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Abstract

Canada's Department of National Defence (DND) and Canadian industry began the collaborative development of an airworthiness certification, or compliance, process for gas turbine repairs and have initiated the development and qualification of a series of repairs for the CF18's F404-GE-400 engines. The airworthiness certification process is applied to flight critical components which have not typically been repaired in the past. Proprietary design information, full scale test facility development and operational overheads, and the costs of qualification test programs for these repairs have precluded operator initiated repair process development. Previous DND Defence Research and Development Branch (DRDB) technology base collaborative investments with industry and the National Research Council of Canada (NRCC) Institute for Aerospace Research (IAR) have established the knowledge and resource base necessary to allow Canada to pursue this technologically challenging venture. The generalized business case for repair development and the establishment of the knowledge base and infrastructure for repair and certification are first described. The qualification methodology and use of the Cost Effectiveness Analysis (CEA) package to ensure continuing awareness of cost and benefit issues are next discussed. Finally, the current phase of this program, which utilizes the qualification methodology to certify a number of repairs for immediate introduction to CF18 service is presented. Although the certification process will initially be applied to the CF18 engines, it is generic in nature and will be also used to achieve cost reduction on other Canadian Forces aero-gas turbines and components.

Introduction

The Canadian Forces (CF) typically operate their aircraft in a manner which is at least as extreme as any user of the aircraft in terms of both mission severity and service longevity. Environmental issues can often complicate the support of CF aircraft by introducing operating conditions, such as extreme low temperature, which were not anticipated by the Original Equipment Manufacturer (OEM) design team. Additionally, the consequences of catastrophic failure become more severe when operating in remote, low temperature areas where safe ejection and descent from the aircraft does not guarantee ultimate aviator survival. For reasons of cost, the CF has periodically chosen not to introduce OEM initiated modifications to aircraft or engines and this has resulted in the requirement to manage unique CF configurations. The CF have had to develop the capability to initiate unique modifications to address issues particular to Canadian operational exigencies, or to capitalize on Canadian industrial capabilities.

In addition to those factors noted above, the CF have always had a very pressing need to minimize operational and maintenance costs. There a number of areas which must be addressed when attempting to reduce the costs of aircraft operation while maintaining the airworthiness and operational effectiveness of military aircraft fleets. These issues, as they pertain to aeropropulsion systems, are briefly discussed below and in more detail in subsequent paragraphs:

- An understanding of the origin and magnitude of program cost factors must be gained in order that investment can be directed at the areas of highest potential return. Numerous informal studies on aeropropulsion costs have been undertaken by the CF in support of life extension programs or like exercises. The reference [1] study attempted to identify overall systems support costs and the impact on operations of the major groupings of aircraft systems, and quantified the program support costs of the F404 engines in the CF18.

- The probability and criticality of failure must also be assessed to understand where repair investments should be directed, and to gain insight on how to improve the durability of those components. Operational loads and damage modes must be correlated to fully understand the consequences of failure and how to mitigate the effects of failure on flight safety.

- Inherent in the foregoing is the need to monitor the usage of individual components, to understand the rate at which life is being expended, and to be able to estimate the life remaining on those components. With the Maintenance Signal Data Recording Set (MSDRS) and In-flight Engine Condition Monitoring System (IECMS) on the CF18/F404, the CF had its first opportunity to gain a comprehensive understanding of individual aircraft/engine usage. DND has invested considerably in the enhancement of data analysis for these on-board systems to allow a full range of diagnostic/prognostic/repair technique development.

- A metallurgical knowledge base was required to not only understand the causes of failure but also to be able to identify and develop novel damage recovery processes. This activity has been underway in a concerted manner in Canada for approximately 15 years with a particular focus on CF18/F404 engine components. The development of the prerequisite technology base and infrastructure to support repair technologies has been a major element of the DRDB aeropropulsion R&D program.

- The development of a qualification methodology for airworthiness certification of repair redesigns was completed in early 1996 and it is now being followed for a number of CF18/F404 engine repairs. The development of this process was challenging in that no equivalent procedural guidance could be found.

- In recent years, the US DoD and US industry has developed a cost/benefits analysis package, Cost Effectiveness Analysis (CEA). This is a major step forward and provides, possibly for the first time, a rigorous and comprehensive approach to analyzing the cost of introducing repair processes and enabling a realistic and consistent assessment of life cycle benefits. The CEA is mentioned specifically, as it has been employed throughout the most recent CF repair scheme development project.

