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ENGINE CONDITION MONITORING SYSTEM FOR THE CANADIAN FORCES F404-GE-400 ENGINE

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Abstract: With the acquisition of the CF-18 fighter aircraft in 1982, the Canadian Forces have developed advanced engine condition monitoring techniques and software programs to aid in the life cycle management of the General Electric F404-GE-400 engine. The early programs that provided parts life and engine maintenance tracking have recently been replaced by PC-based, graphical user interface systems that not only provide configuration and usage management, but have diagnostic and prognostic capabilities as well. These developments have made the Engine Condition Monitoring System (ECMS) unique among F404 users and have conclusively demonstrated significant resource savings in terms of personnel and spares procurement in addition to increased effectiveness at all levels of maintenance. This paper describes the Engine Condition Monitoring System and the impact it has had on the CF-18/F404 engine maintenance program.

Introduction: The air element of the Canadian Forces operates 103 CF-18 fighter aircraft from main operating bases located in Cold Lake, Alberta and Bagotville, Quebec. Each CF-18 is powered by two General Electric F404-GE-400 engines, a twin-spool, afterburning turbofan with a maximum thrust rating of approximately 16,000 pounds.

The acquisition of the CF-18, by the Canadian Forces, has resulted in a new approach to fighter engine maintenance. In particular, an on-condition maintenance philosophy has been adopted whereby maintenance actions are dictated primarily by observations and/or measurements of actual engine condition rather than on a fixed frequency basis. This new approach is made possible by the design features of the engine (e.g. modular construction and borescope access) and by the aircraft's In-flight Engine Condition Monitoring System (IECMS).

In 1983, the Canadian Forces initiated the development of an Engine Condition Monitoring System (ECMS) to capture the IECMS data in a single integrated database which could be used for decision support at all levels of F404 engine maintenance. The early development of this system is described in References [1] and [2]. This paper describes the present system and the impact it has had on the effectiveness of F404 engine maintenance.

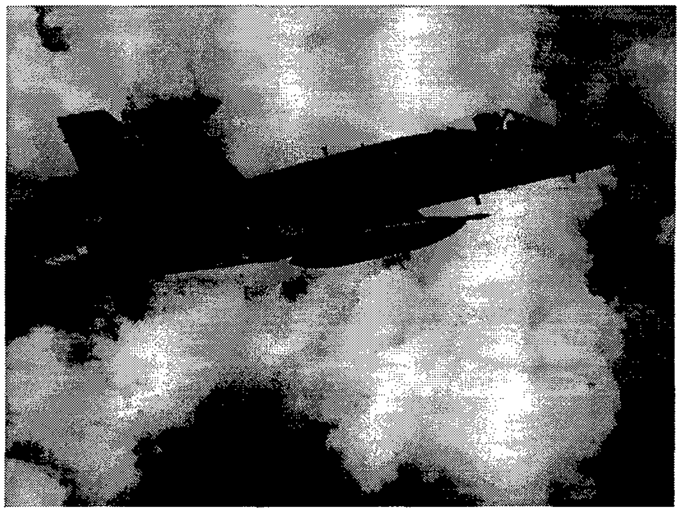


Figure 1 - CF-18 Aircraft (Canadian Forces Photo)

In-flight Engine Condition Monitoring System: Each CF-18 is equipped with a fully integrated In-flight Engine Condition Monitoring System [3]. The IECMS logic is implemented as software on the aircraft Mission Computer and includes the following major monitoring functions:

1. **Life Usage Evaluation** - Engine low cycle fatigue, thermal fatigue and creep damage are evaluated by eight Life Usage Indices (LUIs). Running sums of each LUI are stored in the Mission Computer memory and are recorded to tape twice per flight.

2. **Operating Limit Surveillance** - The IECMS continuously monitors the status of the engine fan speed, compressor speed, exhaust gas temperature, oil pressure and vibration signals with respect to predefined limits for safe operation. If an exceedance is detected a cockpit caution is activated, a three-digit maintenance code is set at the Maintenance Monitor Panel (MMP) located in the aircraft nose wheel-well, and approximately 40 seconds (5 seconds pre-event, 35 seconds post-event) of engine/aircraft performance data are recorded.

