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Engine Condition Monitoring — Technology and Experience

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ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Conference Proceedings No.448

ENGINE CONDITION MONITORING – TECHNOLOGY AND EXPERIENCE

Papers presented at the Propulsion and Energetics Panel 71st Symposium, held in Quebec City, Canada, 30 May—3 June 1988.

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AGARD Report 745 (November 1987)

THEME

In recent years considerable experience with engine condition monitoring (ECM) has been accumulated, both in military and civil aircraft applications. This Symposium has covered a wide range of applications to military aircraft and helicopters, to airline operations and to the use of aero derived gas turbines. The scope included user's experience with o board ECM systems and their integration into logistic systems; comparison of diagnostic methods for fault prediction; experimental results achieved by these methods; the impact of ECM on future propulsion systems; and potential capabili arising from the availability of new diagnostic techniques. The emphasis of the Symposium was on operational experienc and current technological developments.

* * *

Un capital de savoir-faire considérable a été constitué ces dernière années dans le domaine du contrôle de l'état des mot d'aéronef (CEM), tant civils que militaires. Le présent Symposium a couvert une vaste gamme d'applications aux avions hélicoptères militaires, et aux moteurs à turbine à gaz dérivés, des avions de ligne. Les sujets traités comprenaient: l'expérience d'utilisateurs des systèmes CEM embarqués et de leur intégration aux systèmes de logistiques; comparaison méthodes de diagnostic de pannes; les résultats expérimentaux obtenus par ces diverses méthodes; l'impact du CEM sur systèmes de propulsion futurs et les capacités potentielles émergeant de ces nouvelles techniques de diagnostic. Le Symposium a été principalement axé sur l'expérience opérationnelle et les développements technologiques actuellement cours.

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OPERATIONAL REQUIREMENTS FOR ENGINE CONDITION MONITORING FROM THE EFA VIEWPOINT

by

J. V. Goodfellow

Section Leader Engine and Engine Accessories

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FRG

1. Introduction

The European Fighter Aircraft (EFA) is a collaborative project involving four European Nations, Germany, Italy, Spain and the United Kingdom. The purpose is to develop a new fighter aircraft to enter service with the Nations Air Forces in the second half of the 1990's. In order to manage the project on their behalf the four participating governments have established the NATO European Fighter Management Organisation (NEFMO). Within this organisation the NATO European Fighter Management Agency (NEFMA) is a full time joint establishment responsible for the day to day management of the project. The agency interfaces with two industrial consortia, EUROJET (FIAT, MTU, ROLLS-ROYCE and SENER) who are to develop the engine and its accessories and EUROFIGHTER (AIT, BAe, CASA and MBB) who will develop the rest of the aircraft and integrate the whole into a weapon system.

The task of NEFMA over the past year or so has been to convert the four Air Forces joint Operational Target into a firm European Staff Requirement (ESR) and to negotiate the details of the specifications and the contracts required for the development of the aircraft. This paper, based on the experience of that activity, attempts to provide a short general review of the major constraints and factors that can influence the Engine Health Monitoring (EHM) System requirements of an advanced fighter aircraft.

2. Overall Requirement

The objective with EFA, as with all such projects, is to develop a highly cost-effective weapon system and in this age of severe budget constraints that really means the most effective that can be achieved for a given cost.

Overall Life Cycle Costs (LCC) consist of three major elements, development costs, production costs and in-service costs. The exact figures vary but it is generally accepted that the first is the smallest and that the third is by far the largest and increasing attention is b ing given to reducing this element by proper design from the outset of the project. However while every effort is made to minimise the overall total LCC it is inevitable that, in the initial phase of a project, the most immediate attention is directed at the development costs. The amount of money that Governments are able to make available for development can be a major constraint on the system that is able to be developed. However probably even more important than the budget allowed is the very strong pressure to avoid the cost overruns that have occurred in previous projects. In an attempt to ensure that the development cost limits are respected for EFA the participating Nations have required that, as far as possible, the contractors commit to maximum prices for achieving development requirements. It is further required that, again as far as possible, the contractor should eventually commit to fixed prices. The intention is that this will eliminate over optimistic assumptions of the technological advances that can be made and that then result in delays and escalating costs when they are not achieved on-time. This does not mean that the aircraft will be a low technology system, the requirements are too demanding for that, but the discipline is intended to ensure that the requirement and the solution are realistic for the timescales set and the budget available.

The reduction of production costs is also given some priority during this initial phase. Aircraft basic empty mass is often seen as being closely correlated with production cost and in the case of EFA firm requirements have been set for aircraft size and mass limits. Such limits can inevitably pose constraints on all systems within the aircraft.

The in-service costs, although of a long term nature and less immediately subject to budget constraints, are still of great importance to the Air Forces and there is a very firm requirement for EFA overall LCC to be minimised as well as for effectiveness to be maximised. Systems such as EHM are considered to have great potential for improving both the long term costs and the effectiveness of the weapon system, as will be discussed later. A strong requirement for EHM has therefore been written but one which has nevertheless had to take account of the constraints discussed above concerning development cost and time, aircraft mass and size and realistic technology levels.

The potential beneficial influence of the EHM System on both the effectiveness and the overall cost of a weapon system can be illustrated simply as follows.

Effectiveness (E) is dependent on three major factors, Availability (A) for use when required, Reliability (R) once airborne and Performance (P) during the engagements. This can be expressed simply as:

$$E \propto A \times R \times P$$

Costs (C) come in the three broad phases discussed above, development, procurement and in-service. The in-service costs are by far the largest element, and are significantly affected by the maintenance which is necessary to achieve Availability. The more a system requires maintenance the lower will be its Availability. Thus we could say that

$$C \propto \frac{I}{A}$$

Bringing these together gives

$$\frac{E}{C} \propto A^2 \times R \times P$$

The important message is that Cost-Effectiveness is strongly dependent on Availability. To have a high availability a system must have low maintenance requirements and this depends on two factors:

a. Time between failures

A high failure rate will result in the need for frequent maintenance and so an important requirement is for systems and components to have a high reliability or durability, depending on their characteristics. This can only be achieved by good design from the beginning.

b. Maintainability

When a failure does occur there is a need to be able to correct it very quickly. This requires two attributes:

(i) Testability. The overall design must include testing facilities capable of providing a rapid and accurate diagnosis of actual and potential faults. This requires that the necessary testing and analysis systems are built in and developed as part of the overall system.

(ii) Repairability. The system must be capable of rapid and economic repair. This again requires that the appropriate characteristics are designed into the system at the outset.

The recognition by the EFA partners that such attributes as Reliability and Maintainability (R & M) can have a strong influence on overall cost effectiveness, together with the understanding that they must be built-in from the beginning, has resulted in their being given equal priority with performance in the Staff Requirement. This does not mean that any significant trade-off is allowed, the requirement is to achieve the necessary performance and to have good R & M attributes as well. The potential of Testability for improving aircraft availability and operational reliability and for reducing support costs is also recognised and it is in this area that EHM has an important part to play. This has had a strong influence on the development of the detailed requirements and specifications for the system.

3. The Aircraft

The European Fighter is a single seat, twin engine, delta wing aircraft with canards. The aircraft is aerodynamically unstable and depends on its flight control system for stability, a strong reason alone for requiring a reliable power unit. The two engines are mounted at the rear with chin intakes under the fuselage. The empty mass of the aircraft is to be under 10 tonnes.
EFA is to have an Integrated Monitoring and Recording System (IMRS) which will have both an on-board and a ground-based element. The on-board system is to continuously monitor and test all systems and includes the following functions.

a. Detection and immediate notification to the pilot of all failures that affect flight safety or mission capability.

b. Perform sufficient testing and analysis to be able to indicate to the ground crew immediately at the end of a sortie either that the aircraft is serviceable and likely to remain so for at least another mission or that maintenance action is required.

c. Indicate accurately to the ground crew what maintenance actions are necessary to restore the aircraft to a servicable state. All such indications are to be made by a display at a single maintenance data panel.

d. Storage of data for input to and analysis by the ground element of the system.

The functions of the ground system are to include:

a. Diagnostic analysis of defect data for off-aircraft maintenance.

b. Life analysis and recording.

c. Performance analysis and performance trend analysis.

d. Indication of future maintenance requirements.

e. Interface with the various logistics ADP systems that are being developed by the four Air Forces.

4. The Engine

The engine itself is a two spool, reheated turbofan fitted with a full authority DECU. The by-pass ratio is about 0.4, overall pressure ratio around 24 and the SLS thrust is about 90 KN. The engine is to be fully modular and designed generally for on-condition maintenance although some components may be hard lifed. The electronic systems will therefore be required to have a self monitoring capability and there will be an engine health monitoring system which is to be functionally integrated into the aircraft IMRS. The main functional requirements for the EHM can be summarised under four headings:

Serviceability Status Monitoring
Usage Monitoring
Condition Monitoring
Incident Monitoring

Status Monitoring

The EHM is required to monitor the serviceability status of the engine and to provide an indication to the pilot or the ground crew, as appropriate, when the engine becomes unserviceable. Pilot indications are to be limited to those that affect flight safety and mission capability. For the ground crew the requirement is to be able to achieve a rapid turn-round. They need an immediate automatic indication as to whether the engine is serviceable or not and, if not, precisely what maintenance action is required. Faults must be identified accurately down to LRI level. The false alarm rate must be low in all cases and especially low for pilot indications. The system must also notify any need for servicing and ideally this should be quantified when appropriate, e.g. a call for oil replenishment should include an indication of the quantity of oil required.

Usage Monitoring

Many engines have acquired a reputation for unreliability because supposedly lifed components have failed at random times and have failed to achieve the flying hour lives expected. However experience has shown that a simple time count of usage is a poor measure of life consumption for a military engine. Life is strongly dependent on the way in which an engine is actually used and this has been found to vary with many factors including the aircraft's role, its base and the pilot. The EHM is therefore required to monitor the actual usage of the engine, including all changes of temperatures, pressures, speeds etc and to determine accurately the effect of that usage on the life consumption of the engines components. This requires that a full understanding of the factors affecting component life is established and that algorithms for calculating life usage are developed before the aircraft enters service. These algorithms must be sufficiently accurate to provide the best possible usage of the full life potential of the components without endangering flight safety or running too high a risk of expensive failures in operation. For any critical lifed components the calculations must be performed on the aircraft to provide an immediate indication to the ground crew if the components are becoming life expired i.e. due to limit exceedances.

Condition Monitoring

As was stated earlier, the engine is to be designed for on-condition maintenance. The EHM system will therefore be required to detect all failures and impending failures, both mechanical and performance, and isolate them down to maintenance module level. This will require that the appropriate analysis methods are developed. These analyses are expected to be primarily based on data obtainable from such sources as monitoring the oil system, engine vibrations, engine performance and performance trends. However it is anticipated that analysis based solely on such parameters will not be able to fully meet the requirements to isolate failures to maintenance module level and so there is also interest in exploring the potential of new techniques such as gas path analysis for improving capability in this area.

Incident Monitoring

The EHM system is required to automatically detect, monitor and analyse any one of a defined list of engine related incidents. Sufficient on-board analysis is required to enable the serviceability status of the engine to be established immediately. Sufficient data must be stored to enable a full diagnosis to be performed in the ground based station. The analyses required for such diagnoses must also be developed prior to the aircraft entering service.

5. Summary

The Engine Health Monitoring System for EFA is to be an integral part of the overall Weapon Systems Integrated Monitoring and Recording System. This will include both an on-aircraft element and a ground-based station which will ..ave to interface with the different logistics ADP systems being developed by the Air Forces. By means of measurements and analysis the EHM is required to automatically and continuously monitor the condition of the engine and to detect and accurately diagnose any need for immediate and future maintenance actions. The purpose is to provide for a rapid turn-round at the flight line and to reduce both the need and the time required for all maintenance thereby increasing the overall availability for operational use. The intention is that this shall contribute to the significant improvement in Weapon System cost effectiveness that is believed to be achieveable through greater attention to Reliability, Maintainability and Testability.

DISCUSSION

R. FEATHERSTONE

Have you allocated cost and weight requirements for the sensors and processors of the engine health monitoring system?

Author's Reply:

The engine contractor has provided both a mass and a cost for the development of the complete engine system including EHM. The breakdown within these overall figures is strictly the responsability of the engine contractor.

AN OVERVIEW OF US NAVY ENGINE MONITORING SYSTEM PROGRAMS AND USER EXPERIENCE

Andrew J. Hess
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SUMMARY

The Naval Air System Command (NAVAIR) has made a commitment to require inflight engine monitoring capabilities and Engine Monitoring Systems (EMS) on all new aircraft and engine programs. The current EMS requirement and system design concepts are the end result of over 15 years of developing system capabilities and justifying system benefits. These requirements and system design concepts are based on the lessons learned from the F/A-18 and A-7E Inflight Engine Condition Monitoring System (IECMS) programs. The highly successful A-7E IECMS is the cornerstone on which all Navy EMS are based today.

NAVAIR has revised the general engine specifications to contain detailed requirements for a comprehensive EMS. These requirements have been included for flight safety, maintenance, engineering management and operational support benefits. These specification requirements have been used on all new aircraft/engine programs (e.g., F-14A+, F-14D, A-6F, AV-8B, E-2C re-engine and V-22). When justifiable, EMS is also being considered for retrofit on several older aircraft/engine applications.

This paper gives an overview of US Navy EMS program status. Established EMS functional capabilities and requirements are discussed and detailed specification items are reviewed. Current EMS projects are examined with respect to system description, program status and individual peculiarities. Finally, conclusions are given on EMS projected benefits, user experience, lessons learned and future directions of this technology.

