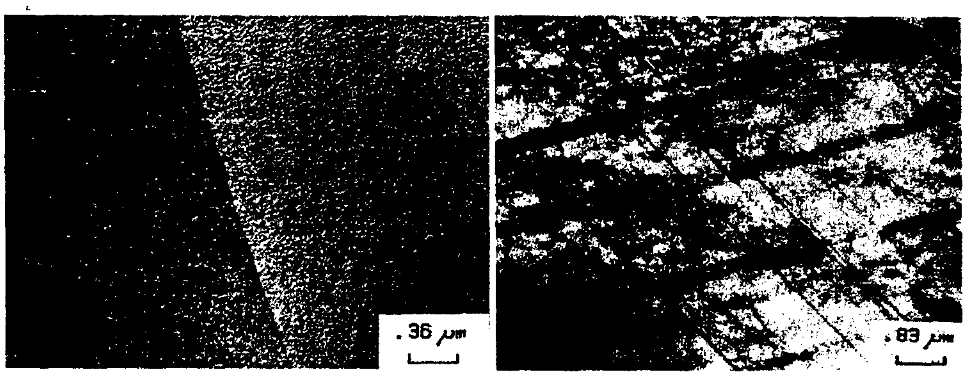
Figure 3. Foreign-Object-Damaged (FODed) fan blade from a CF engine also showing evidence of fretting fatigue damage along the blade dovetail. The surface fretting scar may lead to HCF or LCF failures.



(a) (b)

Figure 4. Microstructure of alloy 713C turbine blades halfway along the blade airfoil: (a) New blade microstructure (b) Microstructure after 5000 hrs of service showing evidence of coarsening of gamma prime precipitates and elimination of secondary gamma prime caused by service exposure. The internal porosity is characteristic of as-cast blades.

Plastic strain accumulation is the product of creep and/or fatigue. It manifests itself in the form of dislocation substructures [13]. Creep deformation leads to creep cavities and internal cracks. The presence of persistent slip bands in the bolt hole region of a disc is indicative of high temperature LCF damage, prior to crack initiation, **Fig. 5.**



(a) (b)

Figure 5. Effects of service exposure on microstructure of disc (a) Virgin disc; (b) Service exposed disc showing evidence of dislocation activity indicative of LCF damage accumulation [12].

Internal microstructural damage is an insidious form of damage because, in contrast with surface damage, it cannot be readily detected by NDI techniques. Its rate of accumulation is strongly influence by service stresses and temperatures, and since there are uncertainties in the temporal variations of these parameters, the extent of damage accumulation cannot be easily predicted. Consequently, the residual life of components is difficult to predict. Under LCF loading conditions, the build-up of microstructural damage in highly stressed components, such as discs and spacers, leads to crack initiation [14]. Cracks initiating at bolt holes or serrated blade slots may grow and lead to catastrophic failures.

2.2. Aging Damage Management

For the purpose of life cycle management, engine components can be classified as either durability-critical or safety-critical parts [2,15]. Durability-critical parts, are those for which aging deterioration affects mainly engine performance and fuel efficiency and may result in a significant maintenance burden, but will not normally impair flight safety. These parts include cold and hot gas path components such as vanes and blades. Safety-critical parts are those for which fracture may result in loss of the aircraft because of non-containment. These parts include most of the large rotating compressor and turbine components, such as wheels, discs, spacers and shafts. Quite different philosophies and techniques are used to manage the life of durability critical and safety critical parts [16].

2.2.1. Durability-Critical Parts

For Durability-critical parts, an "On-Condition" maintenance approach is normally practiced. Parts are removed from service when physical damage limits dictated by design and established through analysis are exceeded. No "hard time" life is set for such parts, but a minimum life expectation is usually guaranteed

2.2.2. Safety-Critical Parts

For Safety-critical parts, two life cycle management approaches are followed. They are (a) the "Safe-Life" approach, for which all components are retired before a first crack is detectable, and (b) the "Damage Tolerance" approach, for which all components are assumed to contain growing cracks, and individual components are retired when a crack is detected.

The Safe Life Approach

With the Safe-Life approach, it is assumed that, should a crack appear, the component has failed. The Safe-Life approach ensures that all components are retired before the first crack appears. This methodology follows a "cycles to crack initiation" criterion, with a minimum safe life (or hard life) capability established statistically through extensive mechanical testing of test coupons and components under simulated service conditions. The statistical minimum is based on the probability that only 1 in 1000 components (-3σ) will have developed a detectable crack, typically 0.8 mm long, at retirement, **Fig 6**.