3. **Sensor Failure Detection** - The IECMS logic checks that the fan speed, compressor speed, compressor delivery pressure, exhaust gas pressure, engine inlet temperature and engine oil pressure signal levels are within normal operating ranges. If a sensor failure is detected, an MMP code is set and a 40 second data recording is taken as described above.

4. **Flameout Detection** - The IECMS logic also includes a flameout detection algorithm based on the behaviour of the compressor delivery pressure and rotor speed signals. If the IECMS criteria for flameout are satisfied, a cockpit caution is activated, an MMP code is set and a 40 second event recording is initiated.

5. **Take-off Thrust Evaluation** - The IECMS automatically records engine and aircraft performance data during the ground roll of each take-off for the purpose of engine performance evaluation. A computed thrust value based on measured exhaust gas pressure and nozzle position is provided for cockpit display and is included as one of the recorded parameters.

6. **Pilot Activated Recordings** - The IECMS logic enables the 40 second event recording feature of the system to be activated by the pilot using a switch located in the aircraft cockpit.

The IECMS data recordings are stored in the form of coded messages on a cartridge Tape Transport Magazine (TTM) that is removed for ground-based processing. Under normal aircraft operations, the TTM capacity is roughly 7 to 10 flights, after which the tape is downloaded, processed and its relevant contents stored in the ECMS database. If an in-flight engine event occurs (i.e. an MMP code is set) or a manual recording is initiated, the TTM is downloaded immediately for troubleshooting of the incident.

F404 Maintenance Concept: Maintenance policy for the F404 engine is based on a judicious balance of scheduled, corrective and conditional maintenance, supported by appropriate modification action. Accurately determining this balance is of paramount importance. Excess scheduled maintenance will lead to reduced aircraft availability and inefficient use of manpower and other resources. On the other hand, insufficient preventive maintenance will lead to an increased need for corrective maintenance, with the associated adverse effects on safety, aircraft serviceability, mission reliability and, possibly, life expectancy of the engine. The ECMS was designed to work within this framework to achieve an optimum balance between the five CF maintenance policy objectives which are to:

a. minimize faults that could produce situations hazardous to the engine, aircraft or personnel;
b. minimize faults that could cause an unacceptable loss of operational capability;
c. minimize the amount of technical manpower and other resources required for maintenance;
d. minimize faults that could result in lengthy downtime and/or expensive repairs; and
e. identify methods of improving reliability and/or maintainability.

Corrective Maintenance: Corrective maintenance comprises maintenance activities carried out on and off the engine after a fault has occurred, in order to restore the engine to a serviceable state. It includes work undertaken to confirm a fault, to diagnose its cause(s), and to complete the necessary repair, replacement and operational or functional checks. An example of corrective maintenance is the replacement of a defective Line Replaceable Unit (LRU) on the engine (e.g. a Main Fuel Control).

Preventive Maintenance: Preventive maintenance is carried out to provide safe and trouble-free operation of the engine and its accessories. It consists of systematic and prescribed work undertaken to reduce the probability of failure, and to ensure that performance is not degraded by time or usage. The determination of preventive maintenance requirements is central to the maintenance plan, since it determines or influences the scope of almost all subsequent activities.

Within the CF, all preventive maintenance requirements are assigned to one of three primary maintenance processes:

a. On-Condition Maintenance (OCM). A primary maintenance process of repetitive inspections or tests to determine the condition and continued serviceability of systems, portions of structure, or items. Corrective maintenance is taken, when required, based on item condition.

b. Hard Time Maintenance (HTM). A primary maintenance process in which an item must be removed from service at or before a specified time or number of cycles, i.e., the item is lifed; and

c. Condition Monitored Maintenance (CMM). A primary maintenance process that is initiated as a result of knowledge of an item's condition gained from periodic or continuous monitoring. Where adequate and realistic condition monitoring techniques exist to detect incipient failure, Condition Monitored Maintenance is applied to the item in preference to OCM or HTM, respectively.