Aeropropulsion System Cost and Operational Impact

DRDB conducted a study [1] to assess the impact of aeropropulsion systems on in-service life cycle costs and operational availability. At the time of the study, the cost of contracted-out support of DND equipment approached $1.4B of which approximately $800M, or 57%, was spent on air force equipment. This high cost of aircraft support reflects the high cost of advanced technology, combined with stringent flight safety requirements. For the purposes of [1], the aircraft was considered as consisting of four major sub-systems: avionics, propulsion, weapons, and airframe and components. A total of eight CF aircraft models were included in the study. Four commercial aircraft having CF military equivalents were also analyzed for flight safety/aircraft availability comparative purposes. For the CF aircraft, the power plant was found to cause from 27 % (CF18) to 46% (CH124 Sea King) of materiel caused flight safety occurrences. The commercial aircraft statistics were similar to those of the military. In terms of unscheduled maintenance manhours, which was taken to correlate with aircraft unavailability, the powerplant consumed from 10% (CH124 Sea King) to 37% (CF5) of resources. Replenishment spares, contracted R&O, CF maintenance labour, petroleum, oil, lubricants, and expendable stores cost data are provided in [1] although only the initial three factors are used by this report for comparative cost analysis. Aeropropulsion systems typically consume 15-46% (average being the CF 18 figure of 28%) of the in-service life cycle costs of an aircraft. This study identified the magnitude of cost and operational impact of the aeropropulsion system on CF operations and was instrumental in obtaining approval for repair technologies development. It was recognized that the knowledge necessary to design and implement a repair process could also be used for failure analysis, to better manage the retirement of components, and in some cases to tailor missions to reduce the damage accumulated.

Failure Mode, Effects and Criticality Analysis

Failure Mode, Effects and Criticality Analysis (FMECA) is a method of reliability analysis intended to examine the potential failure modes within a system and its equipment and to determine the effects on equipment and system performance in order to establish priorities for remedial action. The FMECA consists of two separate analyses, the Failure Modes and Effects Analysis (FMEA) and the Criticality Analysis (CA). FMEA is usually a qualitative analysis of the failure modes of hardware; however, it does not exclude factors of human or software error. The Criticality Analysis combines the concepts of severity of consequences of failure and the rate or probability of occurrence of a failure within a specified time period. The CA can either be conducted in a qualitative or quantitative manner dependent on the quality and availability of failure data. The FMECA will attempt to:

- Determine the effects of each failure mode on system performance;
- Provide data for developing Fault Tree Analysis (FTA) and reliability block diagram models;
- Provide a basis for identifying root failure causes and developing corrective action;
- Facilitate the development of design alternatives for improved reliability repairs;

- Aid in developing test methods and troubleshooting techniques; and
- Provide a foundation for quantitative reliability, maintainability, safety and logistics analysis.

The FMECA can be used at the initial design stage, as well as during the life cycle of a component. Its purposes are to: highlight single point failures which require immediate action, rank failures according to a severity classification of the failures effect on mission success and personal/equipment safety, provide estimates of critical failure rates, and to identify reliability/safety critical components requiring special management approaches. The US DoD has developed a number of standards relating to FMECA which were used in the generation of a DND FMECA for gas turbine components. Additionally, there are a number of generic FMECA codes on the market which have been developed for specific and generic applications. DND decided to generate a specific FMECA capability rather than purchase off-the-shelf, as the costs were comparable. This development facilitates future package improvements and enables the application of the FMECA tool to other aircraft and systems. The FMECA process which has been developed has been demonstrated to satisfy all performance requirements, is adaptable, and can be integrated with current CF maintenance management procedures.

Prerequisite Technology Base

A comprehensive understanding of the metallurgy of the gas turbine components as well as the damage modes that will affect either the aero-thermodynamic performance or lead to physical failure of these components is a prerequisite to any repair redesign activity. High and Low Cycle Fatigue (HCF and LCF) will predominate as damage modes in the compressor section, while pressure burst or thermal fatigue will likely be the dominant considerations in the combustor. However, the area of greatest duress is in the turbine module where creep, thermal mechanical fatigue, erosion, and corrosion all combine to generate the most demanding of operational environments. The NRCC/IAR, as part of its own research program, and as sponsored by DND R&D funding to NRCC, has conducted a focussed and productive research program in current and emerging materials and their characteristics. DND engines have provided the stimulus and many of the specific research challenges as they employ advanced materials for which a store of service experience exists or is being generated. These activities have established the knowledge base and infrastructure necessary within Canada to proceed with a wide spectrum of gas turbine repairs.