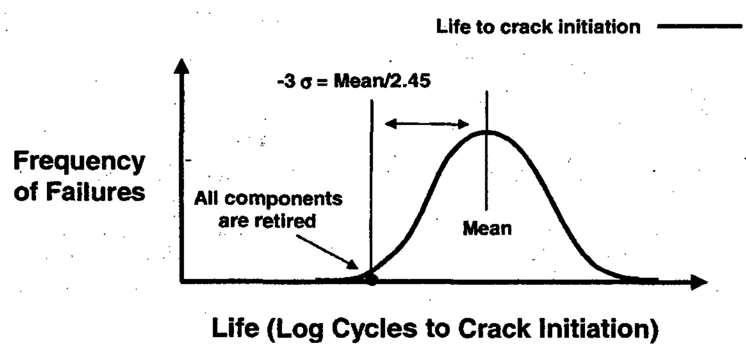


Figure 6. The Safe-Life approach

The advantages of the Safe-Life approach are that the maintenance requirements are kept to a minimum and time in service of components without inspection is maximized. Disadvantages are that the Safe-Life approach is overly conservative because components are retired with a significant amount of useful residual life (practically, 999 out of 1000 components are retired with no detectable damage). Furthermore, the

approach is costly since all parts need replacing nominally at the same time. Under such conditions, the supply of spares may be a serious problem, which is often the case for older legacy engines.

The Damage Tolerance Approach
With the Damage Tolerance approach, it is assumed that fracture critical areas of components contain manufacturing or service-induced defects giving rise to cracks that may grow during service. It is also assumed that components are capable of continued safe operation as the cracks grow under service stresses, of both thermal and mechanical origins. It is further assumed that cracks grow in a manner that can be predicted from linear fracture mechanics, or other acceptable methods. Finally, it is assumed that cracks grow sufficiently slowly to allow their detection through regularly scheduled inspections. The approach follows an inspection schedule established by analysis that ensures cracks will not grow beyond a dysfunction limit. The interval between inspections, or safe inspection interval (SII), is based on the time it takes for a crack to grow from a size immediately below the detection limit of the method used to inspect the component, to a critical or dysfunction size, beyond which the risk of rapid or unstable crack growth becomes too high. The dysfunction crack size is obtained by analysis, for an assumed crack geometry, from the fracture toughness of the material and the stress intensity factor for the component of interest, using appropriate safety factors. The approach is described schematically in **Fig. 7** [2].

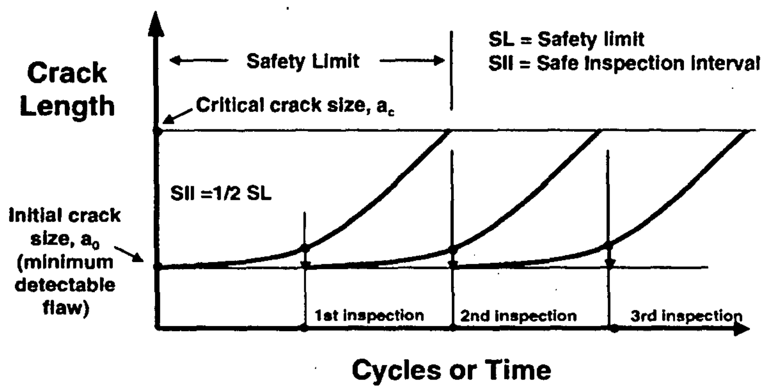


Figure 7. The Damage Tolerance approach

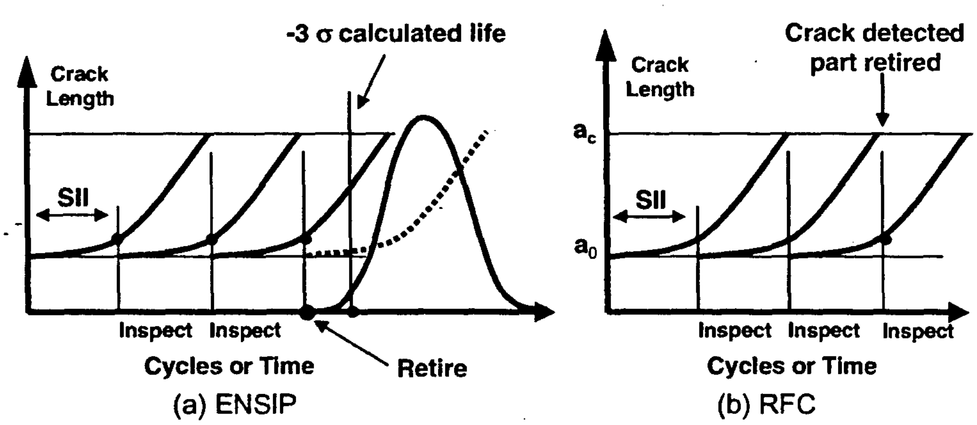


Figure 8. Schematic representations of the damage tolerance approaches based on (a) MIL-STD 1783 (ENSIP) and (b) Retirement for Cause (RFC), respectively.