Maintenance Levels: Maintenance on the F404 spans three organizational levels. The first level is maintenance that is directly concerned with maintaining the engine in a serviceable condition. Here, first line technicians troubleshoot an engine unserviceability and replace LRU's to bring the engine/aircraft to a serviceable state. If the problem is beyond the ability of first line technicians, or a lifed item has time expired, then the engine is removed from the aircraft and sent to the next level of maintenance. Second level maintenance is accomplished at the base engine repair facility. At second level, the engine and its individual modules can be completely torn down, inspected and reassembled. Maintenance at this level is also supported by a fully computerized engine test facility where every engine that is inducted into second line will be tested before being declared "ready for installation" (RFI). The third level of maintenance support on the F404 conducted by commercial contractors who repair and replace components which have been deemed faulty and cannot be repaired by first or second line technicians.

F404 Maintenance and the ECMS: Figure 2 depicts the general flow of data and information in support of F404 maintenance and the role that the ECMS plays as a decision support tool. As previously noted, the CF-18 IECMS continuously and automatically monitors and records F404 **usage** (operating hours, mechanical and thermal fatigue cycles and time at temperature counts), **health** (as determined by engine take-off performance characteristics) and operational **event** data which, in turn, are stored in the ECMS database. Two additional types of information are also input manually into the system database: **configuration** data defining the makeup of each engine in terms of its constituent components and **reliability** data which record specific engine problems, their symptoms and the maintenance activities required to rectify the problem. The ECMS holds the Maintenance Plan for the engine as defined by the preventive maintenance activities and their intervals, the usage limits for life-limited components, the limits specified for health indicating parameters, the fault library which relates health index patterns to specific engine problems and the troubleshooting logic used for fault isolation. In addition to providing day-to-day decision support for the preventive and corrective maintenance processes, the ECMS also provides a database which can be used to continuously refine and improve the engine maintenance plan and, hence, the effectiveness of F404 maintenance.

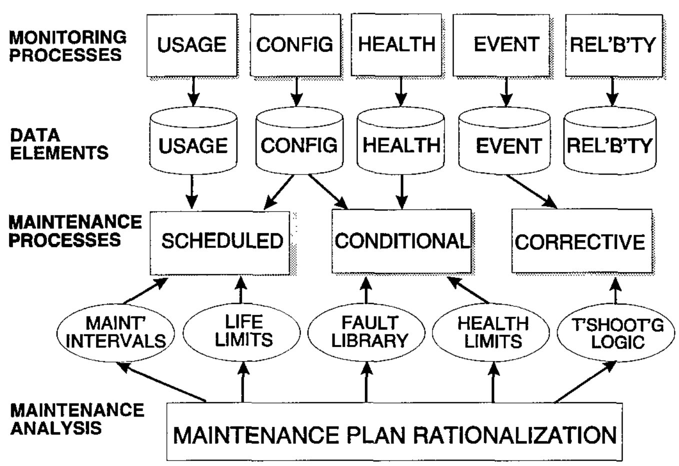


Figure 2 - ECMS Database

ECMS Description: The ECMS is a PC-based maintenance information management system which provides decision support to all levels of the F404 maintenance program. As illustrated in Figure 3, the system operates simultaneously over Local and Wide Area Networks which link together system elements located at each squadron, the two main CF-18 operating bases (CFB Cold Lake and BFC Bagotville), the 3rd line engine overhaul contractor (Orenda Aerospace Corporation) and National Defence Headquarters (NDHQ).