A detailed knowledge of the actual operating environment of the components is also required for the introduction of these repairs. Much of this information is closely guarded proprietary design data which is retained by the OEM. The OEM design assumptions, of necessity, cannot fully address the actual operational spectrum and so it is necessary to analyse in-service experience and to generate the required data. This aspect of the knowledge base has been developed through advanced instrumentation development, experimental methods development, analysis of available histories of failed components, specially instrumented engine and flight tests, and post failure analyses. Much of this knowledge is necessarily specific to type and has been developed for the F404 engines. Test capability has been developed for a full spectrum of gas turbine design considerations including metallurgical analysis equipment, coupon test components, rig test devices, and full scale sea level static engine test facilities. A comprehensive discussion of the facilities available to DND is available from NRCC/IAR and a description of those facilities is provided in reference [2].

Qualification Methodology/Airworthiness Certification Process

DND has a long and well-established record of flight safety which is on par with, or exceeds, civil standards. Repairs to flight critical gas turbine components have not been attempted in the past by DND and no approach had been developed to address the certification of airworthiness. Additionally, no commercial operators have attempted these types of repair in the past and accordingly, no commercial certification procedures exist. Civil regulatory guidance is directed primarily toward the design and certification of new engines and components. To understand the civil regulatory requirements and use such guidance as is available to develop a process which was consistent with aerospace industrial practices, a study of regulatory agency requirements in Europe and North America has been conducted. This allowed for the generation of a certification process on gas turbine repairs which will ideally be compatible with civil regulatory requirements.

Regulatory Agency Review

An initial review of regulatory agency requirements was conducted to identify what, if any, existing guidance could be applied to DND unique repair/redesign activities. This review was also intended to provide the approach for a qualification methodology which would facilitate the acceptance of this concept, and the specific repairs generated under this project, by other military users. It was also hoped that this philosophy would be further pursued in commercial aviation and that eventually DND would be able to benefit from the much larger potential repair industry thus generated. A review was conducted of the procedures followed for design change approvals as specified by Transport Canada Aviation (TCA), the United States Federal Aviation Administration (FAA), the British Civil Airworthiness Authority (CAA), the European Joint Aviation Authority (JAA), the US Department of Defense (DoD), and UK Ministry of Defence (MOD). TCA procedures and definitions were selected as they address the majority of requirements of other regulatory agencies. Differences between TCA and other regulatory agency procedures have, however, been documented for future reference. The DND Qualification Methodology for Advanced Gas Turbine Repair/Rework which was developed is documented at Reference [3].

Qualification Methodology Description

This methodology describes how to design and certify a repair as being airworthy following a systematic, consistent, and auditable procedure. To do so, the methodology must address such issues as repair design, life analysis, verification testing, and personnel qualification requirements. The qualification methodology is applicable to DND aero-gas turbines, and must be valid for flight critical and non-critical components. The process for obtaining a Ministerial Delegation of Authority, and the responsibilities and privileges which may be exercised by the DND equivalents to a Design Approval Representative (DAR) or Design Approval Organization (DAO) are also specified. The Qualification Methodology for Gas Turbine Repair/Rework is comprised of the following components:

- Failure Mode, Effects and Criticality Analysis;
- Coupon level testing requirements and process guidelines;
- Component rig testing requirements and process guidelines ;
- Full scale Engine Block Test (EBT) and Accelerated Mission Testing (AMT) methodology; and
- Design change approval process and documentation.