Two methods may be used to implement a damage tolerance based life cycle management for safety critical parts. The first method, known as ENSIP (Engine Structural Integrity Program - MIL-STD-1783), was introduced in 1984 by the USAF for the structural design, analysis, development, production and life management of engines [16]. ENSIP embraces a fracture mechanics based damage tolerance approach to set

safe inspection intervals for safety-critical parts. However, conventional structural design criteria are also used to minimize the risks of failure due to vibration, LCF, HCF and creep. With ENSIP, individual compressor and turbine discs are retired once their demonstrated Safe-Life (life to crack initiation) is reached.

The second method, known as Retirement for Cause (RFC) also relies on fracture mechanics to set safe inspection intervals for safety critical parts, as practiced with ENSIP. Retirement life is based on periodic inspections until a crack is detected, at which point the part is retired. With RFC, individual compressor and turbine discs are retired only once they are found to contain a crack. The ENSIP and RFC methods are described schematically in **Fig. 8** [2]. A third option, known as 2/3 Dysfunction, may also be practiced, as discussed elsewhere [17].

The advantages of the Damage Tolerance approach are that it ensures that cracks emanating from manufacturing defects (or service-induced cracks) in anyone component will not grow beyond allowable limits. Furthermore, the approach allows life extension beyond LCF based Safe-Life limits through use of the RFC method, if needed. Disadvantages are that the Damage Tolerance approach is more costly to implement than the safe life approach. It requires use of an elaborate NDI infrastructure to support increased inspection requirements. In addition, the handling of components is increased.

3. THE AGING OF ENGINES - WHY IS IT A CONCERN TO NATO OPERATORS

Because of diminishing budgets for new weapons systems, many NATO forces are faced with having to operate fleets of engines well beyond their anticipated service lives. These engines contain components often designed years ago made from materials that lack durability relative to new engine materials. This material obsolescence translates into short component lives and high maintenance costs. In addition, the residual lives of safety critical parts for many of these old engines are not accurately known. This is because the main design factors considered for compressor and turbine discs developed in the 50's and 60's were tensile properties in the bore and the rim of the discs and creep properties in the rim of turbine discs. This was done to provide an over-speed margin without disc burst. For engines of that generation, fatigue lives were not provided for safety-critical parts. Therefore, neither cyclic life consumption nor retirement criteria are available for these engines to dictate the retirement of safety-critical components. How long these engines can be kept in service safely without having to replace their critical components is a growing concern among NATO operators.

4. MANAGING NATO AGING ENGINE FLEETS – THE CHALLENGE

The need to balance risk and high maintenance costs is providing engine fleet managers with incentives to identify and implement strategies for extracting maximum life out of engine components, while ensuring the engines remain safe to operate and reliable in service. Several options to do this are available to LCMs.

4.1. Life Extension Strategies – The Options

One attractive strategy available to LCMs is to equip aging engines with modern health and usage monitoring (HUMS) systems to better predict parts life consumption. This allows component lives to be extended when the assumed mission severity is overly conservative. HUMS in combination with an engine parts life tracking system (EPLTS) allows an operator to optimize engine inspection schedules and the removal of service-exposed parts to achieve more cost-effective maintenance schedules. It also allows more optimal use of parts life potentials and minimizes risks of in-service premature failures. Other strategies for extracting maximum life out of durability-critical components include:

(1) returning service-damaged parts to functional serviceability through use of repairs, such as welding, brazing, rebuilding, re-contouring and rejuvenation heat treatments and

(2) delaying rates of damage accumulation through the addition of protective coatings or surface modifications treatments; a material change for the component is also possible.

For safety-critical parts, the life extension option is to implement a damage tolerance life cycle management approach. The challenge faced by LCMs is to decide upon what option, if any, to implement and to ensure operational safety of the vehicle.

4.2. Life Extension Strategies – Decision factors

The decision to replace or to extend the life of an engine component must consider:

(1) operational consequences of component failure,

(2) cost-effectiveness of the proposed life extension and

(3) qualification testing requirements. Tests are required to qualify as airworthy parts subjected to life extension. These tests must be selected to demonstrate that the parts once returned to service will remain safe and reliable through the life extension [2].

Safety considerations

These are best addressed through use of a Failure Mode and Effect Criticality Analysis (FMECA). A FMECA is a reliability analysis tool used to identify the possible modes of failure on a component-by-component basis, the probability of those failures occurring in service, and the potential consequences of failure [18].

Cost considerations

These are always important and can be addressed through use of a cost benefit analysis (CBA) [19, 20]. However, when there are no spare parts available, either due to a supply shortage, or because replacement components are not made anymore, and the engine must be kept in service, the cost considerations may be less significant or even irrelevant.

A recent trend has been the use of components manufactured by approved sources other than the OEM or OEM approved sources, known as Parts Manufacturing Authority (PMA) components. The PMA parts use is on the rise due to simple economics and parts availability for older generation engines. The users should however ensure that appropriate qualification and quality control procedures have been followed prior to using such parts, as described below.