1. Introduction.

The inflight monitoring of aircraft engine condition has been a technique used since the first airplane became airborne and the first pilots noted engine vibration levels through their "seat-of-the-pants" sensor package. Normal cockpit instrumentation is monitored to determine engine condition and after the flight, provide information which gives indications of engine health and required maintenance actions. Inflight engine monitoring has indeed been around as long as aviation, but what is changing is the relative degree of sophistication of the monitoring techniques. As aircraft gas turbine engines become more complex and costly, and as their maintenance and support costs increase, the use of more effective monitoring techniques becomes a necessity.

Many increasingly sophisticated Engine Monitoring Systems (EMS) have been developed and tried. Some of these systems have been very successful in advancing the state-of-the-art, while others have only been partially successful. All these previous EMS programs have provided valuable "lessons learned". The US Navy has tried to profit from its previous EMS programs and to apply these lessons to the next system development.

This paper will give an overview of US Navy EMS program status. Established EMS functional capabilities and requirements will be discussed and detailed specification items will be reviewed. Several current EMS programs will be examined with respect to background, system description, experience and high light "lessons learned".

2. General EMS Requirements.

NAVAIR has made a real commitment to require inflight engine monitoring capabilities and EMS on all new aircraft and engine programs. The current EMS requirements and system design concepts are the end result of over 15 years of developing system capabilities and justifying system benefits. These requirements and system concepts are based on the "lessons learned" from the A-7E and F/A-18 Inflight Engine Condition Monitoring System (IECMS) programs. The highly successful A-7E IECMS (later called EMS) has been the cornerstone on which all present Navy EMS are based. The positive experiences with these two programs have lead to the inclusion of comprehensive EMS requirements in the General Specification for Aircraft Turbojet and Turbofan Engines, MIL-E-5007E (AS) dated 1 September 1983 ard the General Specification for Aircraft Turboshaft and Turboprop Engines, MIL-E-8593 E (AS) dated 1 March 1984.

The EMS requirements in these general engine specifications are being tailored for use on all new aircraft and engine programs. As a minimum, the comprehensive EMS specified will include the following functional capabilities and requirements:

a. Take-off thrust check with cockpit indication. Provided primarily as a flight safety and engine health indication.

b. Engine operational limit exceedance with five second pre-event and 25 second post-event time history recording with cockpit warning. Provided as both a flight safety indication and maintenance troubleshooting aid. The exceedance event time history records will be used along with a data processing ground station (DPGS) and diagnostic logic to provide automated diagnostic maintenance messages to simplify data analysis.

c. Engine component life usage tracking (e.g., LCF and hot section cyclic usage, engine hours, time-at-temperature). Provided primarily to track individual usage of critical life limited engine components by S/N and to implement engine warranty guarantees. Both a DPGS and an interface with a fleetwide maintenance/logistics management information system is required to adequately perform these tasks. There are also flight safety and reduced engine removal rates associated with this EMS capability.

d. Vibration frequency analysis (narrow band "comb" filters and/or "one-per-rev" tracking filter plus broad band) with cockpit warning. Provided primarily as a flight safety indication and to improve aircraft availability by shortening troubleshooting time for engine vibration pilot "gripes". This capability will also be extremely useful for improving engine discrepancy fault isolation and fault detection and for providing trend data.

e. Performance degradation trending (gas path analysis). Provided primarily to address the Engine Analytical Maintenance Program (EAMP) requirement "to acquire performance data for trending". This data will be used to determine when to reject an engine for low performance and may in some cases be used to fault isolate to the module level. The actual data analysis for performance trending will be done off the aircraft using a DPGS and special software routines. As with engine component life usage tracking, an interface with a fleetwide maintenance/logistics management information system is required to effectively implement engine performance trending. This performance data may also be used for short-term trending to identify FOD and water wash requirements, and in conjunction with other EMS capabilities to generally improve maintenance troubleshooting effectiveness.

f. Surge, bogdown and afterburner blowout detection and documentation. Provided both as a flight safety indication and a means of improving maintenance troubleshooting. Data will be recorded during these events for analysis in a DPGS.

g. Oil system monitoring. Provided both as an important flight safety indication and as an aid to maintenance troubleshooting. The exact type of oil monitoring was not specified to enable each type of aircraft/engine application to take advantage of the best available techniques. These oil monitoring techniques could range from chip detectors to master indicating chip detectors or quantitative debris monitoring devices.

h. Fault detection and fault isolation of engine weapons replaceable assemblies (WRA's). Provided primarily as a means for improving organizational (O-level) maintenance troubleshooting effectiveness and reducing unsubstantiated removals of engine components. There are also flight safety and aircraft availability benefits associated with this capability. An O-level DPGS and automated diagnostic software is require to effectively implement this capability.

i. Engine, engine module and aircraft serial number identification. Provided to facilitate the use of engine component life usage and performance trend data with an automated maintenance/logistic management information system.

These general engine specification EMS requirements also describe overall system elements, interfaces, growth capacity and minimum parameter definition. The following are paragraphs taken from the EMS requirements sections of these specifications:

"The total engine monitoring system will be comprised of engine and airframe sensors, engine and/or airframe mounted signal conditioning and data processing electronics, an airframe mounted visual data display, an airframe mounted removable bulk data storage facility, a ground based data processing station and both airborne and ground station software. The malfunction of any EMS hardware or software shall not affect engine performance throughout the environmental conditions and operating envelope of the engine. The level of fault detection and isolation of engine WRA's shall be determined by failure mode and effect analysis and reliability centered maintenance analysis."

"The EMS shall have Built In Test Equipment (BITE) and self-check capability. The EMS shall have a minimum of 100 percent software growth capacity. Both airborne and ground station data processing software algorithms shall be provided as an appendix of the engine specification. If a digital engine control unit (ECU) is available, a data interface with the EMS shall also be provided. The sensors together with their location shall be specified in the engine specification. Electrical connections and circuit details shall be in accordance with MIL-STD-1553 MUX Bus requirements and shall be shown on the electrical installation connection figure."

"Engine Monitoring Sensors. To support the requirement for inflight engine condition monitoring, engine sensors shall be provided for the following minimum parameters: HP shaft speed (NH), LP shaft speed (NL), compressor inlet temperature (T1), compressor inlet pressure (P1), compressor exit temperature (T3), HP compressor delivery pressure (P3), turbine exit gas temperature (T5), turbine exit pressure (P5), afterburner nozzle position (A8), fuel flow (Wf), power lever angle (PLA), inlet guide vane positions (IGV), oil pressure (Poil) and vibration (VIB). Any additional engine and/or aircraft sensors required for engine condition monitoring shall be defined in the engine specification. The instrument range, system accuracy, time response and electrical characteristics for each parameter shall be present in tabular form in the engine specification."

"Thrust Indication. The engine shall provide signals for thrust computation. The method for computing thrust from these signals shall be provided as an appendix of the engine specification. These thrust computations shall be used by the EMS to provide engine health take-off thrust check, with cockpit GO/NO-GO indication, and to support engine performance degradation trending. Engine droop characteristics following the initial thrust transient (e.g, ground idle to take-off thrust) shall be taken into account when making thrust computations. The method used shall be accurate within ±3.0 percent of the actual net thrust and shall be verified through sea level static and altitude test operation."

"Special Maintenance Instrumentation Provisions. The engine shall provide signals for use in conjunction with other diagnostic equipment and/or technical data to provide diagnosis and fault isolation of malfunctioning engine control functions. Provisions shall be made for installation or connection of any instrument sensing equipment necessary to evaluate engine performance at acceptance after overhaul. The use of EMS supplied data with other engine peculiar ground support equipment (PGSE) shall be defined in the engine specification."

3. A-7E EMS.

The US Navy A-7E is a single-engine light attack aircraft powered by the Allison Gas Turbine (AGT) TF41-A-2 engine. The A-7E EMS is a derivation of the early Inflight Engine Condition Monitoring System (IECMS).

Background. The IECMS program was initiated in 1971 as the US Navy's first effort to develop a comprehensive EMS capability and to address engine related flight safety issues on the A-7E aircraft. The EMS is successor to the IECMS and represents the application of an on-board microprocessor based system to continuously monitor engine health, proide cockpit warning functions and output appropriate maintenance information. The current EMS configuration is the culmination of several phases of system development and evaluation. Both the early IECMS configuration and the EMS were used to provide the experience and data to justify procurement of a relatively expensive (approximately 10 percent of the engine cost) retrofit system. The close scrutiny and the requirement to define and "prove" the cost-benefits of a comprehensive EMS significantly stretched out the system development and evaluation phases of this program. Full retrofit of the A-7E fleet began in 1984 and is now complete.

System Description.

The principal design goal of the original IECMS was to reduce engine related aircraft losses by 50 percent. As the system was developed, evaluated and modified in response to changing program justification requirements (e.g., the increasing importance of on-condition maintenance), other design objectives were introduced. In addition to improved flight safety, these design objectives were: reduced maintenance costs, increased aircraft availability, and increased mission effectiveness. The A-7E EMS is comprised of four major subsystems: an engine sensor kit, an avionics kit, an airframe change kit, and a DPGS. The EMS continuously monitors a total of 46 engine and airframe parameters. The engine kit monitors 35 of these signals by means of 14 transducers added to the basic engine installation. The avionics kit consists of a Teledyne Controls supplied microprocessor based Engine Analyzer Unit (EAU) and a Data Display Unit (DDU). The avionics kit monitors and signal conditions all parameters, activates cockpit warning lights, provides out-of-limit exceedance "flags" for downing gripes and records data on a removable Tape Magazine Unit (TMU) for subsequent post-flight ground analysis. The airframe change kit was designed and installed by the government and includes cockpit modifications, additional sensors and switches and a wiring harness. It should be noted that the EAU is mounted in a specially designed compartment in the engine bay. The DPGS is an "off-the-shelf" ground based computer system utilized for analysis, automated diagnostics, and trending of EMS data.

Allison was the prime manufacturer responsible for developing the EMS airborne and ground based hardware and software. A more detailed description of the A-7E EMS program and operational experience can be found in references (a) and (b).

Accomplishments and Experience. During the progressive fleet evaluation program several major accomplishments occurred. Enthusiastic acceptance of the system and endorsement by the fleet operating squadrons are primarily due to improved maintenance troubleshooting time resulting in increased aircraft availability. During a 1979 fleet evaluation period two squadrons of early IECMS equipped A-7E's documented a 60 percent reduction of engine maintenance man hours per flight hour and a 40 percent reduction in engine removal rate. There has also been a consistent reduction in unsubstantiated component removal rates. The most significant accomplishment has been the absence of engine caused aircraft losses. There were no engine caused aircraft losses with the original two squadrons of IECMS nor with the early fleet EMS. Fleet wide retrofit of EMS on all A-7E and TA-7C aircraft is now complete and there has been only one documented engine related aircraft loss. In this particular incident, the engine problem was related to a HP fuel pump failure that the EMS was not designed to detect.

Lessons Learned.

The very successful A-7E IECMS and EMS programs provided the basis to justify the capabilities and benefits of future US Navy EMS programs. Some of the important lessons learned from these programs are as follows:

a. As the first Navy comprehensive EMS program, a lot of time and effort was required to overcome the management prejudice and uncertainty associated with EMS benefits, reliability, and cost-effectiveness. This really stretched out the program but once accomplished would not have to be repeated on subsequent aircraft programs.

b. EMS works. It saves aircraft, reduces maintenance and improves aircraft availability.

c. Improved flight safety and increased troubleshooting effectiveness sold the system at the time of initial production decision. Use of the system to provide life usage data, performance trending and parts life tracking, though inherent in the system design, did not play a strong part in the production decision process.

d. Fleet-wide retrofit of EMS on an older aircraft is desirable and justifiable. The A-7E aircraft was about half way though its projected operational life when retrofit was initiated.

e. Our one aircraft loss for an engine problem was caused by an accessory failure that was monitored in the early IECMS design but dropped in the production EMS as a system cost reduction item.

f. A dedicated team of contractors lead by one clearly established prime gives the best chance for a successful development program.

g. Vibration monitoring is perhaps the most useful EMS capability. A good vibration monitoring capability can address a very large group of engine problems. Most of the system's flight safety related "finds" have been through the vibration monitoring capability.

h. The longer freezing of the development software can be delayed, the more capable and successful the production EMS will be.

i. Engine manufacturer on-site contractor support for a period following fleet introduction is required.

4. F/A-18 IECMS.

The F/A-18 aircraft is a dual mission fighter and attack aircraft powered by two General Electric (GE) F404-GE-400 engines. The F/A-18 is currently operational with the US Navy and Marines, the Canadian Forces, Australia and Spain. The IECMS was an original design requirement and was developed during the normal aircraft Full-Scale-Development (FSD) program.

Background.

The IECMS was developed for the F/A-18 aircraft by McDonnell Aircraft (MCAIR) with GE responsible for the F404 engine sensor package and software algorithm development. A minimum baseline system was defined in the original aircraft and engine specifications. The system design evolution consisted of extensive trade-studies being conducted by both MCAIR and GE to define the practical and cost-effective levels of monitoring consistent with state-of-the-art sensor, avionics, and diagnostic software capabilities. This trade-study approach made extensive use of failure modes and effects analysis (FMEA), MSG-2 type analysis and sophisticated life-cycle cost models. These trade studies were to be used by the program managers to justify any system growth from the baseline definition and were intended to define an optimized IECMS to be developed during the F/A-18 aircraft and F404 engine FSD programs.