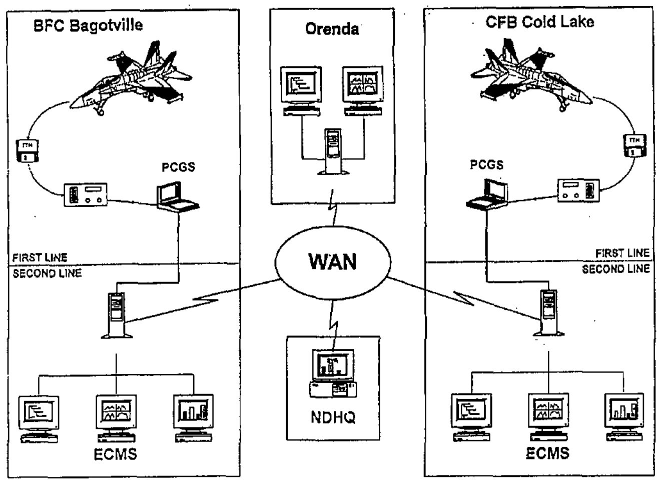


Figure 3 - ECMS Network Configuration

The major elements of the system include:

a. Portable CF-18 Ground Stations (PCGS) located at each squadron;
b. The Base-Level ECMS located at the engine repair section of each base;
c. The Central ECMS located at the 3rd line engine repair and overhaul site; and
d. An NDHQ "Viewer" site.

The functionality of the system at each of these sites is summarized as follows.

Portable CF-18 Ground Station: Each CF-18 is equipped with an on-board Maintenance Data Signal Recording System (MSDRS) which records CF-18 tactical and maintenance data (including the engine IECMS data) to a removal cartridge tape magazine on a continuous and event-triggered basis. The PCGS, which comprises a notebook PC workstation and a specially designed tape reading device (Figure 4), is used to "strip" the data contents of the aircraft cartridge tape and copy these to an Aircraft Data File (ADF) on the notebook. The PCGS software controls the tape reader and provides a number of reporting features for summarizing and displaying the contents of each ADF record block.

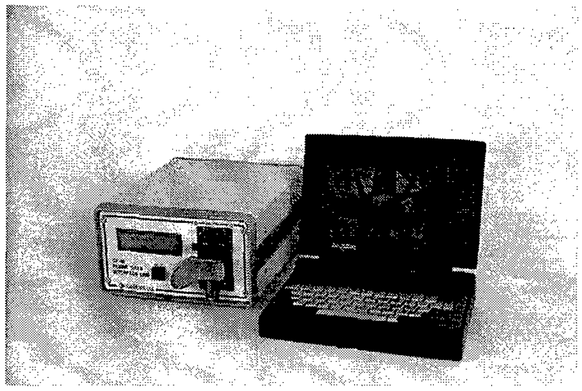


Figure 4 - Portable CF-18 Ground Station

The PCGS software also includes a Flight Line Troubleshooting System (FLTS) feature which uses the IECMS parameter recordings previously described to diagnose engine faults. The FLTS incorporates troubleshooting logic which automatically leads flight line engine technicians through a series of yes/no questions based on the information contained in these recordings (see Figure 5). Over a period of eight years of in-service operations, the Canadian Forces have developed a fault library of over 45 specific F404 engine failure modes and their associated symptoms. Using this library, the FLTS can effectively isolate unserviceable line replaceable items in 60 to 70% of cases, without the need for follow-up troubleshooting ground runs or maintenance test flights.