Technical considerations.

These require that the life extension process be carried out to the same standard used to qualify the original product, or to an equivalent standard. The applicable standards for military aero engines are MIL-E-5007E, MIL-E-8593A, or MIL-STD 1783 (ENSIP) although other standards may apply depending on the engine type and country of origin [21]. MIL-STD-1529 (Vendor substantiation for aerospace products) describes procedures to qualify additional/alternate vendor and fabrication sources other than those qualified for the original product.

5. THE CANADIAN APPROACH TO AGING DAMAGE MANAGEMENT

In Canada, the Department of National Defence has recently adopted a Qualification Methodology, developed jointly by Orenda Aerospace Corporation and NRC, for engine component life extension [18]. This methodology is currently applied to repairs and life extension technologies for durability-critical and safety-critical parts, to reduce CF engine operating costs.

5.1. Canadian Qualification Methodology for Component Life Extension

Development of the Canadian methodology evolved from a careful review of civil and military regulatory requirements used in design and for life cycle management of aero-engines [21]. The methodology consists of (1) a FMECA to establish criticality of damage, (2) a CBA to establish whether it is more cost-effective to apply a life extension scheme than to replace a damaged part, and (3) an Engine Repair Structural Integrity Program (ERSIP), modeled after ENSIP, to ensure that parts will remain safe and reliable through the life extension [2, 18].

The Canadian ERSIP is conceived to establish structural performance requirements and to identify tests for the development and qualification of life extension technologies [22]. ERSIP modifies and extends the limits of ENSIP to satisfy needs for the management of components subjected to life extension. It incorporates the damage tolerance approach implied by ENSIP and is used by the CF to establish structural performance, process development and verification requirements that will ensure structural integrity of the components subjected to life extension. The ultimate goal of ERSIP is to ensure structural safety, durability, reduced life cycle cost and increased service readiness of engines. Depending on type and criticality of the targeted component, ERSIP calls for either all or part of the following qualification tests [2]:

(1) *Dimensional inspection* to ensure that the parts conform with drawing requirements;

(2) *Metallurgical verification* to ensure the material meets engineering specifications (depending on component, specification, this may cover grain size, precipitate sizes, degree of porosity, ductile-brittle-transition temperature, etc…);

(3) *Structural tests* to ensure that relevant mechanical properties are equivalent to or better than properties of original parts (depending on component, properties may include hardness, tensile strength and creep properties, HCF, LCF, TMF, etc...)

(4) *Functional tests* to ensure that part functionality is not impaired by the life extension process (e.g. cooling flow rates for internally cooled parts are identical to flow rates in original equipment);

(5) *Rig and engine tests* to verify that the parts after testing still meet the serviceable limits specified in the applicable R&O Manual and that their general condition is comparable to that of approved parts subjected to identical tests.

Different types of engine tests (accelerated endurance, stair-step, sand ingestion, simulated mission endurance, etc.) may be specified depending on the qualification objectives, as detailed elsewhere [2].

5.2. Life Extension Strategies Covered by ERSIP

Life extension schemes covered by ERSIP include:

(1) restoration of damaged components to serviceable conditions by repair or rework,

(2) modifications intended to improve the structural performance or damage tolerance of engine components (e.g. a material change, the addition of a coating or a surface treatment) and

(3) reuse of components under a damage tolerance-based life cycle management scheme to achieve life extension, all in conformity with the requirements of ERSIP.

5.2.1. Life Extension Through Component Restoration

Much work has been done in the commercial world to develop repairs and reworks for civilian aircraft engines. Repair vendors have been competing quite successfully with original engine manufacturers (OEM) in these developments. The delegation of authority by national aviation authorities to R&O organizations has encouraged such trends. Technologies developed for civilian products are for the most part applicable to military platforms and can be adopted by military organizations to achieve cost-effective management of aging engines [23]. Different types of component restoration schemes have been developed for aero-engines. Examples of schemes developed in Canada for the CF are provided below.

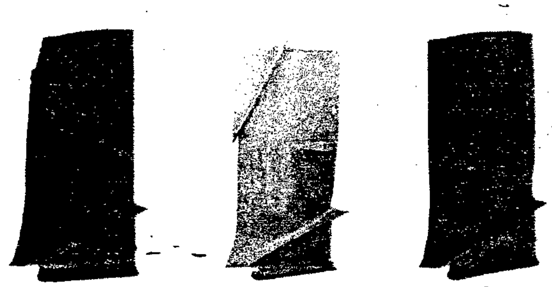


Figure 9. Repair of FODed F404 fan blade by electron beam welding a corner patch to replace damaged portion of blade.