After Navy approval of the trade-study result and prototype system definition, the Phase II system development effort commenced with IECMS sensors being used on the initial F404 development engines, GE developing the software algorithms, MCAIR procuring avionics hardware and the IECMS being flown concurrently with the first full scale development flight test aircraft. Not only was the F/A-18 IECMS developed simultaneously with initial aircraft and engine development programs, the system was intended to be fully compatible with the aircraft/engine maintenance concept as it evolved into an operational maintenance plan.

System Description.

The original design goals of this system were to provide inflight pilot warnings of any detected engine anomaly serious enough to warrant aborting the flight and to provide data to track the actual life usage of the intended life limited engine components. A secondary design goal was to reduce maintenance costs by recording information during an engine anomaly for fault isolation on the ground. This secondary design goal would increase maintenance troubleshooting efficiency and reduce aircraft turn around time. The F/A-18 IECMS is a real-time engine monitoring and life tracking system and has been installed on all production and test aircraft. The system is highly integrated with other avionics systems, minimizing cost and weight. The system alerts the pilot during flight to serious engine anomalies and sets maintenance codes for the ground crew. Engine data is automatically recorded up to five seconds before and 25 seconds after the anomaly. In addition, life usage parameters, used for tracking remaining engine life, are calculated during flight.

The primary components of the on-board system are as follows:

Engine Sensors - 13 engine sensors are used by IECMS. All but five of these sensors are required for engine control or cockpit display purposes. The sensor signals are passed to the airframe in an analog or frequency form and are then converted to digital form. Each signal is carried by a discrete wire.

Airframe Parameters - The IECMS airframe parameters include Mach number, altitude, freestream total temperature, angle of attack, normal load factor, fuel pressure and temperature. All of these parameters are required for the aircraft flight control system and are therefore available without additional cost.

Maintenance Signal Data Converter (MSDC) - The Bendix supplied MSDC, which is located in the right Leading Edge Extension (LEX), converts the engine sensor signals from analog or frequency form to digital. In addition to converting the IECMS signals, the MSDC converts the signals from seven other systems (fuel, environmental control, electrical, etc.). Thus, the MSDC is not dedicated to the IECMS, but is shared by the other systems.

Maintenance Signal Data Recorder (MSDR) - The MSDR, located in an easily accessible avionics bay under the left LEX, receives the digital data from the MSDC and records the engine data on a magnetic tape called the Tape Magazine Unit (TMU). Data is recorded when an anomaly is detected by the IECMS logic and prior to takeoff (for engine performance trending). The MSDR is a part of the MSDC. The data recorded on the TMU also includes airframe fatigue data, and a "crash tape" recording. The TMU has sufficient capacity for approximately seven flights.

Maintenance Monitor Panel (MMP) - The MMP is located in the nose gear wheel-well and provides the ground crewman with a three-digit number, called an MMP code, for each event detected by IECMS during the flight. Currently, IECMS defines 44 maintenance codes for engine anomalies detected during flight. In addition, 231 codes are defined for monitoring other systems on the aircraft. The MMP code provides a direct entry into the troubleshooting trees in the maintenance manual.

Mission Computer (MC) - The MC contains all of the logic used by IECMs. The IECMS logic consists of 5400 16-bit words, which is two to four percent of the MC capacity, depending on MC model. The logic can be thought of as falling into three categories: continuous engine operation monitoring logic, "as required" monitoring logic, and engine life usage tracking logic.

Digital Display Indicator (DDI) - Two independent cathode ray tubes, called DDI's are used to display engine data and other system information as requested by the pilot. Each DDI can display information independently, allowing different systems to be simultaneously presented to the pilot.

Engine data is displayed in the cockpit. Five engine parameters are continuously displayed on digital gages and, when requested by the pilot, eight additional parameters are displayed on the DDI. When these parameters are displayed on the DDI, the current engine and flight data can be recorded by pressing a DDI button. The record button is located immediately below and to the right of the DDI screen. When pressed, five seconds of prior engine/flight data and 25 seconds of subsequent data are recorded on the TMU. This same pre/post-event data record is automatically recorded by IECMS whenever an engine exceedance is detected. The "pre-event" recording feature is accomplished by continuously storing the last five seconds of data in the computer memory and freezing that data when an exceedance is detected or a data record is requested by the pilot.

In addition to the operational exceedance engine monitoring functions of IECMS, engine life usage is also monitored during flight. Eight Life Usage Indices (LUI's) were developed by the engine manufacturer specifically for the F404 engine. These LUI's are recorded on the magnetic tape and transferred to a ground based Parts Life Tracking (PLT) program via a ground station. The LUI's tracked by IECMS are:

- Full N2 RPM Cycle - This LUI, sometimes referred to as a "Type I Cycle", is defined as an Off to Intermediate to Idle N2 RPM Cycle.

- o Partial N2 RPM Cycle - This LUI, sometimes referred to as a "Type III Cycle", is defined as an Idle to intermediate to Idle N2 RPM Cycle.

- o Equivalent Full Thermal Cycle (EFTC) - This LUI is the number of temperature cycles occurring in the high pressure turbine blades weighted in severity according to the magnitude of the cycle.

- o Stress Rupture Counts (SRC) - SRC's are accumulated at a rate dependent on high pressure turbine (HPT) blade metal temperature. The higher the blade metal temperature, the faster SRC's are added.

- o Time at Maximum Power (TAMP) - TAMP is the time at Intermediate power setting or above.

- o Full PS3 Cycle - This LUI is used to track pressure cycles for the core engine. A full cycle occurs when the compressor discharge pressure reaches a level near the maximum allowed. These cycles occur only at high-speed flight at low altitudes.

- o Partial PS3 Cycles - Partial PS3 cycles occur when the compressor discharge pressure reaches 85 percent of the maximum allowable.

- o Engine Operating Time - This is simply the time the engine operates at or above ground idle.

Additional capabilities have been added to IECMS over a period of time, either as a response to new fleet discovered engine deficiencies or as better understanding was gained on how to monitor original requirements. A more detailed description of the F/A-18 IECMS system can be found in reference (c).

Accomplishments and Experience.

During the course of system development and subsequent fleet use of the system, many significant accomplishments occurred. Probably the most significant has been the continued use and support of the system by the fleet, even though only a marginally functional ground based data processing station, the Enhanced Comprehensive Asset Management System (ECAMS), was provided.

Recording data during engine anomalies has provided valuable feedback which accelerated the development of the engine. Many times problems that occur in the flight environment are nearly impossible to duplicate on the test stand. Lack of insight into these problems delays their solution, resulting in a less mature engine and greater retrofit costs when the solution is found. Acquiring pre/post-event data as the engine anomaly occurs during flight provides the insight to understand the cause of the problem. The benefits have been a more effective Component Improvement Program (CIP) and a more rapid development of the engine.

Tracking engine usage during flight has reduced engine spare parts costs. The engine usage is tracked using the LUI's as previously described. Based on actual usage data, spare parts costs savings for one life limited engine component were estimated to exceed $18.10 per engine flight hour, or $72,400 over the 4000 hour life of an engine. Total Life Cycle Cost (LCC) savings would be greater if all elements of costs in the LCC accounting system were considered.

Lessons Learned.

The F/A-18 IECMS program has and is continuing to provide many significant lessons learned. Some of the more important of these are as follows:

a. Extensive trade-studies to design and justify the most cost-effective system doesn't always cause the optimum design to be implemented. A much more success oriented approach is to specify desired system functional capabilities and to maintain these specification requirements as mandatory.

b. To reduce weight and cost, engine monitoring systems can be integrated with the other avionics on the aircraft. This is best achieved during initial design of the aircraft.

c. Using a central Mission Computer (MC) as an airborne memory for the EMS software greatly limits development and growth. The EMS software requirements in the MC will always take a secondary priority of importance to tactical capabilities and needs.

d. To enhance flexibility and reduce cost, the monitoring system software should be fully re-programmable without requiring hardware modification to accommodate logic modification as more experience is gained in the operational use of the weapon system.

e. To accelerate engine development, the monitoring system should have the capability to record data during and prior to a detected engine exceedance. This is beneficial for developing the monitoring logic and for understanding the cause of engine anomalies.

f. To accelerate development of the monitoring logic, a continuous recording system is desirable during the flight testing stage. Such recording can be achieved via a separate on-board recorder or through ground telemetry.

g. To avoid electromagnetic interference (EMI), all low voltage signals, especially vibration signals, should be amplified as near as possible to the sensor. To avoid saturation of the charge amplifier, the vibration signal should be filtered to eliminate the high-frequency signal above 10,000 Hz prior to amplification.

h. A maintenance recorder can also provide a crash recorder function. The TMU has survived and been successfully used in the post-crash investigation of most F/A-18 crashes.

i. Ground Station software development must be part of the original system and aircraft FSD program. The F/A-18 ECAMS program was added as an after thought and has continuously limited the development and full implementation of IECMS capabilities.

j. Without full development of IECMS troubleshooting and diagnostic capabilities, fleet support of engine component life usage tracking is difficult. This is because improved troubleshooting and diagnostic capabilities are used by the fleet operators on a daily basis while life usage tracking is a more long term benefit.

k. Poorly designed vibration monitoring capabilities will cause erroneous indications which are not tolerated by the fleet. The ICEMS avionics design left out a required high frequency vibration filter. This design ommission caused high energy noise from the vibration accelerometer to sometimes saturate the signal processing electronics and resulted in erroneous vibration warnings. The fleet quickly turned off the cockpit vibration warning function.

l. To avoid setting false cautions and maintenance warnings, engine operational limit exceedances should persist for several computer iterations.

m. Through aircraft FSD and continuing into production, there will be a great use of EMS supplied data to address many types of engine problems in the engine CIP.

5. AV-8B EMS. The AV-8B Harrier Aircraft is a Vertical and Short Take-off and Landing (VSTOL) attack aircraft powered by a single Rolls Royce F402-RR-406 engine. The AV-8B aircraft is an updated design of the British AV-8A aircraft and is being built jointly by (MCAIR) and British Aerospace. The EMS was developed jointly by NAVAIR and the UK Ministry of Defense (MOD) for application on both the AV-8B and the British GR-5 aircraft. This system is also being procured for the Spanish Harrier Aircraft.

Background.

The Harriers EMS evolved from a UK MOD attempt to define and develop a standardized EMS for application on several British Aircraft. The initial application for such a system was the GR-5 aircraft. Since the AV-8B and GR-5 aircraft were being developed under a joint program it became natural for a common EMS effort to be proposed. Under a joint US/UK Memorandum of Understanding (MOU) a common system was developed meeting both the US and UK requirements. Originally the UK requirements stressed life usage monitoring while the US was more interested in the increased flight safety afforded by vibration monitoring and the improved troubleshooting provided by limit exceedance and incident recording. After much collaboration a standard EMS with common hardware and software was developed and is being implemented in both services' Harrier aircraft.

The development of the Plessey EMS avionics was a government furnished equipment (GFE) effort, lead by UK MOD. The engine kits and software algorithms were supplied from Rolls Royce. The installation considerations and integration were divided between British Aerospace and MCAIR. This required quite a management coordination effort.

Accomplishments and Experience.

The major accomplishment has been the successful development of a standard EMS with common hardware and software meeting both countries' and services' peculiar requirements. Even though the AV-8B and GR-5 aircraft are similar, how they are to be used and how the individual services perceived the use of EMS data in their own maintenance concepts are somewhat unique. This took a significant management effort on the part of all parties and often involved some good compromise.

System development and qualification is complete and production delivery is under way. Flight test evaluations were conducted both by the US Navy and MCAIR at their facilities and by the British Aerospace and the RAF in England. The systems are just now being implemented in fleet aircraft.

System Description.

For the AV-8B and GR5, where great emphasis has been placed on size and weight constraints, the EMS hardware comprises two airborne and two ground units as follows:

Airborne:
- Engine Monitoring Unit (EMU)
- Quick Access Recorder (QAR) optional
- The US Navy will use a Data Storage Unit (DSU) Maintenance Recorder

Ground:
- Data Retrieval Unit (DRU)
- Data Processing Ground Station (DPGS)

The airborne units are mounted in the wheel-well and used respectively to compute engine life and store raw data. Ground data handling equipment consists of the DRU which is a back pack or hand held unit. This unit can also be used to diagnose transducer/signal input failures and/or produce first line engine diagnostics for service use.

The EMS is designed to provide the following functional capabilities:

LCF Cycles - Centrifugal LCF counts can be calculated for up to 14 specified components and up to 18 for combined thermal and centrifugal LCF counts. Additionally, torque and pressure induced LCF functions can be incorporated.

Turbine Blade Life Usage - Thermal fatigue and creep usage can be calculated on up to four specified components. Blades will be lifed on either thermal fatigue or creep.

Limit Exceedances - The EMS can be programmed to detect any limit or rate of change exceedance. On detection of an exceedance it will continue to monitor and record its duration and magnitude.

Vibration Monitoring - The EMS will receive a broad band vibration signal from one piezoelectric transducer. The signal will be conditioned through an integrating charge amplifier and passed through an array of 15 discrete band-pass filters. The filters can be selected to isolate a specific frequency band associated with gearboxes and accessories.

Incident Recording - When a limit exceedance occurs, or a specified rate of change is exceeded, the relevant data will be recorded for a minimum period of five seconds before and 20 seconds after the incident. In addition to recording data from exceedances, more complex incidents can be programmed in the same way as software becomes available. At the request of the US Navy a pilot initiated record capability has been incorporated.

Continuous Recording - A continuous recording device can be fitted to any aircraft when whole flight data is required. All input, and some calculated parameters can be obtained.