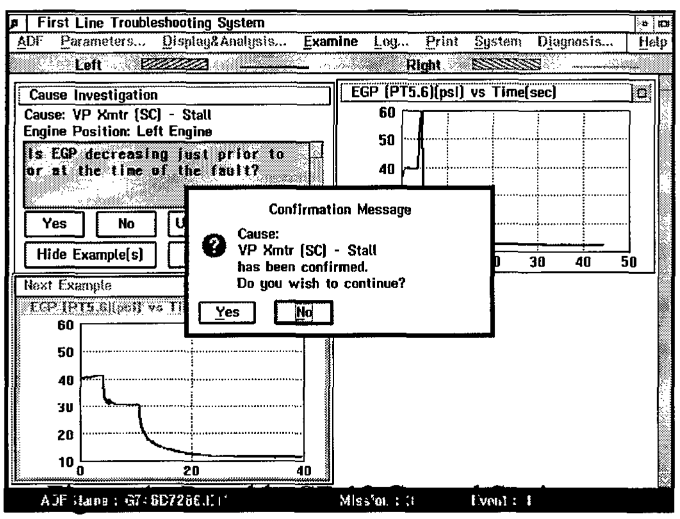


Figure 5 - Flight Line Troubleshooting System

Base Level ECMS: The base level component of the ECMS is used to support the planning and scheduling of second line maintenance; that is, the off-wing repair and replacement of engine components at the base level. The ECMS provides a database of

F404 condition data, including the location, configuration, modification status, life usage history, and maintenance history of all engines resident at the base. Decision support is provided by a number of database application programs as described below.

a. **Maintenance Manager** - To effectively track maintenance information for a modular, field-repairable engine such as the F404, accurate serialized component tracking is required. As shown in Figure 6, the ECMS incorporates a flexible and intuitive graphical tool for this requirement. The various locations where engines and their components are held (operational squadrons, second line repair, serviceable spares, etc.) are represented by individual "windows". Within each window, engine components are represented by a hierarchical "map" of the engine, its modules, assemblies and parts. Configuration changes are made by "dragging" a component from one location and "dropping" it in a compatible location in another assembly or organizational window. Upon the conclusion of a transaction, the appropriate pre-completed maintenance action form is displayed for review and completion by the system user. As well, as each transaction is executed, it is carefully validated using database rules for component attachment compatibility and access restriction. The Maintenance Manager is also used to register modifications (generally resulting in a part number change) and special inspections against specific serialized components as part of the overall configuration management process.

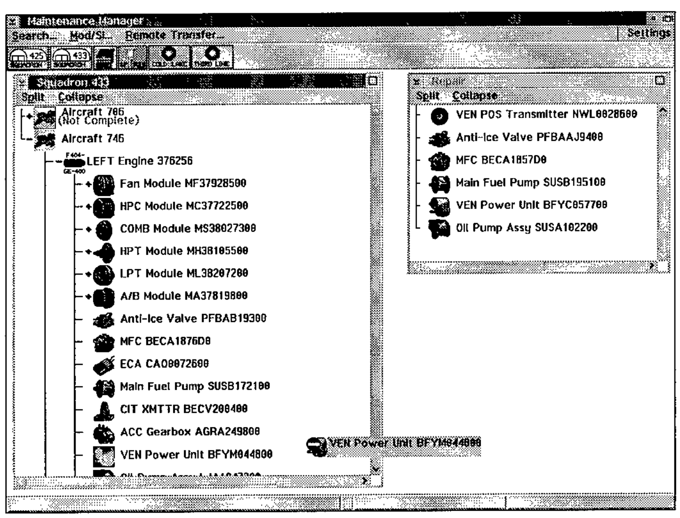
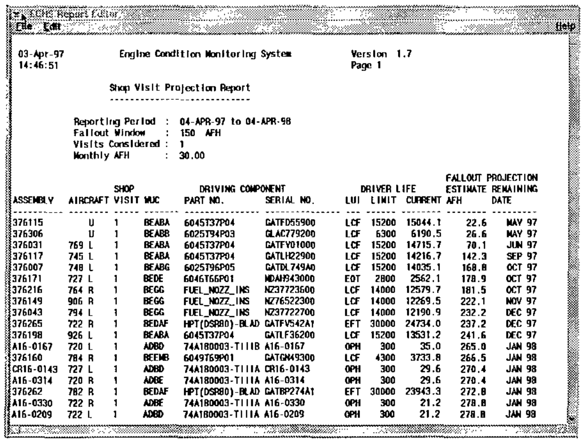


Figure 6 - Maintenance Manager

b. **Life Usage Monitor** - The ECMS tracks the cumulative life usage status of 26 life-limited and 54 logistically critical components of each F404 engine and uses this information to forecast engine shop visits and lifed component replacement requirements. Usage data (in the form of Life Usage Indices computed by the IECMS and downloaded from each TTM tape) are automatically applied to the appropriate aircraft tail number and subsequently, through the configuration tracking features of the system, to each aircraft, engine, module, sub-assembly and part. Historical usage accumulation rates are then used to project the estimated flying hours remaining on each part and when replacement or maintenance is required (Figure 7).