CF18/F404-GE-400 Repair Certification Program

The feasibility of a number of advanced repair and life extension techniques for high cost F404 engine components has been demonstrated over the past years through collaborative research projects with NRCC/IAR and Canadian industry. The feasibility of the repairs has been demonstrated through testing of metallurgical integrity, vibration properties, mechanical integrity (ballistic impact, fretting fatigue, and low cycle fatigue testing), and durability in a simulated gas turbine environment. Following the development of the qualification methodology, a contract was let to Canadian industry to demonstrate the methodology through repair design and qualification on a number of CF18/F404-GE-400 components. The contracted obligation specified a minimum number of specific repairs/reworks which were selected based on a preliminary cost benefit analysis, failure mode analysis, preliminary design and analysis as well as process development studies. Repairs/reworks for the following components were identified:

- Stage 1 fan blade FOD repair;
- Stage 1 fan blade dovetail fretting fatigue improvement;
- Stage 1 fan blade LCF life extension;
- Stage 3 HPC blade dovetail fretting fatigue improvement ;
- HPT vane segment cracking and braze loss;
- HPT vane life extension;
- HPT blade tip repair;
- HPT blade life extension; and
- LPT vane segment cracking and braze loss.

The failure modes and these proposed repairs are briefly described below:

Fan Blade Repairs/Reworks

The first stage Ti-6Al-4V fan blade of the F404 engine suffers Foreign Object Damage (FOD) in service. The blades which sustain extensive FOD damage at the upper leading edge are repaired by using an Electron-Beam Welding (EBW) technique. The damaged portion of the blade is removed using an abrasive waterjet cutting technique and then weld repaired using a specialized fixture and a pre-designed and fabricated aerofoil patch. A CNC machine is used to finish the aerofoil to a contour within OEM blade dimensional tolerances.

The F404 engine first stage fan blade is life limited by LCF damage at the blade critical location, the leading edge radius below the blade platform. Finite element analysis was used to pinpoint the LCF critical region of the fan blade. It was felt that a rejuvenation process could recover, at a minimum, 80% of the original design LCF life. A localized heat treatment process for service exposed blades was then developed and the effects of annealing on the mechanical properties of the material were predicted through microstructural characterisation and microhardness evaluation. This rework development was stopped when the OEM modified the fan blade design and increased the LCF life of the fan blade by a factor of three, as the rework did not offer sufficient Return-On-Investment (ROI).

Fretting damage has been observed in all stages of F404-GE-400 fan blades and discs. Understanding the fretting mechanisms on the fan blade dovetail has required considerable attention. Canadian industry in collaboration with NRCC/IAR has developed and optimized a fretting fatigue test rig capable of simulating the loading conditions (blade/disc contact pressures, relative sliding, and overall fatigue) of the F404 stage 1 fan blade. This rig has been used to test a variety of surface modification techniques and protective coatings for life extension of fan/disc couples. The process specification has been developed and this repair/rework tested for airworthiness. The goal of this repair/rework is to improve fretting resistance by a factor of two.

By way of example, and only for stage 1 fan blade repairs, the tests and analyses specified in the qualification methodology as being required for the recovery of the above types of fan blade damage are summarized below:

1. Equipment type/name: Stage 1 fan blade
2. Category: Cold, Rotating
3. Failure Mode: FOD
   a. Severity Class: II - Critical
   b. Repair: EBW
   c. Repair Qualification Tests and Analyses
   - Metallurgical examination
   - Surface hardness
   - NDI: cracking, porosity, residual stresses
   - Dimensions: geometry, mass properties
   - Natural frequency
   - Weld joint tensile
   - HCF - coupon or component
   - LCF - coupon
   - Impact - component
   - Engine Block Test
   d. Extra Tests and Analyses required before EBT
   - Nil
   e. Extra Tests and Analyses to be conducted with EBT
   - Determination of maximum allowable defect size
4. Failure Mode: Fretting Fatigue
   a. Severity Mode: III - Marginal
   b. Repair: Surface Modification
   c. Repair Qualification Tests and Analyses
   - Metallurgical examination
   - NDI: cracking, porosity, residual stresses
   - Dimensions: geometry, mass properties
   - Natural frequency
   - Weld joint tensile
   - HCF - coupon or component
   - LCF - coupon
   - Impact - component
   - EBT
   d. Extra Tests and Analyses required before EBT
   - Fatigue notch sensitivity - coupon
   e. Extra Tests and Analyses to be conducted with EBT
   - nil
5. Failure Mode: LCF
   a. Severity Mode: n/a
   b. Repair: Electron beam localized heat treatment
   c. Repair Qualification Tests and Analyses
   - Metallurgical examination
   - NDI: cracking
   - Microhardness
   - Dimensions: tolerance check
   - LCF - coupon
   - Spin pit - component
   - Engine Block Test
   d. Extra Tests and Analyses required before EBT
   - Nil
   e. Extra Tests and Analyses to be conducted with EBT
   - Analytical determination of fracture critical locations on the component and damage tolerance assessment.