Data Retrieval - The life usage and incident data can either be displayed on a LED display, or in the case of the AV-8B, on the cockpit CRT. However, the amount of information displayed in this way is, of necessity, very limited, and the displays are not suitable for the output of stored data associated with incidents. A Data Retrieval Unit (DRU) has therefore been provided. The main function of the DRU will be to transfer data from the aircraft to the ground data computer. Hard copies of parameters versus time and trend plots will be available from the ground computer, and parts life records will be automatically updated. A data processing ground station capability is being developed by both services.

The data required to perform these functions are available from five different types of data source:

- Analogue Transducers
- Multiplex Data Bus (1553)
- Digital Engine Control System Data Bus
- Engine Display panel UART link
- Vibration Transducer

Results are stored in non-volatile memory and are available for output to ground based support equipment (DRU), the cockpit Digital Display Indicator (DDI) or, in the US Navy's case by reading the DSU. Discrete outputs are provided in the form of a cockpit amber caution lamp and a refueling panel incident/exceedance warning indicator. Raw data obtained from continuous recording are available in tape cassette or tape cartridge form.

By design, significant system growth capacity is available to add future functional capabilities. A further detailed description of the AV-8B and GR-5 EMS can be found in reference (d).

Lessons Learned.

The joint AV-8B and GR-5 aircraft EMS program has and still is providing may lessons learned. Some of the more important ones are as follows:

a. The unique EMS requirements of two services in two countries can be merged into a common system development. This approach takes a large government management effort and is based on the willingness to make intelligent compromises, keeping communication paths open and having lots of face-to-face meetings of all participating parties.

b. Interfacing the EMS with a DECU is very desirable and can help obtain a very comprehensive monitoring functional capability with the addition of only a few extra dedicated EMS sensors. This is particularly true in regard to the parameter signals necessary to increase fault detection/fault isolation capability of control input and output related accessories and WRA's.

c. Similarly, a standard MUX Bus interface gives the EMS access to a large number of aircraft parameters which normally would not be easily and affordably available. This capability lets EMS interface with many other aircraft subsystems and lets the EMS pickup new parameter inputs which were not defined as necessary in the original system design.

d. An adequate EMS stall warning capability can require a Ps3 parameter sampling rate as high as 50 to 100 times per second.

e. High EMI environments and electronic noise considerations can mandate mounting the vibration signal charge amplifier on the engine as close to the vibration pickup as possible. The low level signal of a vibration accelerometer makes long runs of unshielded wire very undesirable if the charge amplifier is located in the EMS avionics "black box."

f. Noise in the aircraft wiring, subsystem signals, and MUX Bus can require additional EMS signal input filtering to avoid erroneously interpreted data spikes.

g. Other aircraft subsystem BITE capabilities can be misinterpreted by the interfaced EMS software causing data interrupts, erroneous diagnostics, or equipment shutdown.

h. Troubleshooting system development problems over long distances, particularly during flight tests with inadequate funding, no central contractor as prime and confused contractual support requirements is very difficult to impossible. The optimum solution, of course, is to have one well funded contractor as prime in charge of and responsible for making the system work at a single flight test site.

i. Aircraft wiring problems, if not adequately attacked and attended to will greatly retard system development.

j. Late attention to all of the systems ILS elements and to DPGS development will delay system production incorporation and subsequent fleet implementation.

k. A GFE system development is very management intensive and makes software changes difficult to manage and implement.

6. E-2C EMS.

The US Navy E-2C is an all weather airborne early warning and control aircraft that patrols defense perimeters to detect approaching enemy threats and directs the friendly aircraft to engagement. The current E-2C is powered by two Allison T56-A-425 Series III engines. The US Navy is procuring new E-2C aircraft with updated avionics and powered by a new technology engine and using improved maintenance concepts. An EMS to monitor the health of the engine was initiated in 1984 and was incorporated into the engine design.

Background. An EMS for the T56-A-427 engine was developed by Allison Gas Turbine under Navy contract for retrofit into the E-2C aircraft. The system, designated as T56-A-427 EMS, is designed to continuously monitor engine health, record pertinent information, and through a ground station provide diagnostic information to operating personnel. In-house and fight testing are under way and system completion is expected in late 1988. Advances in state-of-the-art computer and sensor technology have improved system cost and reliability over previous EMS systems. The EMS was originally to be developed as part of the engine FSD program, but funding cuts caused the EMS to be developed as a separate contractual effort.

System Description.

The EMS system is comprised of the elements necessary to perform continuous engine monitoring for the purposes of providing: flight safety-related cockpit warnings, postflight exceedance/maintenance indicators, postflight data analysis specifying maintenance requirements and procedures, and long-range tracking of engine performance and parts life usage criteria. The elements consist of dedicated EMS components, data outputs from the engine Digital Electronic Control (DEC), and airframe discrete (switch position) recognition via an airframe installed harness. The dedicated EMS components include an airframe mounted GE supplied Engine Analyzer Unit (EAU) with a removable Tape Transport Cartridge (TTC), engine-mounted transducers and a Ground Station (GS). The airborne equipment functions to acquire data while the ground station performs detailed maintenance diagnostics and engine usage data bookkeeping functions.

The EMS concept and design philosophy for the E2-C/T56-A-427 is based on the following objectives: enhanced flight safety, reduced maintenance costs, increased aircraft availability and reduced in-flight mission aborts. This system concept and design philosophy is common to all new Navy EMS programs.

Flight safety, the main emphasis of the T56-A-427 EMS, is enhanced by advanced detection of malfunctions and computer assisted maintenance decisions. Advanced detection of engine malfunctions in their early stages is intended to provide sufficient warning to the pilot to enable safe landing prior to major engine/component failure. The system is designed to provide the pilot with a degree of information regarding engine health equal in measure with his work load and need.

The overall reduction in engine maintenance costs ranks second only to flight safety in justifying the need to have an operating EMS. Maintenance expenditures (man-hours and material) are reduced through elimination of shotgun troubleshooting, reduced fault isolation time, early detection of malfunction (reducing or eliminating secondary damage), and on-condition maintenance capability (versus fixed time intervals).

Aircraft availability is automatically improved via reduced maintenance actions and man-hours. Improved availability can ultimately pay off in reduced inventory. In addition, valuable manpower resources can be redirected from engine-related maintenance to other areas, helping increase aircraft availability.

The system objective of in-flight mission abort reduction is best fulfilled through improved overall maintenance and early detection of engine malfunctions. These system capabilities enable corrective maintenance to be performed in the early problem stages to reduce the number of malfunctions requiring mission aborts.

Accomplishment and Experience.

The accomplishments to date have only involved the system design, development and qualification efforts. No real user experience has been accumulated. Much of the system design and development efforts have centered on trying to manage issues that were continuously arising between the development prime and his subcontractor. This situation was compounded by the Navy breaking out the avionics for a direct procurement from the development subvendor before the system was fully developed and qualified.

Large slippages in the engine FSD and flight test programs have both helped and hurt the EMS development effort. The additional time afforded from these slippages has enabled similar delays in the EMS development program to be seen as less critical to the overall program. Conversely though, the test cell and flight test slippages have greatly reduced the amount of operational test time the EMS will experience prior to production incorporation. This will most significantly impact the amount of development software changes possible prior to production delivery.

Of significant note concerning this EMS design is the use of Fast Fourier Transforms (FFT) data analysis for the vibration monitoring capability. This is the first US Navy application of FFT vibration analysis in an airborne EMS, and should, if successful, provide the most powerful form of engine vibration monitoring yet.

Lessons Learned.

The E-2C EMS program though not yet fully developed and implemented into production has already provided many significant lessons learned. Some of these are as follows:

a. Funding cut backs and management redirection can certainly adversly impact a well planned program. The EMS development was originally an integral part of the new T56-A-427 engine FSD program. An urgent funding cutback caused the EMS effort to be redirected as a separate development effort. Many of the planned EMS development items normally procured were dropped just to keep the program alive. This particularly affected testing and software documentation. At the same time, the EMS avionics was redesigned to handle a four engine application of the current model T56 engines. Only problems resulted from this program redirection.

b. The EMS avionics should not be broken out from the development prime prematurely. Because of pressures of new procurement regulations, a decision was made to break-out the first production lot procurement of the EMS avionics before qualification and flight tests were finished. This was a very bad move since both Allison, the development prime and Navy program management immediately lost management leverage with the avionics subvendor.

c. Aircraft delivery pressures should not force premature EMS production commitments. Because of aircraft delivery schedule pressures, a pilot production contract was signed for EMS avionics before much engine test cell and flight test experience was accumulated. This leaves very little time and management leverage for cost-free software changes prior to production delivery. It is very likely that the program structure and production delivery schedules will cause us to freeze the software configuration too early.

d. The EMS avionics subvendor pilot production contract should not be signed until all development specification issues are resolved. The Navy signed a pilot-production contract with the EMS avionics subvendor before all development problems and prime/subvendor specification issues were resolved. This again was a Navy management mistake, caused by delivery schedule pressures, which left the user in the middle of some costly and unresolved development issues.

e. Design trade-offs within the EMS system should not adversely affect the systems overall performance. The EMS avionics design failed to adequately isolate some sensor input failures from affecting similar sensor inputs. This was because of poor design trade-offs of internal fault tolerance versus fault detection.

7. F-14D, and A-6F Fatigue and Engine Monitoring System (FEMS).

The F-14A+ aircraft is a re-engined version of the current F-14A Tomcat fighter powered by two GE F110-GE-400 engines. Besides the new engines, the F-14D introduced a new set of avionics including a standard 1553 MUX Bus. The A-6F aircraft is an upgraded version of the current A-6E Intruder aircraft with among other modifications two new F404-GE-400 engines, a 1553 MUX Bus, and new avionics. All three of these new aircraft are built by Grumman Aircraft and include very comprehensive FEMS capabilities.

Background.

After several unsuccessful attempts to structure and fund an EMS program, the current F-14A aircraft still does not have a monitoring system. With the proposal of a F-14A re-engine project, an EMS requirement was specified. This requirement was especially easy to justify since the USAF version of the F110 engine already had an EMS capability in the F-16 aircraft. Also new engine warranty guarantees mandated some level of EMS to track life usage. Very early in the program definition this basic EMS requirement was combined with a similar requirement for an airborne aircraft fatigue monitoring system. As the CFE prime, Grumman Aircraft conducted a competition and selected Northrop Electronics to built the avionics for a common FEMS.

The A-6F aircraft planned to use the original F/A-18 aircraft MSDR system to meet its aircraft fatigue and engine monitoring requirements. Concerns over the state-of-the-art of the current MSDR hardware and the undesirability of using the Mission Computer (MC) for the airborne application program changed this plan. Previous EMS programs' "lessons learned" were applied, and a version of the F-14D FEMS was proposed for the A-6F application. Commonality goals were applied and the Northrop FEMS was re-defined to provide a 100 percent common hardware system for use on the F-14A+, F-14D and A-6F aircraft. It should be noted that along with the common FEMS functional requirements, the A-6F system also monitors the status of approximately 80 other subsystems.

System Description.

FEMS is intended to extend the life and safety of the fleet by permitting maintenance to be performed as a function of actual life usage instead of costly time scheduled maintenance routines at periodic intervals.

FEMS is comprised of an Airborne Data Acquisition Set (ADAS), a Data Storage Set (DSS), an Engine Mounted Signal Processor (EMSP) and the Data Processing Ground Station (DPGS).

Airborne Data Acquisition Set. The ADAS is maintained common to the F110-GE-400 (F-14A+ and F-14D) and the F404-GE-400D (A-6F) EMS requirements by containing the necessary hardware/software for both engines. Configuration of the ADAS for each engine is accomplished through the use of external aircraft harness pins. The ADAS is comprised of an Airborne Data Acquisition Computer (ADAC) and the Flight Maintenance Indicator (FMI).

Airborne Data Acquisition Computer. The ADAC processes data and interfaces with the MC as a 1553 MUX Bus remote terminal. In the case of the F-14A+, the ADAC receives data from the Computer Signal Data Converter (CSDC) via a Serial Digital Data Interface (SDDI). The ADAC is responsible for executing fatigue and engine monitoring algorithms and setting engine failure alert flags for the MC. The ADAC also interfaces directly with the FMI to display FMI codes, flag the FMI's failure indicator and clear the FMI display.

Flight Maintenance Indicator. The FMI is located in the nose wheel-well for easy access by maintenance personnel. The FMI has the capability of inputing discrete data to the ADAC to initiate the fluids check function and initiate the fault code display function.

Data Storage Set. The DSS consists of a Data Storage Unit (DSU) and a Data Storage Unit Receptacle (DSUR). The DSU contains the necessary electronics to communicate with the MC as a 1553 MUX Bus remote terminal and is transportable between the aircraft and ground stations. The DSU contains enough solid state non-volatile memory for two to eight flights before removal, and data received from the MC is sequentially stored. The DSUR is connected on a MIL-STD-1553 avionic bus and is located in the aircraft cockpit.

Engine Mounted Signal Processor. There is an EMSP mounted on each engine to provide elementary data acquisition functions for reading data from engine mounted sensors. The engine data collected by the EMSP is then sent to the ADAC via the 1553 MUX Bus.

Data Processing Ground Station.

The DPGS features include in-flight event data outputs for trouble-shooting and failure investigations, performance trending alerts and charts, and an event and maintenance history database. The DPGS incorporates a Parts Life Tracking System (PLTS) to provide:

- Automated life consumption and configuration tracking by part.
- Removal forecasting.
- Fleet usage data reporting.
- Identification of part location.
- Transaction history.
- Opportunistic maintenance advisory.

Accomplishments and Experience.