ECMS Report Editor
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03-Apr-97 14:46:51 Engine Condition Monitoring System Version 1.7 Page 1

Shop Visit Projection Report

Reporting Period : 04-APR-97 to 04-APR-98
Fallout Window : 150 AFH
Visits Considered : 1
Monthly AFH : 30.00

		SHOP		DRIVING COMPONENT		DRIVER LIFE			FALLOUT ESTIMATE	PROJECTION REMAINING
ASSEMBLY	AIRCRAFT	VISIT	WUC	PART NO.	SERIAL NO.	LUI	LIMIT	CURRENT	AFH	DATE
376115	U	1	BEABA	6045T37P04	GATFD55900	LCF	15200	15044.1	22.6	MAY 97
376306	U	1	BEABB	6025T94P03	GLAC779200	LCF	6300	6190.5	26.6	MAY 97
376031	769 L	1	BEABA	6045T37P04	GATFY01000	LCF	15200	14715.7	70.1	JUN 97
376117	745 L	1	BEABA	6045T37P04	GATLH22900	LCF	15200	14216.7	142.3	SEP 97
376007	748 L	1	BEABG	6025T96P05	GATDL749A0	LCF	15200	14035.1	168.8	OCT 97
376171	727 L	1	BEDE	6046T66P01	MDAH943000	EOT	2800	2562.1	178.9	OCT 97
376216	764 R	1	BEGG	FUEL_NOZZ_INS	NZ37723600	LCF	14000	12579.7	181.5	OCT 97
376149	906 R	1	BEGG	FUEL_NOZZ_INS	NZ76522300	LCF	14000	12269.5	222.1	NOV 97
376043	794 L	1	BEGG	FUEL_NOZZ_INS	NZ37722700	LCF	14000	12190.9	232.2	DEC 97
376265	722 R	1	BEDAF	HPT(DSR80)-BLAD	GATFV542A1	EFT	30000	24734.0	237.2	DEC 97
376198	926 L	1	BEABA	6045T37P04	GATLF36200	LCF	15200	13531.2	241.6	DEC 97
A16-0167	720 L	1	ADBD	74A180003-TIIIB	A16-0167	OPH	300	35.0	265.0	JAN 98
376160	784 R	1	BEEMB	6049T69P01	GATGN49300	LCF	4300	3733.8	266.5	JAN 98
CR16-0143	727 L	1	ADBD	74A180003-TIIIA	CR16-0143	OPH	300	29.6	270.4	JAN 98
A16-0314	720 R	1	ADBE	74A180003-TIIIA	A16-0314	OPH	300	29.6	270.4	JAN 98
376262	782 R	1	BEDAF	HPT(DSR80)-BLAD	GATBP274A1	EFT	30000	23943.3	272.8	JAN 98
A16-0330	722 R	1	ADBE	74A180003-TIIIA	A16-0330	OPH	300	21.2	278.8	JAN 98
A16-0209	722 L	1	ADBD	74A180003-TIIIA	A16-0209	OPH	300	21.2	278.8	JAN 98

Figure 7 - Shop Visit Rate Forecast

c. **Performance Monitor** - The Canadian Forces have undertaken an extensive research and development program in co-operation with GasTOPS Ltd. to develop a prognostic capability for the F404 engine using data recorded by the IECMS during the ground roll portion of each take-off. These recordings consistently and repeatedly capture the dynamic response of the engine to a slam acceleration from ground idle to takeoff power. From these recordings, the ECMS automatically computes nine "condition indicators", (e.g. rotor acceleration times, N_1/N_2 speed ratio, fuel ratio units and Variable Exhaust Nozzle position) and stores these indicators in the system database against the appropriate engine serial number. The Performance Monitor tool, which is still under development at the time of writing this paper, can graphically display the condition indicator trend plots for a selected engine (Figure 8). The software also incorporates a rule-based expert system to automatically interpret these trends and provide maintenance recommendations.