<u>Improvement of HPC Stage 3 Blade Dovetail Fretting Fatigue</u>

The third stage HPC blades have experienced dovetail failures during service as well as during factory engine testing at the OEM. The OEM has attributed the failure to Ti-6Al-4V alloy degradation due to HCF/LCF/Creep interaction at dovetail temperatures of 454°C. A material change to Ti-6Al-2Sn-4Zr-2Mo, which has a better high temperature fatigue strength, was implemented in addition to an increase in the dovetail thickness. An extensive investigation has been conducted for DND to determine the mechanism of crack initiation and propagation causing HPC blade failure in CF engines. The results of this investigation demonstrated that the blade cracking was initiated due to severe loading conditions, excessive temperatures, and degradation of the Cu-Ni-In coating under engine operating conditions. It was demonstrated that the Cu-Ni-In coating did not provide adequate protection from fretting fatigue to the base material; it was found to be oxidised and severely extruded. Since then, the OEM has proposed two alternate coating systems. It was felt that these coating systems did not address the actual problem of fretting fatigue, as they were intended primarily for, and qualified for, wear and friction properties rather than the complex fretting fatigue, low cycle fatigue, and creep modes of damage. A number of coating systems have been proposed and communication with the OEM has been initiated to pursue the coating evaluation. Within the scope of this work, test specifications have been developed and techniques evaluated to improve fretting fatigue resistance by a factor of two.

HPT Vane Improvements

The HPT Vane Segment of the F404-GE-400 suffers from thermal fatigue cracking both in the MA754 vane and in the MM-509 platform or band. The vane and platform cracking is due to complex thermal and gas bending loads during a typical military cycle of operation. Temperature gradients, mechanical constraints, and the time variation of both the temperature and the stresses at both high and low frequencies can lead to low cycle fatigue damage and eventual failure. The cracking in the internally cooled component is so severe at times that a portion of the vane or platform is lost into the gas stream during service. The repair process developed for the HPT nozzle consists of a vacuum diffusion braze process which is accomplished by filling the service induced cracks with selected and optimised braze material. Prior cleaning by a hydrogen fluoride (HF) ion process is necessary to ensure the removal of oxide from the crack enclosure. Optimized process parameters such as temperature and brazing cycles are used to achieve metallurgical integrity of the braze joints. Finish machining is normally required after the braze repair. The component is coated after braze repair.

The HPT nozzle segment currently uses Codep B-1 Aluminide coated MM-509 platforms and uncoated MA754 nickel base superalloy for the vane (aerofoil). The uncoated vane aerofoil is subjected to cyclic oxidation and thermal fatigue cracking leading to spalling of oxides and loss of subsequent protective ability to sustain required functionality. A protective coating has been designed and optimized by a Canadian contractor to combat the above problem. The coating system design takes into account the MA754 alloy and its interaction with the F404-GE-400 operating environment, the alloy/coating chemistry, and prior experience on burner rig testing of hot section coatings. The developed coatings have been successfully applied and tested at the coupon level and in a high velocity Mach 0.8 burner rig. Metallic coatings with interdiffusion barriers are applied to the vane and a thermal barrier coating applied the platform. The coating processes developed are applicable to both new and repaired components. It is anticipated that repaired components will have twice the service life of current configuration new components. In the future, the coating system will also be applied to new DND nozzle guide vanes by the overhaul contractor prior to installation in turbine modules.

HPT Blade Life Improvements

Two separate repairs/reworks are proposed for the HPT blade: a localized thermal barrier coating and a blade tip weld repair.

The HPT blade experiences severe thermal fatigue and thermo-mechanical fatigue loads during service which result in cracks and can cause premature component failure. Thermal fatigue cracking at the trailing edge tip will be repaired using a welding process. A thermal barrier coating (TBC) will be applied only to the tip region after repair. The bond coat required will be a NiCrAlY coating applied by a plasma spray or an electron beam physical vapour deposition process. The thermal barrier coatings are typically ceramic coatings based on ZrO_2 stabilized by CaO or Y_2O_3 and can provide excellent thermal protection, reducing metal temperatures by up to 200°C. The effects of thermal fluctuation during transient periods are minimized by the use of TBC's as well. The goal of this repair/rework is to improve thermal fatigue life by a factor of at least two.