As of this date the FEMS has not been operational in the fleet so there has been no real user experience. Because of program slippages, there has been only limited Grumman and Navy flight test experience using the system. What little there has been was used mainly to troubleshoot specific system development problems. These problems mainly involved fine tuning the software and getting the system interfaces and installation integration to work right. The system integration efforts were greatly enhanced by the extensive use of the Grumman avionics development laboratory "benches" and aircraft front frame avionics integration facility.

The major accomplishment of the FEMS program has been the design development and implementation of a common aircraft fatigue and engine monitoring concept with 100 percent common avionics hardware on three different aircraft using two different engine types. This accomplishment is extremely significant since it shows that when it makes sense, a standard monitoring system can be used on differing aircraft applications. In this case there were two different basic aircraft types, three sets of installation and integration problems, two very different engine type with their own sensor sets, and three unique software application programs. Also, the A-6F added other subsystem monitoring functions. In this case these three aircraft programs were happening at approximately the same time frame and would all be done by the same prime aircraft manufacturer. A common FEMS made sense and worked.

Lessons Learned.

The F-14A+, F-14D, and A-6F FEMS programs have provided many lessons learned. Many of these deal with program management and system integration. Some of the more significant ones are as follows:

a. A common combined fatigue and engine monitoring concept using standard avionics hardware can be designed, developed and implemented on two different aircraft types, using different engines and requiring unique software programs. Attempts to apply standard EMS hardware should not be applied universally, but only when it makes sense.

b. One prime contractor for system development and early production implementation works best.

c. Too many different contracts for various parts of the program, though a programmatic and funding necessity, was very difficult to manage.

d. Use of very extensive avionics system bench integration tests were extremely valuable but did not completely eliminate aircraft installation and software problems during flight test.

e. Changes in other aircraft subsystems software which interfaces with the FEMS can adversely affect the FEMS software. This is particularly bothersome when these other interfacing subsystems are having development problems, either known or unknown. It takes time to troubleshoot and fix these subsystem software problems and the FEMS development and evaluation process suffered.

f. It is unwise to adopt unchanged engine algorithms used for another EMS application of the same engine. The initial FEMS position was that the older USAF F110 engines algorithms would change by not more than 20 percent for the F-14 application. This was a naive position and caused too little software changes to be budgeted, did not take into account that USAF F-16 software was changing as they corrected their field problems, caused the production software configuration to be frozen prematurely and resulted in production system delivered with known software errors.

g. Not enough funding was allocated for FEMS software changes during aircraft FSD. Similarly, post-development aircraft support budgets require adequate FEMS funding items for continuation of fine tuning of the system and software changes. The danger is that this type of required support gets minimized or left out of fixed-price contractual commitments.

h. It is very hard to predict and budget all FEMS development requirements in a fixed-price development contract. Also sub-vendor "buy-ins" in this type of contractual arrangement could kill a good program either in development and/or production.

i. DPGS software development is best done by the engine manufacturer.

j. A real time clock with continuous Julian Date capability is extremely desirable to life usage monitoring and parts life tracking.

k. Getting the DPGS software and parts life tracking system developed correctly and concurrent with fleet introduction of this airborne FEMS is still one of the most difficult tasks.

l. With two aircraft developments being conducted simultaneously, man-hour priorities and shifting aircraft schedules greatly affect a common FEMS development program. This type of situation presents a unique management challenge.

m. Having gone through the F/A-18 IECMS experience greatly contributed to GE's ability to develop new F404 algorithms and enhanced FEMS applications software. This is true for both the airborne and ground system elements.

n. The responsibility split by the GE team developing F-14 and A-6 ground station software worked well and resulted in relatively common, "user friendly" software with standard output formats.

o. The A-6F FEMS turned into the first US Navy comprehensive mechanical condition monitoring system by monitoring the engine, aircraft fatigue usage, and the status of up to 80 other aircraft subsystems.

8. V-22 Vibration, Structural Life and Engine Diagnostics (VSLED).

The V-22 is a new multi-mission aircraft design using tiltrotor technology, combining the efficient flight characteristics of a modern turboprop aircraft with the vertical take-off and landing characteristics of a conventional helicopter. The V-22 aircraft will be used by US Marine corps, Navy, Air Force and Army for their respective unique missions. The V-22 is powered by two Allison T406-AD-400 turboshaft engines and depends heavily on monitoring techniques to optimize maintenance efficiency.

Background.

The next generation of integrated aircraft health monitoring systems is now under development for the Bell-Boeing V-22 tiltrotor aircraft. The VSLED system will be instrumental in minimizing operational maintenance costs on this aircraft.

Bell Helicopter Textron Inc. is developing and integrating the VSLED system for the V-22; Allison Gas Turbine is supplying the algorithms unique to the engine monitoring function. The hardware and operating system for the VSLED airborne unit are subcontracted to Teledyne Controls of Los Angeles, California.

The V-22 program has stringent maintainability and serviceability requirements, and the VSLED system is being developed to help meet them. One of these requirements is that the V-22 require half as many maintenance hours as helicopters of an equivalent class. This means the V-22 must have a system to support the on-condition maintenance concepts pioneered on earlier military aircraft. The application of on-condition maintenance to the EMS will alone account for significantly lower operational costs and enhance system readiness.

System Description. Recent years have seen great progress in the development of systems for processing and using data for the control of aircraft and the monitoring of their condition. The V-22 has computers and data buses that exploit this progress heavily for controlling and monitoring every aspect of flight. In addition to supporting such obvious aspects as flight performance, engine performance, and navigation, the data system can collect and process information on the functioning and condition of system components for maintenance purposes. VSLED is the combination of dedicated hardware and software that permits development of an on-condition system for maintenance purposes.

Overall VSLED monitoring requirements.

Bell is developing all of the VSLED applications software that integrates the following major monitoring functions:

a. A set of vibration diagnostic algorithms for the drive train, rotors and engines.

b. On-board analysis of rotor track and balance and generation of instructions for adjustment.

c. A structural-life monitoring program for the airframe.

d. A structural-life monitoring system for the rotor system and associated dynamic components.

e. An engine monitoring system (EMS).

The central nervous system of the V-22 is a MIL-STD-1553 dual-redundant data bus. The VSLED avionics hardware operates as a remote terminal on this bus, receiving data from a wide range of aircraft systems via one of two AN/AYK-14 mission computers that direct traffic on the data bus. Through this avionics bus VSLED has access to the triple-redundant flight control computers and their wealth of navigational and control system data, all of which it uses in its algorithms. The avionics bus is also a gateway for the display of maintenance data, rotor track and balance data, and performance data on any of the four multi-function cockpit displays.

The avionics package includes a solid-state data storage cartridge. Data stored in the VSLED airborne unit can be transferred to the cartridge for post-flight processing at a designated ground station. The cartridge, which is part of the aircraft data storage system (DSS), is also used to upload preflight mission data and can be used to establish VSLED parameters peculiar to a specific aircraft configuration.

The V-22 monitoring concept represents the most comprehensive system yet. A more detailed description of the VSLED system can be found in reference (e).

Engine Monitoring System.

Design Goals.

The engine monitoring system is being designed to achieve the following goals: increase flight safety, support on-condition maintenance, reduce life cycle costs and acquire warranty data.

Improvements to flight safety result primarily from automatic in-flight display of out-of-limit operating conditions. Display of in-flight operating limit exceedances gives the pilot the timely information he needs in order to take action to avoid a major engine failure. The system further improves flight safety by giving maintenance personnel post-flight diagnostics for timely and accurate corrective maintenance. In some cases, the fault isolation and detection capabilities of the system provide information on maintenance requirements that is not otherwise available. For example, trends in vibration levels can indicate the need to perform maintenance long before a failure occurs.

The system supports on-condition maintenance by acquiring and analyzing the data necessary for the direction of corrective and preventive maintenance. Performance and vibration trending, parts life usage tracking, and full-time exceedance monitoring and fault detection combine to make an on-condition maintenance concept possible. Instead of being based on fixed intervals, inspections and maintenance will be scheduled as a result of a measured rate of performance degradation or parts life usage. Operating limit exceedances will be confirmed and quantified through the recorded data and, depending upon their severity, the appropriate maintenance action will be scheduled.

Accomplishment and Experience.

The main accomplishments to date have resolved around establishing a final system definition, getting development hardware built, generating initial algorithms and software programs, and solving aircraft integration problems. At this time, only very limited subsystem qualification has been performed and no flight-testing has occurred. The management coordination of all the various subvendors involved in this fully integrated monitor system has been a major accomplishment.

The design effort required to develop the small, light weight and very functionally capable VSLED avionics unit with its large growth capacity has been significant. The designed in hardware growth potential to add expanded gearbox vibration monitoring at some future date is a significant accomplishment. The use of FFT vibration analysis techniques implemented by a separate microprocessor is also significant. This is the US Navy's first attempt to monitor a complete aircraft power drive train including engine, gearboxes, proprotor, shafting and hangar bearings. Much of the V-22 VSLED monitoring functions will apply directly to any future comprehensive helicopter monitoring system.

Lessons Learned.

Even though the V-22 VSLED program is only in the initial stages of system development, there have been several items that could be classified as lessons learned. Some of the more important ones are as follows:

a. The new aircraft and engine maintenance concepts and warranty guarantees are depending more and more on the data that an EMS can provide. The V-22 maintenance plan and the T406-AD-400 engine warranty requires an EMS capability as provided by VSLED.

b. There is a definite trend in the new aircraft programs to provide a more integrated monitoring system. This is true in that the avionics supplying the monitoring functions is not stand alone but integrated into the complete aircraft avionics suite, often involving several "black boxes", the mission computer, the 1553 MUX Bus, and common data storage units. This is also true in that more aircraft subsystems are being monitored by the same integrated monitoring system.

c. There is a trend toward grouping the mechanical subsystem monitoring functions into one area of the integrated monitoring system, while the avionics monitoring functions are accomplished in another area. This trend is exemplified in the V-22, where the avionics monitoring function is performed in the mission computer while engine, airframe fatigue, proprotor, gearbox, and hangar bearing monitoring is performed by VSLED.

d. There is a trend, supported by increased airborne computer processing capacity, to provide a higher level of on-board diagnostics and troubleshooting capability. As the airborne system provides increased fault detection and fault isolation capability, there is a lesser requirement to analyze recorded data in a ground station before supporting aircraft turn-around decisions.

e. The DPGS software development can easily get off-track if it is not contractually scheduled as an integral part of the aircraft FSD program. The VSLED ground station software development was not part of the original FSD contract and therefore, is significantly lagging the airborne system development. Airborne and ground station system software development should be concurrent and managed by the prime contractor.

f. With careful planning, significant growth capacity can be designed into the airborne system with minimum cost and weight penalties. Comprehensive gearbox vibration monitoring was a desired growth capability of the VSLED. This growth capability was achieved by estimating necessary hardware and software requirements, allocating the necessary spare connectors and input channels, increasing the power supply, leaving two spare card slots and designing the mother board with this increased capacity specifically in mind.

9. Conclusion.

Fully profiting from the experiences of previous EMS programs and applying available lessons learned to current and future development efforts is a continuing task requiring attentive management practices and good "corporate" knowledge. Most EMS benefits have now been well established and there is no continuing need to re-justify these for every new program. The best way to ensure having an EMS as part of a new aircraft development program is with detailed functional capability specification requirements.

To date, if the top three lesson learned for EMS development were listed, they would be as follows:

a. EMS works and the benefits are accepted.

b. One contractor should be established as prime for any development effort.

c. With an integrated avionics systems approach, careful management attention must be paid to ensure that EMS functional requirements are not compromised.

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ENGINE USAGE CONDITION AND MAINTENANCE MANAGEMENT SYSTEMS IN THE UK ARMED FORCES

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SUMMARY

The cost effectiveness of engine condition monitoring has often been questioned. The Royal Air Force (RAF) has considerable experience of engine condition monitoring based on a series of trials. Recently aircraft have been introduced with comprehensive monitoring systems. Previous condition usage monitoring trials are outlined together with the reasons for changing from scheduled based maintenance to condition based maintenance. The cost effectiveness of various methods is revealed and the difficulty of justifying the retrofit of equipment fleetwide is discussed. Finally, some of the current activities in the RAF on condition monitoring are presented.

1. INTRODUCTION

This is the second paper in a series of three prepared by the Air Force Department of the UK Ministry of Defence on the subject of Engine Usage and Condition Monitoring Systems (EUCAMS). The first, at reference 1, dealt with the broad aspect of the UK requirement. The third, at reference 2, will be presented to ASME in June on the subject of the application of Engine Health Monitoring (EHM) for future technology engines.

The Armed Forces of the UK have been accused of not revealing the cost effectiveness of EUCAMS and this paper has been prepared to answer that challenge. EHM is regarded as part of the wider term EUCAMS which includes information management and the control of assets. It is often not a clear argument whether one system or method is more cost effective than another, but the RAF does have a perspective on the cost effectiveness of EHM based on RAF experience. This experience is based on three major exercises that have sought to show the advantages in terms of:

a. Improved flight safety.

b. Aircraft availability.

c. Reduced support costs.

The equipments available to the RAF for EHM are discussed briefly together with a cost effectiveness study for the application of those equipments to the Hawk and the Tornado. The case for retrofitting equipment to aircraft is examined and the policy for EHM on future aircraft is outlined. The advantages of parts life tracking is available to the RAF in limited form on Tornado, but this will be much enhanced for the Harrier GR5 and could be improved for the Tornado. The systems currently being brought into service are quite diverse, but their anticipated performance leads to the advantages sought by the policy of introducing EUCAMS to the RAF. EUCAMS permits the move towards condition based predictive maintenance, but this philosophy needs to be incorporated in the design of an engine from the inception.