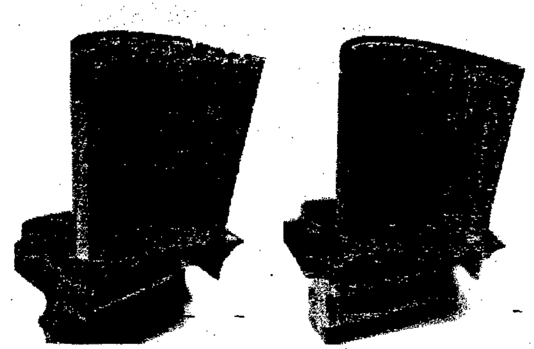


Figure 10. Weld tip repair of DS René 80 first stage turbine blade form CF F404 engine (Courtesy Liburdi Engineering Ltd., Hamilton, Ontario)

Electron Beam Weld (EBW) Repair of FODed F404 Fan Blades

In this repair scheme developed by OAC to eliminate foreign object damage from fan and compressor blades, the damaged area is replaced with a patch of matching material (Ti64 in this case), which is joined to the airfoil by EBW, as shown in **Fig. 9**. Details of the technique and its qualification for the repair of F404 fan blades were presented at the AVTP Workshop on Cost Effective Applications of Titanium Alloys, in Loen, Norway, April 2001 [10]. Qualification testing for this repair included (1) an assessment of weld microstructure and residual stresses, (2) an evaluation of strength and fatigue properties of welded test

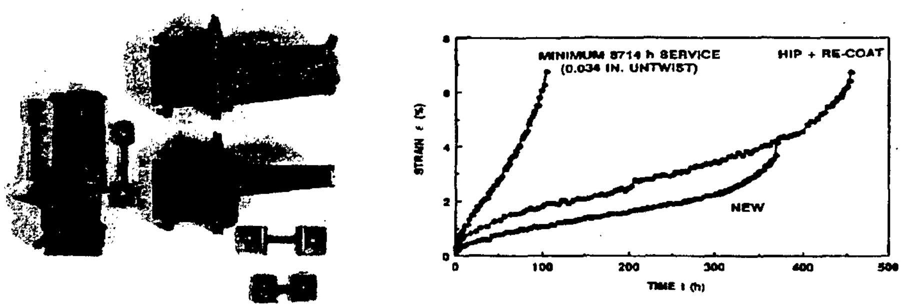
coupons, (3) a comparison of the vibration characteristics, fatigue properties and ballistic impact resistance of new and weld repaired components and (4) engine block testing of repaired components, as part of an accelerated mission test (AMT) performed in one of IAR's test cells on a CF F404 engine.

Weld Tip Repair of High Pressure Turbine Blades

A weld tip repair was developed by OAC in collaboration with Liburdi Engineering (Hamilton, ON, Canada) for the DS Rene 80 HPT blade from the CF F404 engine, **Fig. 10.** For this repair, the tip damage is removed by grinding and the blade tip is rebuilt using an automated welding technique. The weld material is chosen to provide enhanced oxidation resistance at the blade tip to prevent oxidation of the underlying columnar grain boundaries. Details of this repair were presented at the RTO-AVTP Workshop on Qualification of Life Extension Schemes for Engine Components, Corfu, Greece, October 1998.[Liburdi Corfu, 10].

Advanced Braze Repairs for Nozzle Guide Vanes

Hydrogen fluoride (HF) cleaning, in combination with diffusion brazing, makes it possible to repair nickel base superalloys. The presence of thermodynamically stable oxides along crack faces makes these alloys difficult to braze. Cleaning with HF removes the oxides and promotes wetting and penetration of the crack by the braze alloy, thereby creating a structurally sound and durable joint. Special low temperature braze alloys have been developed for this type of repair. The braze alloys contain elements that lower their melting point. The molten braze alloys re-solidify at brazing temperatures once the melting point suppressant has diffused away from the joint into the bulk of the component. The AFOR-DBR process developed by Vac-Aero International in collaboration with NRC is an example of this type of repair [24]. The Liburdi Engineering LPM™ joining/cladding process [7,25] was developed as a hybrid wide gap brazing technique that has proven successful for the repair of both blades and vanes. The process enables a wide range of alloys to be used for crack repair and surface build-up. The damage is first removed by grinding and a powder metallurgy putty of matching or custom composition is applied and diffused into the surface to complete the repair and achieve the desired mechanical and metallurgical properties.



(a) (b)

Figure 11 (a) Miniature creep specimens machined from the airfoils of different T56 turbine blades; (b) Creep curves for new, service-exposed and HIP rejuvenated 713LC blades [13,32].