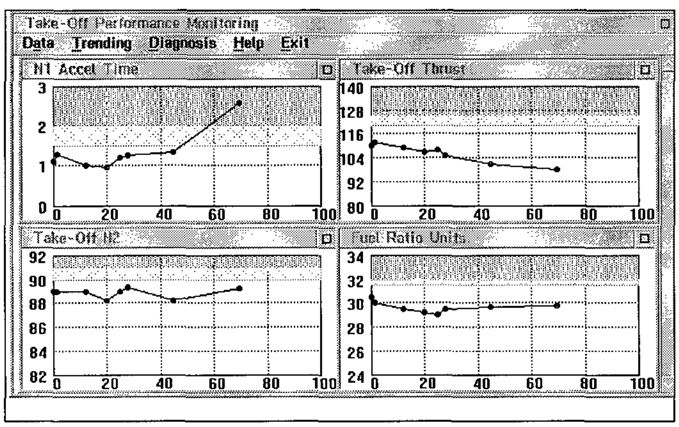

Figure 8 - Trend Plot

Central ECMS: Condition data for the entire CF-18 engine fleet is maintained in a central database at the engine overhaul contractor, Orenda Aerospace Corporation. The central database is updated nightly by data transferred from each of the two main operating bases. Information pertaining to new components are entered into the central database by Orenda as they are received and incorporated into the database. Repair histories and strip reports are also entered into the central database by Orenda.

The central database is used by the F404 Engineering Officer at National Defence Headquarters for fleetwide maintenance management. The most significant aspect of this management support is the planning and scheduling of life limited component removals. The F404 engine, as previously noted, has 26 lifed components, each with a different life limit. Several of these components, such as the HP turbine blades, have long lead times for ordering replacement parts. It is therefore necessary that some form of forecasting tool be available that enables the Engineering Officer to project when lifed components will reach their expiry limits. Moveover, because of the operational impact of the shop visits necessary for component removal, it is often advantageous to remove certain components opportunistically when an engine is in the shop for repair or overhaul anyway. The central ECMS includes a Logistics Planning Model which uses fleetwide historical usage accumulation rates and projected flying rates per mission to forecast the fallout of lifed items and, hence, the requirements for replacement parts. As part of this model, a "window" can be defined whereby parts are opportunistically removed if they will reach their life expiry limit within a specified number of flying hours. By adjusting this window, the Engineering Officer can adjust shop visit rates to match field and depot repair level capabilities and can optimize the material and labour costs associated with lifed component replacement.

The central database also contains the maintenance histories of all CF-18 engines including operational problems which occur in the field, the symptoms associated with these problems and the resolution of the problem in terms of the component or components which were at fault. This information is used by the Engineering Officer to establish priorities for the allocation of resources in support of F404 reliability enhancements, such as turbine blade repairs. As well, whenever an engineering change (e.g. a component modification or maintenance procedures change) is implemented to address a problem, the ECMS provides a means of monitoring the effectiveness of this change. The maintenance histories and failure rate information provided by the ECMS are also being used to quantify the benefits of the ECMS in terms of its impact on the frequency of certain repair activities.

The final major use of the central ECMS database is for ongoing refinement of the ECMS system itself. The central ECMS provides a database for engineering analysis and maintenance methods development. For example, studies have been done which have quantified the effects of mission type and ambient temperature on the usage rates of F404 engine components. This information has, in turn, been used in the Logistics Planning Model to enable more accurate forecasting of life-limited component removals.

Similarly, statistical analysis has been performed to establish reliable alarm levels for F404 performance monitoring and to correlate the performance characteristics of the engine as captured by the IECMS recordings to specific component faults.