2. THE BENEFIT OF EUCAMS

EUCAMS should give us the facility to monitor engine condition accurately and hence to carry out maintenance activity only when necessary. All the following advantages involve considerable cost implications:

a. Flight Safety. A comprehensive monitoring system would not have prevented all 6 or so of our engine-caused aircraft losses per year. However, a significant number of the mechanical failures and pilot overload events could be avoided with appropriate monitoring techniques and one aircraft, costed at say £15M, saved per year would pay for a sizeable EHM programme.

b. Life Cycle Costs (LCC). The engine represents a large part of the in-service support costs for aircraft. For example, the engine represents 47% for Harrier and 32% for Hawk. These costs need to be reduced, because currently we spend 25% of the LCC procuring an aircraft and then 75% supporting it over its life. These ratios are similar for engines but high support costs are preventing us from having better equipment and updating equipment as often as is necessary.

c. Aircraft Engine Availability. In 1985, engine unserviceability was the single largest reason for lost Tornado flights. This has a severe operational implication from cancelled missions, but there is an associated loss of training which causes frustration to our aircrew and groundcrew alike.

3. EHM EXPERIENCE

The major exercises that have shown the financial advantages of EHM are as follows:-

a. Engine Usage Monitoring System. Engine Usage Monitoring System (EUMS) was started in the 1970s to show engine usage and enable the calculation of accurate LCF exchange rates. EUMS records engine parameters, via a data acquisition unit, onto a standard C-120 cassette. The method is based on sampling engines. At each unit flying the aircraft, a number of engines are instrumented for data sampling; the data is then processed in industry who recommend exchange rates. £45M has been saved over the life of the Adour in Hawk where the exchange rate has been reduced from 8 to 2 cycles per hour.

b. Air Staff Target 603. Air Staff Target (AST 603) involved the embodiment of EHM equipment to show the cost effectiveness of automatic data recording as an EHM technique in conjunction with an on-condition maintenance policy. It commenced in 1975 and the trial on 12 Hawk aircraft ran from October 1981 until the beginning of 1985. The work in AST 603 included LCF calculation, assessment of creep and thermal fatigue and condition monitoring through gas path parameter analysis of limit exceedance for diagnostic purposes. A number of lessons learnt are detailed at reference 1 and AST 603 formed the basis of the EMS for Harrier GR5.

c. Air Staff Requirement 1943. Air Staff Requirement (ASR) 1943 became the basis of on-board calculations of LCF life used. The method has been a success, but the cost of retro-installation has, so far, precluded its use on any aircraft other than on those of the Red Arrows aerobatic team. Engines used by the team have been shown to have a variability in cyclic consumption of up to 16:1 for aircraft in different positions in the team's formation. Red Arrows engines are now lifed directly by using the Smith's Industries Low Cycle Fatigue Counter (LCFC).

4. CHOICE OF EQUIPMENT

In 1984 Rolls Royce were commissioned to carry out a study on behalf of MOD into the financial benefits that might have accrued by fitting various equipments for EHM to the Hawk and the Tornado. From this study the RAF considered the advantage of the existing EUMS fit against an additional fleetwide fit of an LCFC and then against a fleetwide fit of an engine monitoring system (EMS) which includes the same lifing facilities as the LCFC. The EMS used for the study was similar to that being procured for the Harrier GR5.

a. Hawk. The savings attributed to EUMS for Hawk were estimated over 15 years from 1982. Savings for LCFC and EMS were estimated for a 15 year remaining life of the aircraft, with an assumed start date of 1984. Actual and theoretical savings have been estimated as follows:

	Cost	Total Cost	Saving	Cumulative Saving
EUMS	1	1	45	45
LCFC	1.05	2.05 (EUMS+LCFC)	9	54
EMS	2.7	3.7 (EUMS+EMS)	7	61

All the above figures are in millions of pounds Sterling. From the cost and saving data, an LCFC fit would cost twice as much as EUMS but give only 16.5% saving beyond that attainable with EUMS. An EMS would give all the benefit of the LCFC, but would cost 270% more than a EUMS installation. It was clear to MOD that the return on investment fully justified the cost of EUMS on Hawk but 83% of the benefit had been obtained without making a further investment in LCFC. By tripling the cost, EMS could have been installed but EUMS had already given 74% of the potential total advantage. Now these deductions assume that EUMS would have been fitted regardless of the other solution chosed.

b. Tornado RB199. Assessment of cost effectiveness for RB199 was a different exercise because exchange rates from EUMS had shown that the design assumptions were reasonable. Tornado EUMS has contributed to enhanced flight safety as well as having assisted with logistic management. A reappraisal of the stress features and a reassessment of the data base for the engine lifing showed that there are substantial differences between operating units LCF exchange rates. The problem has been highlighted because of the present system which calculates lifing for all Mks and modification states of the engine in the same way. Studies are now in hand to see whether such a common life policy is safe and cost effective. To examine whether a fleetwide fit of an LCFC is cost effective needs the establishment of the baseline for savings. In the case of the RB199 this is not the highest exchange rate in the fleet, but the acceptance that flight safety has been confirmed and that the logistic element of critical component lifing can be tackled in the fut re. EUMS on Tornado cost £1.3M but the cost of a fleetwide fit of LCFC would have been £4.0M. For an expenditure on EUMS of 32.5% of the cost of an LCFC fit, a considerable flight safety benefit has been achieved. Based on Tornado EUMS results, we know that variability of LCF consumption would result in a cost saving on 25% of components. Currently, the exchange rates are based on a weighted average. From the report we have assumed that 25% of the saving would be spread over 2/3 of the fleet, but the remaining 1/3 of the aircraft would be found to be consuming LCF at twice the average rate. The forecast saving in the Rolls Royce report for LCFC was £48M. However the saving would drop to £20M if the variability of exchange rate were only 10%. Figures for both cases appear below:

Variability of usage	25%	10%
Saving RR Report	= £48M	£20M
MOD estimate Likely saving	= 2/3 x 48 - (1/3 x 48)/2	2/3 x 20 - (1/3 x 20)/2
	= £24M	£10M

These figures assumed the actual saving will be abated over 1/3 of the fleet because for those aircraft the exchange rate is higher than for the majority. Hence, a return on investment of between 2 and 6-fold could be made through a fleetwide fit of LCFC despite the advantages already accumulated through EUMS. Unfortunately, this calculation assumed that the modifications for an LCFC could be implemented quickly for the aircraft fleet; this is often not the case.

5. PARTS LIFE TRACKING

Since the study, referred to above, the advantages of the Engine Structural Integrity Programme (ENSIP), detailed in reference 3, have been evaluated. In addition we have found that variability of engine cyclic usage in the Tornado Fleet can be as high as 5 times for some components. One of the major features of the ENSIP approach is the requirement for a life management plan including a parts life tracking (PLT) record for individual components. The RAF has not tracked the life of individual components other than on the basis of "lowest life part gives the life of the engine or module". Calculations from EUMS showed that the variability on intermediate pressure compressors (IPC) was particularly high for different roles of the aircraft. A poor logistic position for the components led to the entire fleet being reassessed to see if some components could have life extensions. This resulted in some 200 hours per component being clawed back on some 300 IPC. This was equivalent to a saving of 60 IPC, represented a considerable financial saving and led to the concept of the fleet based exchange rate as opposed to the more usual common exchange rate.

The advantage of this method of lifing cannot be realised unless a safe appreciation of variability and its causes is obtained for a fleet of aircraft. In hand is a study of the causes of variability, using the EUMS data base, together with a study to show how often parts move between various operating units. Fleet-based exchange rates can only be operated after statistically sound levels of data are available from each operating unit. It has been found that after 100 sorties have been recorded for a role or unit, the exchange rate tends towards a constant value. This true value can take some time to emerge, particularly where training squadrons change role to operational duties. Thus it is necessary to continue recording, to guard against small changes in usage or tactics which can substantially affect exchange rates and the logistical position for the engine. As a result, it has been proposed to increase the number of EUMS aircraft on the Tornado Fleet to 60 (from the 15 in procurement) so that each group of aircraft has 10% with EUMS fitted. The cost of retro-fitting the aircraft will be recovered in the first year's full saving which has been estimated at £3M. The total saving over the remaining life of the aircraft should amount to some £60M.

The first RAF aircraft to have an individual engine monitoring system (EMS) will be the GR5 Harrier. This will therefore be able to give the life of individual components against the engine usage. The RAF has insisted that the lifing with the EMS should be executive from the introduction of the aircraft to service. The changes in aircraft configuration make estimates of saving against the equivalent costs for the GR3 Harrier an unfair comparison.

6. THE CASE FOR RETRO-FIT

The cost of individual health monitoring equipments is comparatively low. Unfortunately, the same is not true for the parallel aircraft modifications. In paragraph 4 the Rolls Royce cost effectiveness study seems to have considerable benefits available from a commitment to fitting LCFC or an EMS but a return on investment would have taken many years. Modification of a large fleet of aircraft can take up to 10 years in the RAF and this does not include the approval time for a new modification. Any life calculation method for individual engines would need to be implemented much more widely to show a return on investment and attract the interest of military financiers. The benefit for a retro-fit of part of the Tornado fleet with EUMS has been compelling for 2 reasons:

a. The EUMS modification for the aircraft already exists and would not have to be subjected to an approval procedure involving other Nations in the Tornado programme.

b. There are a number of aircraft in engineering programmes, including major modification that could have the EUMS modification embodied within a reasonably short timescale.

Other than for a compelling flight safety reason, the RAF is unlikely to retro-fit a fleetwide engine monitoring system. This has only occurred once in the RAF and that was for the installation of the LCFC on the Red Arrows Aerobatic Team, this is discussed in greater detail at paragraph 3.

7. AERO-ENGINE INFORMATION MANAGEMENT

The high cost and the in-service support cost of the Military aero-engine has led to a need for a system of management for engines within the RAF. The disposition and serviceability status of all engines and modules is monitored very closely by the Supply Aero-Engine Records Office (SARO) at MOD Harrogate. With the introduction of modular aero-engines the amount of data flowing into SARO increased dramatically, to the point where normal telex status reporting and manual input were slow, manpower intensive, and prone to error. The modular policy generated a significant increase in the in-service strip and build of aero-engines, and modular aero-engine maintenance documentation was also found to be an order of magnitude greater than that of the earlier non-modular types.

Better handling of increased levels of engine data and the need to overcome some of the high paperwork overheads has led to a much greater use of computer data communications. the close management of engine assets, accompanied by the use of sophisticated mathematical modelling of spares requirements, ensures that whole-item and spares purchases are kept to an absolute minimum. Much of the data for the management process is captured daily by high-speed data links and now development is underway to extend the on-line data transfer of logistic, usage and configuration histories between the RAF and industry. As the number of modular engines increases, and industrial repair and overhaul becomes subject to fixed price contracts, there is a greater need for engine data by industry. Future engine requirements dictate that high quality, resilient data handling networks should exist.

8. NEW AIRCRAFT PROGRAMMES

It is RAF policy to fully implement condition based maintenance and include the provision for EHM within the EUCAMS structure for all future aircraft. There are a number of aircraft coming into RAF service or at the requirement stage, and all of these aircrafts have engine monitoring requirements. The complexity and use of the systems varies depending upon the specific aircraft and role. The following briefly describes the systems:

a. Tristar. The Tristar in RAF service has a system called the Aircraft Integrated Monitoring System (AIMS). Working continuously, AIMS records flight data which is processed in a ground computer for EHM, auto pilot performance and aircraft operational performance. It has been shown that LCF calculation and automatic exceedance detection are cost-effective for this application.

b. BAe 146. The aircraft of the Queen's Flight are fitted with the Smith's on-board Engine Life Computer (ELC). Gas path performance monitoring of the aircraft engines will permit on-condition monitoring. The ground-based computer for storing ELC data will eventually be used for lifing critical components in the engine.

c. Harrier GR5. The Harrier GR5 Engine Monitoring System (EMS) uses on-board processing to record engine usage. Engine parameter limit exceedances are automatically identified and recorded in a solid state memory. A Data Retrieval Unit (DRU) is used to extract engine information from the EMS at the end of the flying day. Data can be displayed to the groundcrew at the aircraft, but the display of trend patterns requires the support of a ground-based data processor. The on-board system has a performance snap shot at each take-off and it is still being considered whether automatic diagnostic routines should be triggered by certain exceedances.

d. Tucano. The Tucano has an integrated monitoring system for its systems and this includes engine information.

e. European Fighter Aircraft (EFA). The requirement for engine monitoring in EFA was given in the European Staff Requirement (ESR) for the aircraft. The EFA system will be very different from previous systems, but the experience gained during AST 603 and the Harrier EMS should be included in the proposal made by the aircraft and engine supplier. It is well known that stress levels in EFA engine components will dictate that damage tolerant criteria will have to be employed for lifing. This dictates some of the recording requirements for the engines since an accurate account of usage is required. In addition, to get a reduced cost of ownership, there should be a comprehensive condition monitoring programme for the engine.

f. E3A-Sentry. It is RAF policy to maintain the E3A engines on condition. MOD staffs are in the latter stages of negotiating for the installation of a suitable system before the aircrafts are built.

g. EH-101. The requirement for the EH-101 utility version includes statements on the inclusion of an engine monitoring system.