Component Rejuvenation through HIPing or Heat Treatment

Combinations of heat treatments and hot isostatic pressing (HIPing) have been used to eliminate service induced microstructural damage in turbine blades and vanes to restore creep properties. HIPing eliminates creep voids that may have formed during service. It also eliminates casting porosity, which improves the component reliability by reducing scatter in material properties. The re-coating heat treatment completes the rejuvenation. HIP rejuvenation cycles have been developed at IAR for alloy 713C and IN 738, both of which are used for blades and vanes in T56 engines [26,27]. HIPing can also be used in conjunction with other forms of repairs, for instance to eliminate shrinkage porosity within braze joints [24]. Qualification of rejuvenation treatments for T56 blades relied in part on tests performed on miniature specimens machined from the blades. Results indicated that HIP cycles can be optimized to achieve rupture lives and creep elongation that are significantly higher that those for new blades with a nominally identical minimum creep rate, **Fig. 11.**

Rebuilding of Worn Seal Teeth

The repair of worn seal teeth from rotating air seal components is another economically desirable refurbishment procedure. The tips of the damaged teeth are first ground down and then rebuilt with over-lays of similar alloys, using welding techniques such as Dabber™ welding or pulsed laser or plasma torch welding [7]. Example of refurbished seal teeth are shown in **Fig 12**. The teeth are first rebuilt by laser cladding with a pre-alloyed powder and subsequently finish-machined to design specifications. Before implementing such types of repair, it is essential to assess the risk of cracks initiating at imperfections in the built-up weld or at the weld metal/parent metal interface. Simulated seal tooth specimens are desirable for this qualification work but the interpretation of results can be quite complex [28].

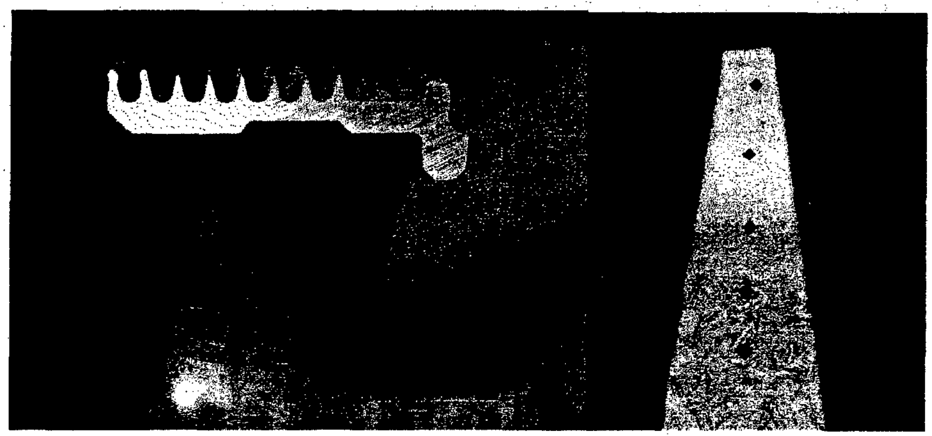


Figure 12. Example of seal teeth repair by laser welding (Courtesy of Standard Aero Ltd., Winnipeg, Manitoba).

5.2.2. Life Extension Through Material Modifications

The objective is to enhance component durability either by:

(1) substituting the component material for another to improve, for instance, the component creep properties, or to eliminate a problem,

(2) substituting or adding a protective coating to improve resistance to wear, fretting, erosion, oxidation or corrosion (e.g. adding a hard coatings to compressor airfoils or a TBCs to hot parts) or

(3) applying a surface modification treatment such as shot peening, ion implantation or laser surface processing to improve the resistance to various modes of surface degradation or fatigue.

Retrofitting with New Materials

This is occasionally implemented by an OEM, usually under the umbrella of a client-supported component improvement program (CIP). There are examples of material changes involving both blades and discs. For CF F404 engines, the first stage HPT blade material was changed from a conventionally cast René 125 to a directionally solidified (DS-columnar grained) René 80, to improve the creep strength and thermal fatigue resistance of the blades. A subsequent change to single crystal alloy N4 was approved to further improve properties of the blades. With changes of this type, the expected improvements are not always met, because a new and unexpected mode of damage may prove life limiting. This happened with the change to the DS blades in F404 engines, which suffered tip oxidation and thermal fatigue cracking along the columnar grain boundaries. Disc materials are more rarely changed. One of the CF J85 CAN40/15 engine compressor disc was changed from an AM355 martensitic stainless steel to a DA718 nickel base superalloy to eliminate premature bolthole cracking.

Substituting or Adding a Protective Coating

Titanium nitride (TiN) applied by physical vapor deposition (PVD) has been qualified as a coating for the protection of compressor airfoils against particulate erosion. The RIC™ PVD TiN coating from Liburdi Engineering is a bill-of-material option for T56/K501 RR engines. Testing to qualify TiN coated blades for CF engine use included fatigue testing in a specially designed test rig at resonant frequencies under the blade

1st bending mode [29]. Weibull analysis of the results for bare and coated blades indicated that coated blades have marginally higher fatigue strength and a lower probability of failure than bare blades at an equivalent blade root stress [3].