The HPT directionally solidified René 80H blades have a design life of 30,000 equivalent full thermal cycles. According to design criteria, the life limiting region of the blade is the leading edge and the life limiting mode is thermal fatigue. However, HPT blades suffer from intergranular corrosion tip damage and cracking at the trailing edge during service which can result in rejection much earlier than their expected design life. The repair process that will be used to refurbish the blade tips will involve damage assessment, coating stripping, HF cleaning, and weld repair followed by post weld heat treatment and finish machining. The repair process already developed for a similar application on other engine HPT blades will be assessed. Other options related to laser alloying will also be evaluated. When the tip is eroded beyond weld repair limits by oxidation, replacement of the tip may be necessary to ensure acceptable aero-thermodynamic performance of the components. The replacement technique will have to be addressed by designing a process of casting the tip and joining it to the blade by a transient liquid phase bonding process. The qualification requirement for the repair by tip replacement would be a fairly lengthy and costly process and is outside the scope of the current repair proposed.

LPT Nozzle Segment Vane Cracking and Braze Loss Repair

F404 Low Pressure Turbine (LPT) nozzles are currently retired due to thermal fatigue cracking in the René 80 vane aerofoil, platform bands, and in the braze joint. The nozzles are repaired by a diffusion braze repair technique. The repair includes a coating stripping method for the current Codep B-1, HF cleaning for removal of oxides from the crack surfaces, diffusion brazing and post brazing machining. Repaired components will be recoated with Codep B-1 or an alternative prior to qualification testing for airworthiness.

Cost Effectiveness Analysis

In a revenue generating corporation, cost and benefits can more readily be equated to a dollar value than in a typical military flying operation. For example, the value of aircraft availability may be perceived differently in times of tension as opposed to peacetime for the military operator; however, commercial operators will consider aircraft availability as a consistently necessary precondition to profitability at all times. No attempt has been made to assess the value of this intangible benefit or others such as security of supply or increased confidence in operating hardware. An initial cost/benefit analysis was conducted to identify repairs offering greatest potential for returns. Once access to the CEA tool was obtained, this more comprehensive approach was pursued.

The Cost Effectiveness Analysis (CEA) [4] approach has been developed by the US Air Force (USAF) in collaboration with their industrial and university partners. This CEA provides a consistent and engineered approach to cost and benefit issues and is directly applicable to the DND project on gas turbine repair development. The CEA analysis will be rigorously applied to repairs being considered for development. The process essentially identifies each step in a repair process and the total cost picture associated with that step.

The CEA inputs are divided into three areas: standard inputs, which define the current environment; incorporation data, which account for one time changes caused by the implementation of the repair process; and scheduled/unscheduled inputs which reflect current maintenance schedules, and current unscheduled removal rates. CEA outputs can be given in terms of dollar cost or in investment terms, such as Net Present Value (NPV), or ROI. An important capability of this CEA software is that one can perform a sensitivity analysis to identify and address the critical functions and further optimize costs or benefits. This CEA can also be used to assess the cost impact associated with situations such as a fuel cost increase, critical materials shortages, or parts unavailability.

Table 1 below provides summary results from both the initial Cost Benefit Analysis (CBA) and from the CEA conducted after the repair development and qualification program had begun. Repairs included in Table 1 are only those which were contractually specified in the initial F404-GE-400 repair development and certification contract. Savings are computed for a fifteen year period. Current CEA estimates are NPV calculated at 5%. It should also be noted that buy year savings are $18.7M as compared to constant dollar savings of $12.3M as shown in Table 1.

Table 1 - CF18/F404 Program Cost Reductions

Component/ Repair	Initial CBA Estimate of Savings (CAN$M)	Current CEA Estimate of 15 Year Savings (CAN$M)
1st Fan Blade FOD	2.9	1.4
1st Fan Blade Fretting Fatigue	na	0.9
1st Fan Blade LCF Extension	7.4	Cancelled
3rd Stage HPC Blade Dovetail Fretting Fatigue	na	na
HPT Vane Cracking and Braze Loss *	21.0	1.2
HPT Vane Life Extension		
HPT Blade Tip Repair	na	na
HPT Blade Life Extension	na	na
LPT Vane Cracking and Braze Loss	12.0	8.8
Total Savings (15 years) (CAN$M)	43.3	12.3

* Includes recovery of an estimated 2000 HPT nozzle guide vane segments which have been previously rejected and quarantined pending repair process development.