9. CONDITION BASED MAINTENANCE

There are a number of activities that can be carried out prior to service entry of an engine and contribute to the effective maintenance of the engine. Such activities can contribute to the effective introduction of an EHM and make the monitoring system credible with our experienced tradesmen. The following are 2 important areas for action by engine suppliers:

a. Accelerated Mission Testing (AMT) and Data Base Information. The RAF has embraced ENSIP detailed in reference 3 and the testing and AMT involved with the ENSIP methodology will ensure that a data base of information is available at service entry. Advantage should be taken of this information to compile rules to assist the diagnosis of probelms for early flying. If the operator is forced to use such a data base from the outset of a new programme there is every possibility that the methods will be better accepted by experienced tradesmen.

b. Reduction of Manpower and Training. Comprehensive EHM can help with diagnosis and reduce the time spent in trouble-shooting engine problems. Given an on-line transfer system for information, it should also be possible to create an instant update of diagnosis information at the operator's level. This concept requires training in the facilities available and their use. In addition, manufacturers of engines and EHM systems should allow for the cultural changes in maintenance that such developments in information technology imply. Inevitably, the more experienced technicians will be more used to traditional maintenance methods and they may not take kindly to diagnosis by a ground-based computer. Eventually such changes will result in down-skilling at squadron level.

10. CONCLUSION

The RAF needs EHM to help to improve flight safety, enhance aircraft availability and achieve reduced support costs. The majority of the UK experience in EHM has been based on component lifing enhancement and this has been the area in which the majority of the cost savings have been achieved. The goals of a programme and the choice of equipment are a major factor in any return on investment that is possible with EHM. For aircraft types that are already in service it has been shown that sampling of aircraft usage gives the maximum return on investment due to the cost of aircraft fleet modifications. It is RAF policy to install fleetwide condition monitoring systems for engines because of the ease with which equipment can be installed during aircraft build. The individual lifing of aircraft parts and aero-engine information management are areas in which the RAF is now gaining experience. Aero-engine information is a topic that has greater scope for development due to the need for the creation of information interfaces between the supplier of the engine and engineering and logistic agencies within the service. The RAF is embarking upon a number of aircraft programmes which include a variety of EHM equipments, there will be scope for reports on the progress of these programmes over the next few years. It will be necessary to monitor the programmes to ensure that the monitoring technology we espouse gives the required return on investment and that the methods are suitable for use within the cultural environment of the RAF. Training and understanding at all levels within organisational maintenance are the key to the success of condition monitoring leading to predictive maintenance.

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CANADIAN FORCES AIRCRAFT ENGINE CONDITION/HEALTH MONITORING - POLICY, PLANS AND EXPERIENCE

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ABSTRACT

The paper highlights current Canadian Forces (CF) policy with respect to aircraft Engine Condition/Health Monitoring (ECM/EHM). In doing so a summary of CF aircraft types and the ECM/EHM techniques applied to each is presented. The paper reviews the CF's experience to date with the development and application of ECM/EHM techniques. This includes an examination of the effectiveness of the CF's Spectrometric Oil Analysis Program and the use of magnetic particle detectors and manual performance trending.

The paper goes on to present plans for further development and implementation of policy, methodologies and techniques and for the integration of these into an effective ECM/EHM capability that will pay benefits both in terms of life cycle costs and operational availability.

INTRODUCTION

Engine Health Monitoring (EHM) is defined as the collection, analysis and use of many types of data relevant to the mechanical or thermodynamic health of an engine which will assist in its operations, maintenance, management, design, safety and logistics. In the Canadian Forces (CF) the custom has been to use EHM rather than Engine Condition Monitoring (ECM) to label this discipline. The acronym EHM is used in this paper in the sense defined above and does not represent any specific recognized engine monitoring program.

The concept of EHM is directly related to the maintenance requirement of an aerospace propulsion system. Its origin dates as far back as the piston engine era and its evolution has mainly paralleled advancements in the field of the gas turbine engine (1). Military EHM programs have been paced largely by cooperative development programs between the US and UK military operators and the engine manufacturers. In Canada, EHM has been an element of aircraft maintenance for some three decades concentrating, until recently, on a short term monitoring approach, using limited semi-automated and manual monitoring techniques (2).

With the extension of the service life of many of its aircraft fleets and the progressive implementation of the concepts of On-Condition Maintenance (OCM), the CF has been exploring new monitoring approaches through research and development (R&D)[1] in the fields of EHM and engine life usage management. The CF is presently sponsoring R&D efforts in the field of on-line oil monitoring, vibration analysis and other engine monitoring techniques to gain the required knowledge and expertise to face the years ahead. Furthermore, EHM activities will increase with the procurement of new shipborne, transport, Search and Rescue (SAR) and light helicopters. The New Shipborne Aircraft (NSA) program has already taken a lead through its requirement specification (3). The specification calls for a condition monitoring program to provide the necessary support to effectively make rational decisions with respect to flight safety, preventive and corrective maintenance, life cycle maintenance and logistic support.

This paper reports on the present CF policies related to EHM, and the effectiveness of current EHM techniques as applied to CF aircraft engines. The paper also looks at the future of EHM in the CF concentrating on the on-going R&D programs and future policies.

CURRENT CANADIAN FORCES POLICIES RELATED TO EHM

The CF Aircraft Maintenance Policy is defined at reference (4). Present EHM policies are techniques specific and address spectrometric oil analysis (5) and non-destructive testing (6). A future vibration analysis policy is presently undergoing review. Techniques such as filter debris analysis, performance trending, magnetic particle detection and some others have been used on a requirement basis, usually at the recommendation of the engine manufacturer, but their use has yet to be covered by formal policies. The major factor having led to this situation has been the large variety of engine types in the CF inventory (see Table 1) and the maintenance concept employed with them.

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1 This R&D has been conducted primarily through the National Research Council of Canada (NRCC) with specialist support from GasTOPS Ltd. Funding for R&D efforts, since 1982, has been provided through the Department of National Defence's (DND's) Chief of Research and Development.

A number of developments have led to the requirement to establish an overall EHM policy for the CF which would eliminate the fragmented approach used to date. First, the trend towards extending time between overhaul for old engines as well as the introduction of OCM as a maintenance concept for new engines has made EHM a key maintenance support factor for engine life cycle managers. Second, the NSA powerplant maintenance concept will rely on an advanced health monitoring program which is presently in the definition phase. This EHM program will form the basis for other acquisition projects and will require the CF to formalize and integrate its approach to EHM. Third, the CF is presently revising the long term plan for the Aerospace Maintenance Development Unit (AMDU) which will establish at the unit a CF center of expertise in EHM. Part of AMDU's present tasks are to develop techniques and procedures for EHM, assess those developed by contractors, and provide training in those techniques. In its expanded role AMDU will impart the knowledge gained through such activities to the field units. They will also develop the methodologies and procedures to ensure EHM is successfully applied in the field.

EHM development programs are monitored at National Defence Headquarters through a Propulsion Working Group. This working group is presently defining an EHM policy to become an integral part of the CF engine life cycle management.

EFFECTIVENESS OF CURRENT EHM TECHNIQUES
USED IN THE CANADIAN FORCES

The effectiveness of present EHM techniques has been analyzed through engine data obtained from engine life cycle material managers, the AMDU, flight safety records and the CF Aircraft Maintenance Management Information System.

OIL MONITORING TECHNIQUES

Spectrometric Oil Analysis

Spectrometric Oil Analysis (SOA) is carried out on 36 different aircraft component types, 15 of which are engines. The technique consists of taking oil samples periodically for analysis at an area SOA laboratory. In the CF there are eight SOA laboratories; one in Germany and seven located across Canada. These laboratories carry out the analysis of some 30,000 oil samples a year. Atomic Emission (AE) spectrometry is used to analyze the oil; 10 elements are measured simultaneously and the wear metal levels are given in parts per million for each element.

This technique provides quantitative information on the amount of the different wear metals in the oil which allows the identification of abnormal wear. Also, knowing the material composition of each engine's oil wetted components usually permits the identification of the faulty component. The technique is limited by the particle size produced, failure mode, filter size, and engine design. Because AE spectrometry only has a good response to particles up to five microns in size, any larger particle produced will not be measured accurately. Thus SOA is not effective in cases of failure by fatigue which usually produces large flakes. The use of very fine and effective filtration systems in new engine designs is a major limitation for SOA because almost all particles produced due to abnormal wear or failure are removed on the first pass through the filter leaving little wear debris in the oil. The effectiveness of the CF SOA program has been quantified in two different ways. The first consists of calculating the proportion of SOA recommendations confirmed by a failure or abnormal wear. The second consists of calculating the proportion of failures involving oil wetted components for which there was a SOA indication.

Using the data produced by AMDU in the last five annual SOA program reports from 1982 to 1986 inclusive, it was determined that 90% of all the SOAs recommending corrective maintenance action on engines were confirmed cases of significant component degradation. If the data from the other component types, ie, gearbox, accessory drive, APU, etc, are included, the proportion dropped to 84%. These numbers indicate that the SOA recommendations are reliable.

The records on four types of engines and two gearboxes have been reviewed to assess the proportion of failures where SOA indicated a problem. The results are provided in Table 2. The study shows that SOA effectiveness is dependent on engine design, filter size and failure mode. For the CT-64 and T-400 engines it is to be noted that there is a common oil system for the gearbox and engine. This reduces the apparent effectiveness of SOA for these engines because the exact location of the faulty component becomes more difficult to determine. This results in having both components removed and sent to the contractor for investigation and/or repair. For the T-55 and T-58 engines, the relatively good SOA effectiveness is mainly due to the oil filter size which is large enough to leave sufficient wear debris in the oil. Due to the periodic nature of SOA program sampling, rapidly developing failures can proceed to the point of detection by other means in the period between samples.

Magnetic Particle Detectors

Magnetic Particle Detectors (MPDs), which include both magnetic and electric types, are in use within the CF in several different types of engines and have performed with various degrees of effectiveness. Depending on the aircraft type and engine configuration, MPDs can be located in the main power section oil return line, the reduction gearbox or main transmission system. The system may have a warning light in the cockpit or may provide a warning indication through a continuity check done on the ground. The periodicity of this check varies from once each flight to every hundred hours.

MPDs have been useful in detecting the initial stages of internal breakdown of gears, bearings and other oil-wetted components. They have, however, been susceptible to false alarms caused by a build-up of normal wear metal across the detector or by electrical malfunctions. In certain aircraft types, special pilot-activated "fuzzbusters" have been used to burn off non-critical sized wear metals thereby reducing the number of false alarms.

The results of a limited study on MPDs used in CF aircraft is reported in Table 3. Some observations on these are as follows:

a. MPD success rates vary widely depending on the detector location and whether or not it is equipped with a fuzzbuster. For example, the CH135 Twin Huey helicopter has a very low detection success rate for the engine (19%) but a relatively high success rate for the gearbox (66%). A prototype fuzzbuster has shown the potential for a significant reduction in the false alarm rate for this aircraft.

b. For those aircraft for which there have been few occurrences, the average success rate is 60%. An exception to this is the CH124A Sea King helicopter, which even though it is equipped with a fuzzbuster, has experienced only an average success rate. This can be attributed in part to excessively large fuzz associated with the breaking in of the new transmission.

c. In helicopters such as the CH113A Labrador, and CH118 Iroquois (Single Huey), where there is already a very low occurrence rate, the value of installing a "fuzzbuster" is questionable.

For fixed wing aircraft, MPDs have been used without a cockpit indicator (except for the CP140 Aurora) and have proven to be a simple and effective maintenance tool.

In summary, MPDs have played an important role in preventive maintenance and have contributed greatly to the flight safety of CF aircraft. They have been useful for detecting gearbox and engine problems, and have been employed in conjunction with cockpit indicators in all CF helicopter types. In general their effectiveness has improved when used in conjunction with a fuzzbuster.

Vibration Monitoring

Vibration levels have traditionally been seen as a measure of the mechanical health of a machine. Vibration Monitoring (VM) is carried out on a limited number of CF turbo-jet and turbo-fan engines. Monitors provide continuous readouts of vibration at selected pick-up points. These monitors are read periodically during flights and the vibration levels trended and/or compared to established limits. The application of vibration monitoring on the CF engines is specific to each engine type both in flight or in the test cell.

On the F404 engine only one accelerometer per engine is used for in-flight monitoring while three are used in the test cell. In flight, the accelerometer is constantly and automatically monitored by the In-flight Engine Condition Monitoring System (IECMS). If the predetermined limit is exceeded, there is a maintenance code produced for the flight line technician's use. To date the system has not functioned up to expectations. When there is a vibration limit exceedance, it must be corroborated by the pilot or another related malfunction indication before any maintenance action is undertaken. The engine is then removed and sent to the test cell for confirmation and/or troubleshooting. To date, none of the engines removed because of in-flight vibration level exceedance have been rejected when tested in the test cell. Vibration monitoring has not led to substantial results in detecting mechanical degradation on the F404.

On the JT3D engine, the application is somewhat different. There are two velocimeters on each engine with monitors in the cockpit that are observed periodically during flight to detect significant vibration changes. The readings are taken at stabilized thrust settings and trended. No specified limits are provided. If, at any time, with a stabilized thrust setting, a rapid increase in vibration level and other abnormal engine indications are observed, the thrust of the affected engines must be reduced. If the thrust reduction does not return the vibration level to the previous value or if engine abnormalities persist, the engine is shut down. To date, however, no engine removals have been the direct result of in-flight vibration indications. The problem most often has been found in the monitoring system itself.

Vibration Analysis

Vibration Analysis (VA) was introduced in the air element of the CF as a diagnostic tool for engine problems in the late 70's. While continuous vibration monitoring may be used to indicate general machine condition, through a frequency content analysis of vibration signals it is possible to isolate a troublesome component. Mass imbalances caused by FOD damage, blade loss or bearing failure can be detected by properly mounted transducers. Lesser damage such as misalignment or deterioration of bearing condition may also be uncovered. The technique was successful in solving dynamic and engine problems on the CH124A and CH113A on numerous occasions as reported by Dubé (7).