Turbine blades and vanes are routinely re-coated at overhaul. This provides an opportunity to change the coating for one that is better suited to a particular operating environment. For instance, Pt aluminides offer durability enhancement over conventional aluminides when hot corrosion is life-limiting. A coating can also be added to internal cooling passages [8] or to a normally uncoated component, as did OAC with the MA-754 high-pressure turbine nozzle in the F404 engine [30]. The addition of thermal barrier coatings (TBC) to airfoils, including the tip region of turbine blades, lowers metal temperature, thereby minimizing the rate of material consumption due to oxidation. When applied to the leading edge of an NGV, stress gradients may also be reduced, thereby reducing thermal fatigue cracking.

Qualification testing requirements for turbine coatings typically include:

(1) a metallographic evaluation of coating quality and its impact on microstructure and phase stability of the substrate,

(2) an assessment of the effects of coating on the mechanical properties of coated material test coupons (Tensile and creep strength, HCF LCF, TMF, DBTT)

(3) rig tests to ensure flow rates across cooling passages of internally cooled parts are identical for new and refurbished parts

(4) rig tests to compare durability and damage tolerance of new and repaired parts under simulated service conditions, for instance in a burner rig

(5) engine block testing as part of an AMT and

(6) field evaluation in a lead-the-fleet engine.

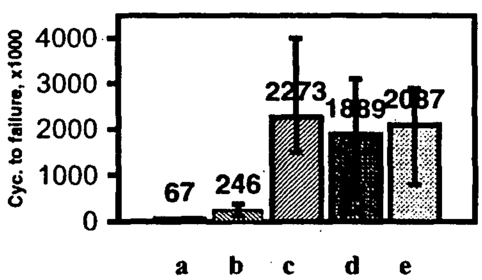


Figure 13. The fretting fatigue life of Ti-6Al-4V:
a = base metal; b = CuNiIn + MoS_2; c = shot peened; d = shot peened + CuNiIn + MoS_2; e = shot peened + MoS_2.

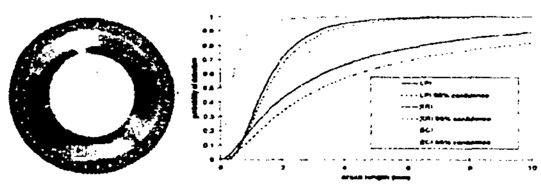


Figure 14. Probability of detection of natural cracks in Fe-Ni-Cr alloy turbine discs using liquid penetrant inspection (LPI), eddy current inspection (ECI) and x-ray inspection (XRI) [35]

Applying a surface modification treatment.

Surface treatments such as ion implantation and chemical surface treatments have been explored for use in conjunction with shot peening and soft coatings to minimize fretting fatigue damage along the dovetails of F404 fan blades. Shot peening in combination with chemical treatments is quite effective in laboratory tests but other surface treatments, including soft coatings and lubricants, appear to have the potential for improving the fretting fatigue resistance of titanium alloys. The effects of these treatments on fretting fatigue life of two titanium alloys (Ti64 and Ti17) have been evaluated using equipment developed at IAR. Some of the results, presented at an AGARD-SMP Workshop on Tribology for Aerospace Systems, Sesimbra, Portugal, April 1996 are shown in Fig.13 [9].

5.2.3. Life Extension Through Re-use of components under RFC based LCM

As noted previously, cyclic fatigue lives are rarely available for the fracture-critical parts of old engines. This is cause for concern to LCMs who have no safety criteria on which to base component retirement. Faced with this problem, it is not unusual for an OEM to establish LCF safe lives of engine rotors

retroactively, at a late stage in the life of an engine. This is occasionally done for the benefit of users under a user supported component improvement program (CIP). However, experience shows that the service lives of a significant fraction of components from lead-the-fleet engines can be greater than the calculated LCF safe lives, sometimes by quite significant margins. This reinforces the often-expressed view that components retired at their design safe-life limits may have significant fractions of usable life remaining.

Implementation of a damage tolerance/RFC approach provides opportunities for safely managing parts from these old engines [31]. Components from three CF engines are being analyzed at IAR in collaboration with others for implementation of a life cycle management approach based on a damage tolerance/RFC concept. The engines include the Rolls Royce Nene X, the GE J85 and the Rolls Royce Allison T56. Implementation of a RFC based management philosophy for these legacy engine components requires that six basic steps be followed [2]. These are:

Step 1: Determination of stress and temperature data

This can be achieved by instrumenting targeted engines to determine temperature distribution and strain profiles across the components of interest. The results are used as boundary conditions in FEM models to establish the stress distributions within the components.

Step 2: Identification of the fracture critical location in the component of interest

This is normally achieved through finite element analysis. The lowest serration at the bottom of fir-tree slot is usually identified as the fracture critical location in discs.