Benefits of ECMS: The ECMS is unique amongst Canadian Forces' engine fleets, and is constantly scrutinized for technical and economic performance, both technical and economic. The complexity of aircraft operations and maintenance makes quantifying the benefits of the system challenging. The following sections describe those benefits.

Flight Line Troubleshooting System Benefits: As discussed previously, the FLTS was developed to enable engine technicians to rapidly and accurately diagnose engine faults. The Canadian Forces commissioned a study that was released in October 1994 to determine the annual cost savings realized by the FLTS. The results of this study are discussed briefly below.

The FLTS system has been designed to reduce maintenance costs at all three levels by minimizing false or unnecessary LRU removals and maximizing fault diagnosis/resolution at first line. This is achieved by providing the technicians with a fault diagnosis capability for engine incidents that are caused by a defective LRU or by improper operation of the engine. This diagnosis is only possible if the cause of the unserviceability impacts the performance of the engine and this performance change is recorded by the IECMS system.

In order to quantify the annual cost savings realized by the FLTS, all engine incidents for a two year period (1990-1991) prior to implementation of the FLTS and a one year period (1993) following its implementation were examined. Analysis of the pre- and post-FLTS periods revealed that the system significantly reduced the maintenance activity at all three maintenance levels. For example, the FLTS system resulted in a reduction of LRU removals per incident of 26%, a 50% reduction in false engine removals and a significant reduction in submission of serviceable LRU's to third line for repair (24% for fuel control units, 61% for engine control assemblies). The reduction of assets returned to third line has resulted in a number of additional spares that can be utilized by the CF and these excess spares result in a cost savings when a component is attrited (i.e. an additional component does not have to be purchased when a component is scrapped). The end result of all these cost savings is that the development of the FLTS software showed a pay-back period of approximately 8 months. The Canadian Forces is anticipating that these savings will continue to grow as the system is further automated and refined.

Usage Monitoring Benefits: Traditionally, aircraft engine components and structure were maintained on time-based criteria since measurement and recording of actual stress or life cycle usage was not possible. That is not the case with the CF18, due to the IECMS capability of recording real-time cycles for the F404, which was safe-lifed in those terms. No life is lost in conservative conversion to airframe hours. The Engineering Officer at National Defence Headquarters takes advantage of the ECMS usage monitoring capabilities to ensure that operations are affected neither by exhausted supplies nor by logistics confusion, due for example to configuration or modification status. The value of an accurate, up-to-date and user-friendly configuration database has been proven many times in the past. This is especially true during times of unexpected component life reductions. For example, in March 1992 the US Navy experienced an uncontained Stage 1 Fan disk failure. Following this incident, the life of this component and its mating blades, disks and shafts were immediately reduced in life by over 1000 engine flying hours. This was totally unexpected and CF was placed in a very difficult logistic situation. To compound the problem, subsequent analysis predicted a safe life well below that of the current field limit. In order to maintain flying operations, the CF initiated a risk management program that was only made possible through the use of a system such as ECMS. ECMS allowed DND to micro-management assets at both operating bases in order to minimize the impact of the life reduction. This process relied heavily on ECMS to provide fallout forecasts, asset inventories, supply schedules and asset recovery from modules with time-expired components for mix/match rebuilds of complete serviceable rotors. Through the use of ECMS, this incident was not responsible for any negative impact on fighter operations.

Conclusions: The CF-18 Engine Condition Monitoring System, developed jointly by the Canadian Forces and Canadian Industry, has enabled the CF to adopt on-condition maintenance practices for the F404-GE-400 engine, with consequent savings in engine life cycle costs and improvements to aircraft availability. The ECMS integrates, in a single database system, the data necessary to support decision making at all levels and all locations of F404 maintenance. The system incorporates unique diagnostic and prognostic methods for F404 fault identification as well as sophisticated logistics planning features for shop visit and spare parts forecasting. Because the ECMS was developed in close co-operation with CF field technicians, the system has proven to be extremely flexible and easy to use.

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