During the past four years of dedicated qualification methodology development and F404-GE-400 repair design and qualification, a number of other repair or life extension opportunities on the CF18 engines have been identified and pursued. These repairs are identified in Table 2 below, with their expected program cost reductions based on CEA analysis. These repairs would not have been possible without the significant shift in attitude towards engine repair and without the availability of the AMT/EBT, which is being conducted as a part of the concentrated repair development program.

Table 2 - Additional CF18/F404 Program Cost Reductions

Component/Repair	Current CEA Estimate of 15 Year Savings (CAN$M)
LPT Nozzle Segment Joint	4.3
Combustion Chamber Case	3.2
LPT Nozzle Air Seal	20.9
HPC Vane Segment	0.3
LPT Blade Coating	0.8
HPT Shroud Support Repair	27.9
Front Frame Repair	9.0
Total	66.4

As shown in Tables 1 and 2, the total estimated NPV savings for the F404 program are CAN$78.7M generated from a dedicated investment of less than CAN$5.0M.

Conclusion

Not only are the savings identified in Tables 1 and 2 significant, they also represent a shift in management approach for aeropropulsion components. In the past the costly process of repair by replacement has been accepted as standard operating procedures. DND has generated a qualification process which documents the requirements for comprehensive airworthiness certification and enables the generation of repair techniques independent of the OEM. There are a number of specific conclusions or observations which are summarized below:

- The repair of aeropropulsion system components can significantly reduce the cost of operating high performance military aircraft without prejudice to airworthiness.

- Having access to individual asset operational usage, and having the technology base necessary for generating unique repairs, it is possible to provide repaired components which actually have a longer service life than as-delivered items. The coating processes and HPT blade tip weld repair are anticipated to yield HPT nozzle guide vanes and HPT blades which have twice the service life of current new components.

- Developing the life usage/life remaining analysis knowledge necessary for the generation of repairs enables a more comprehensive user-oriented analysis of unexpected in-service failures and promotes timely fleet management decisions based on a complete understanding of the consequences of failure.

- For a relatively small operator of typically older aircraft, confident repair of parts provides DND with some measure of security of supply during periods when global fleet-wide problems cause temporary parts shortages or result in greatly increased replacement parts costs.

- A number of the repairs, in particular the LCF rejuvenation originally proposed and the stage 1 fan blade repair, have developed an approach which is of particular importance for advanced technology engines. Integrally Bladed Rotors, or Blisks©, provide benefits including reduced weight and cost, elimination of fretting at blade disc fixings, and overall enhanced durability. However, individual blade damage can result in the rejection of a much larger and more expensive component. Repairs or rejuvenation of these components will be necessary for cost effective operation of future military engines.

Nomenclature

AMT	Accelerated Mission Test
CA	Criticality Analysis
CAA	Civil Airworthiness Authority
CBA	Cost Benefit Analysis
CEA	Cost Effectiveness Analysis
CNC	Computer Numerical Controlled
DAO	Design Approval Organization
DAR	Design Approval Representative
DND	Department of National Defence, Canada
DRDB	Defence Research and Development Branch
EBT	Engine Block Test
EBW	Electron Beam Weld
FOD	Foreign Object Damage
FMECA	Failure Mode, Effects and Criticality Analysis
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
HF	Hydrogen Fluoride
HPC	High Pressure Compressor
HPT	High Pressure Turbine
IAR	Institute for Aerospace Research (of NRCC)
IECMS	In-flight Engine Condition Monitoring System
JAA	Joint Aviation Authority
LPT	Low Pressure Turbine
MSDRS	Maintenance Signal Data Recording Set
NDI	Non-Destructive Inspection
NPV	Net Present Value
NRCC	National Research Council of Canada
OEM	Original Equipment Manufacturer
TBC	Thermal Barrier Coating
TCA	Transport Canada Aviation
ROI	Return On Investment

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