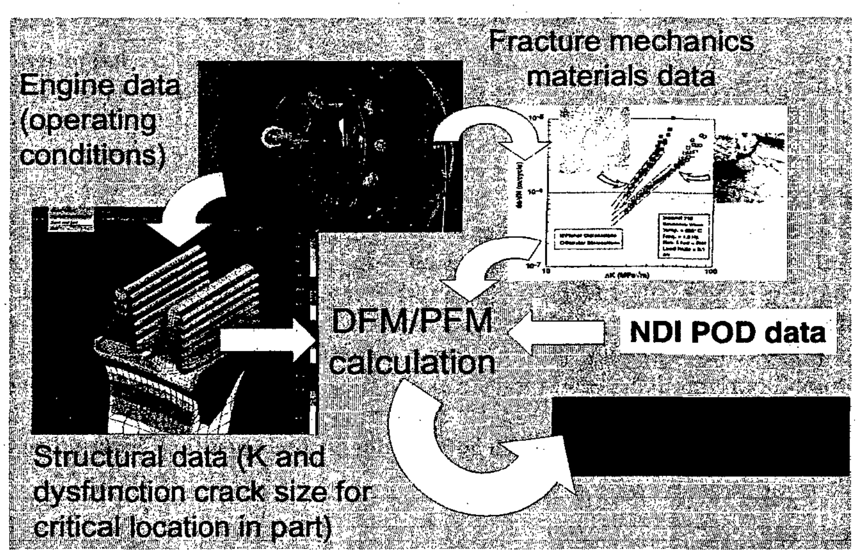


Figure 15. Steps associated with SII calculation for damage tolerance based life management of critical engine parts.

Step 3: Determination of the stress intensity factor (SIF) at the fracture critical location in the component

This is also obtained by finite element analysis at the tip of a crack of specified geometry, assumed present at the fracture critical location of the component. The FE analysis yields the variation of the stress intensity factor with crack depth for a single crack in the fracture critical region of the turbine disc [32]. The SIF values are obtained for a crack with a geometry preferably chosen to provide a worse case scenario.

Step 4: Generation of fracture mechanics data for safe inspection interval (SII) calculations

Relevant FCGR data should be generated at the operating temperature of the fracture critical location, using specimens machined from actual components. The reason for using specimens machined from components is to capture the effects of prior service history on the microstructure and therefore properties of the

component [29]. Experience shows that high time IN 718 discs have higher fatigue crack growth rates than low time discs [33].

Step 5: Generation of NDI POD data

Probability of detection (POD) data for the NDI methods of interest are needed to establish the initial flaw size for the analysis. It is best that the POD data be generated from actual life-expired parts [34]. In a program sponsored in part by AGARD, a large number of retired J85 compressor discs were examined for fatigue cracks using a variety of NDI methods. The NDI results were verified by prying open each inspected bolthole and examining the pried-opened areas for evidence of service induced cracking. Actual crack sizes were established from microscopic examinations in a scanning electron microscope. The POD data were generated through standard POD analysis. The POD curves for three common NDI techniques, including Eddy Current Inspection (ECI), Liquid Penetrant Inspection (LPI) and x-ray inspection (XRI) obtained for the J85 Can 40 compressor disc are compared in Fig. 14 [35]. The NDI Detection Limit is defined as the crack size at 90% POD and 95% Confidence. For damage tolerance analysis, the initial flaw size is defined to be either the maximum crack length missed or the crack length value at 90% POD and 95% Confidence. The data indicate that the Eddy Current Approach is more sensitive than the other methods. The substantial amount of POD data derived from this work is available through the USAF supported Non Destructive Testing Information Analysis Centre (NTIAC) of Austin, Texas.

Step 6: Calculations of the safe inspection interval (SII)

The SII for the component of interest is obtained through the application of either probabilistic or deterministic algorithms [36,37], which require as input for analysis (a) POD data for the NDI used to inspect the component, (b) values of the stress intensity factor (SIF) and (c) crack growth rate data. The process is summarized schematically in **Fig. 15**.

Details of the damage tolerance analysis for the CF Nene X turbine disc are being reported at the AVT Symposium on Damage Mechanisms and Control – Part B on Monitoring and Management of Gas Turbine Fleets for Extended Life and Reduced Costs [38]

6. CONCLUDING REMARKS

The deterioration of engine components begins as soon an engine enters service. This deterioration or aging cannot be avoided and must be managed. Managing aging components to extract maximum life from expensive parts requires a good understanding of deterioration modes and their potential impact on engine performance, reliability and safety. From a fleet manager's perspective, a number of options are available to extend component lives beyond book limits. These options include repairing service-damaged parts, enhancing their durability through material modifications, including the substitution or addition of protective coatings, or applying a damage tolerance based life cycle management methodology for safety critical parts. Canadian related experience shows that significant savings in the operating costs of engines accrue from such initiatives [19].

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