CF experience has indicated that the hardware technology used in VM/VA is not yet reliable enough to be an effective tool, and secondly, the retention of knowledgeable and experienced technicians to interpret VM/VA results correctly is very difficult.

Performance Trending

It is recognized that the performance of gas turbine engines decreases with the accumulation of operating hours due for example to erosion and fouling. The CF has four engine types on which trending is carried out.

The T400-CP-400 engine on the CH135 Twin Huey helicopter has a power assurance check carried out before the first flight of each day during which N_G and ITT are recorded. Using these data, engine bay personnel produce a trend chart that is maintained as long as the engine is installed in the aircraft. By monitoring this chart, it has been possible to detect when a compressor wash or hot section inspection is required.

Similarly, for the PT6A-27 engine in the CC138 Twin Otter aircraft, Tq, ITT, N_G and W_F are recorded in flight by the flight engineer. These figures are reduced and computed by the maintenance control and records section who then produce trend charts for these parameters. From this information it has been possible to confirm such faults as dirty compressors, bleed valve irregularities, FOD-damaged compressors, hot section problems and dirty fuel nozzles which had been originally detected by other means.

The JT3D-7 engine in the Boeing 707 has four different parameters, N_1, N_2, EGT and W_F, recorded in flight. These data are plotted on trend charts by engine bay personnel and then forwarded to Pratt and Whitney Canada for interpretation. However, there has often been little or no feedback to the engine bay personnel to assist them in engine diagnostics.

The CF-18 Hornet has the capability to record 13 engine parameters continuously to a magnetic tape cartridge. The data from these tapes form the major contribution to the F404 trending program which is currently under development.[2] A prototype of this trending program was trialed in the field from 1985 to 1987. It involved performance test ground runs every 25 flying hours. Performance data were measured in a specific data capture window based on the engine pressure ratio. This approach was abandoned for two reasons. First, the process of down-loading data from the tape and processing them was cumbersome. Second, the cost in man-hours and aircraft downtime associated with the frequent ground-runs was significant.

In summary, the CF experience with the application of existing EHM techniques has been mixed. This has been due to the complexity of some of the techniques and the difficulty in providing well trained, experienced technicians to apply the techniques. As well, a general policy providing direction to the field and the identification of resources required has been lacking.

LOOKING AHEAD

This part of the paper looks ahead at EHM from a CF viewpoint. The status of the present R&D program is reported along with some projections of future applications.

ON-GOING DEVELOPMENT

On-Line Wear Debris Monitor Testing

DND is involved in a testing program of an on-line wear debris monitor soon to be installed on two CC115 Buffalo aircraft. This device, called Ferroscan(R), was developed by Atomic Energy of Canada Ltd (AECL) for determining the concentration of suspended ferromagnetic particulate material in CANDU reactor heat transport systems (8). DND has since funded work by AECL oriented towards the modification of the device so that it may be used to measure ferromagnetic wear debris in the lubrication systems of propulsion engines. This device provides continuous quantitative output as well as a wide detection range of particle size from less than one micron to greater than 1,000 microns. Consequently, the gradual deterioration of oil wetted components can be monitored and maintenance planned accordingly.

Ferroscan(R) has been successfully tested on a helicopter tail rotor gearbox and on a T-56 engine mounted in an engine test cell (9). A flight trial on the Buffalo aircraft with its CT64 engines is about to get underway. It is scheduled to last four months during which time data will be gathered by an on board micro-controller. This data will be compared with data derived from other currently used oil and debris monitoring techniques in order to assess its accuracy and reliability.

Filter Debris Analysis

As filter mesh sizes become smaller, methods such as SOA and ferrography are expected to become less useful. Consequently, in addition to on-line wear debris monitoring, Filter Debris Analysis (FDA) is anticipated to become increasingly important in CF EHM. DND scientists have been conducting extensive research into the use of FDA as a method of determining wear rates of oil wetted components. In particular, methods for determining the exact constituents in the wear debris collected on filters are being developed and tested. For example, a data base is being established for the F404 and CT-64 to allow correlations between FDA determined oil debris constituents and the condition of various oil-wetted components. A similar initiative for the CH124A Sea King engine and transmission is presently underway.

SOA Applications

Although the overall experience with SOA has been mixed, the CF is continuing to develop and enhance its SOA program for those engines and components where SOA has demonstrated to be effective. For example, Spectroil Junior(R) portable emission spectrometers are being introduced into service to support aircraft such as the CH124A Sea King helicopter during deployed operations. This device is used for on-site oil analysis of up to 10 different wear metals simultaneously. However, on-line wear debris monitors threaten to replace SOA as the optimum oil monitoring technique for many engines and components since 95% of the total debris in many cases is ferromagnetic. SOA will likely continue to be relied upon for the oil monitoring of components where there is a high probability of non-ferrous wear debris being produced.

Vibration Analysis

A project investigating the use of VA for diagnosing engine problems is being conducted at NRCC. NRCC staff are evaluating the use of currently available systems for VA. Various signal conditioning and data handling methods will also be developed in collaboration with industrial partners. Current work is

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2 See paper by Muir, Rudnitski and Cue

oriented towards identification of the vibration signatures associated with specific engine faults. In particular, these fault signatures are being characterized through a process of introducing seeded faults in test rig studies and on the T56 and F404 engines. Among other phenomena, rotor imbalance and bearing damage effects will be investigated. In addition, further analysis of signal conditioning and analysis methods is being carried out including developments which should make possible the isolation of actual mechanical faults from vibration data. Finally, a prototype system, appropriate for field application, will be demonstrated.

Performance Trending

NRCC staff are examining the efficacy of various gas turbine engine GPA techniques as they relate to thermodynamic performance and fault diagnosis. It is intended to establish diagnostic algorithms based upon a library of fault signatures to be established experimentally (through implantation of specific engine faults). In this way, it is hoped to be able to develop computer simulations of both healthy and problematic engines. Currently, work underway is aimed at determining the changes in thermodynamic performance of an engine as a result of specific faults. The experimental studies will make use of the F404, T56 and J85 engines currently at the NRCC Engine Laboratory.

NRCC staff are also conducting an examination of experimental performance assessment techniques as they relate to the aforementioned study. It is hoped that a more precise determination of measurement accuracy in basic instrumentation as well as the development of more automated test cell equipment will be achieved. Generally, this project is also aimed towards developing more accurate and reliable sensors and test methods, in particular non-intrusive sensor techniques. It is also NRCC's intention to investigate better methods of data acquisition and calibration of equipment. Application will initially be on engines installed in test cells and eventually on engines installed in aircraft. The investigations are focussed mostly on steady state operation with some work on transient data analysis as well. In the future there will be an increasing emphasis on the use of data collected during transient operating condition found in actual operation while continuing to work with steady state data as well.

Expert Systems applied to Engine Monitoring

With the support of DND, NRCC is in the first year of a three year project to develop. demonstrate and evaluate the use of knowledge-based and expert system for fault diagnosis. A technology demonstration of a system for use with the J85 engine is slated in December 1988; the application will be for the troubleshooting of engine faults during functional and performance tests. In the second year, the methodology and applications will be generalized for other EHM cases. The third year will see the application and evaluation of more advanced artificial intelligence and information processing technology. The emphasis will be to develop packages which could integrate the diverse and complex diagnostic methods and fault characterizations of the new EHM techniques, described previously. Such packages would be aimed at field operations in both training and actual maintenance.

CF5/J85 Loads and Engine Health Monitor

DND is funding the development of an on-board Loads and Engine Health Monitor (LEHM) for the CF5 aircraft. This system will include both EHM and structural condition monitoring (as well as information collection required for possible future parts life tracking development) and is intended to eventually be applicable to several aircraft in the fighter/trainer category. From an engine perspective, this work was initiated primarily to monitor the parameters relevant to understanding the J85-CAN-15 engine's stall propensity. It is currently planned that this package will gather data and flag exceedances only and that further fault detection and isolation will be carried out by ground-based software.

Leigh Instruments Inc were contracted by DND to define the requirement specifications for the LEHM system. This work was completed in late 1987 and is now to be followed by the development of a prototype system. It is anticipated that the prototype system will then be installed on a test aircraft at the CF's Aerospace Engineering and Test Establishment early in 1989 for flight and ground testing. If the test and evaluation program prove to be satisfactory the CF plans to initiate production of these units for fleet-wide installation in late 1989. The CF5 Freedom Fighter, CT133 Silver Star and CT144 Tutor are the most likely aircraft to eventually see installation of this system.

F404 Engine Fault Diagnosis and Performance Trending Procedures

GasTOPS Ltd, under DND contract, is working to establish three improved software tools designed for use in the field. The tools concern IECMS troubleshooting, Engine Test Facility (ETF) troubleshooting and data trending. A fault library is a basic part of the IECMS and ETF troubleshooting software. The data for the building of this fault library are being obtained from NRCC and are the result of their work noted in the section above on performance trending.

F404 In-flight Real Time Thrust Recorder System

Computing Devices of Canada (CDC) Lt' has been contracted to design a Real Time Thrust Recorder System (RTTS) to measure in-flight thrust on the F404. The RTTS will initially be used to facilitate flight testing of the CF-18 Hornet aircraft when investigations are carried out into the effects of new arrangements of external stores. However, by comparing measured thrust with that expected at a certain fuel flow rates, the operator may be able to detect degradation in powerplant performance and hence initiate the appropriate troubleshooting action. The potential for the application of the RTTS to EHM use will also be explored. CDC will report on the application of the RTTS to the CF-18 and then will define a CF requirement specification. A laboratory program at NRCC is planned for 1988 which will validate the RTTS concept and to study the possible reduction of the number of pressure sensors required. The CF are planning to have a RTTS installed for mid 1989. The development of this project is being funded by National Aeronautics and Space Administration and the Defence Advanced Research Project Agency in the United States, and by the Department of Industry, Science and Technology, and DND in Canada.

PLANNED DEVELOPMENT

General Policy on EHM

EHM has become the corner stone of OCM for gas turbine engines, leading to improved engine availability and airworthiness, and reduction in life cycle cost. The long term establishment of OCM as the main maintenance concept for aircraft engines will require a comprehensive and coordinated approach to EHM. Such a comprehensive EHM program will require dedicated specialist personnel to collect and collate engine condition data, analyze engine condition trends, and consequently make recommendations to flight line and engine bay technicians for action. Thus the fragmented approach taken with EHM policy to date will need to be changed. A general policy outlining direction and responsibility for the various tasks involved in EHM is being developed.

Studies Ahead

EHM systems available today are neither complete nor easily fitted on a variety of aircraft. These systems have been developed in response to a specific set of requirements for a particular aircraft (10). As well, these systems do not provide diagnostic capabilities beyond some simple alerts on-board and the ability to download recorded data to a ground-based computer for review. The data processing required in order to contribute meaningfully to the engine maintenance program is usually not addressed. It is believed that a comprehensive approach to EHM system design is needed, from data gathering on-board aircraft to a recommendation for maintenance action when problems arise.

With this in mind the development of a generic on-board Aircraft Condition Monitoring (ACM) system is presently under consideration. A design aim will be to provide a modular system, in order to provide maximum compatibility with all CF aircraft while providing the benefits of hardware and software commonality. This ACM system would be part of a comprehensive aircraft management system. The proposed system would consist of installed flight, structural and engine sensors, data acquisition, storage and processing hardware as well as a ground-based processing and diagnostic capability for engine, transmission and airframe condition and usage monitoring, performance trending, and prognosis. This system would be specifically designed for use by engineering, maintenance and logistics staff. This project is different from the CF5/J85 LEHM project described earlier in this paper in that the latter will initially be tailored to the CF5 aircraft specifically and will use contemporary hardware and software. The generic ACM system will be designed using a top-down approach. The conceptual design study for a multi-purpose EHM system has been completed (11). Lessons learned from the LEHM projects will be invaluable to the generic ACM system development.

Before commencing the aforementioned development project, DND will be performing several preliminary studies oriented towards determining the feasibility of this proposal and if warranted, defining the system requirements. This would include the determination of the most meaningful parameters to be monitored and the most appropriate methods to handle the data to allow effective OCM.

While the activities described above are underway, a related study will be undertaken with the objective of determining the long term cost effectiveness of EHM generally. The program will involve the installation of off-the-shelf engine monitoring hardware to selected aircraft. The data provided by the on-board system as well as other sources will be reviewed on an on-going basis by specially trained technicians who will recommend corrective maintenance actions as required. Following a three year trial period during which detailed records will be kept on all cost and benefit parameters, the overall effectiveness of this approach to engine maintenance will be assessed.

As in the case of the generic ACM development project, the EHM trial is being preceded by a feasibility study and a project definition study. The aim of the former study is to determine whether an effective and meaningful aircraft gas turbine EHM trial program can be carried out with currently available "off-the-shelf" EHM equipment on contemporary CF aircraft. Should such a trial prove feasible, the latter study's aim will be to establish the overall definition of the work including the project's schedule, cost, structure and recommended EHM related equipment and CF aircraft. The feasibility study is currently underway.

Aircraft Acquisition Programs

As in the past, new aircraft acquisition programs will import new monitoring technologies into the CF. The condition monitoring requirements for the NSA air vehicle have been specified early in the program (5, 12). The specific objectives of the NSA engine condition monitoring program are to improve flight safety, track and record the engine health and usage, and provide troubleshooting and diagnostics capability. The Canadian Forces Light Helicopter, the New Transport Helicopter and the New SAR Helicopter acquisition projects are more likely to take the same approach to EHM as for the NSA from both hardware design and system engineering viewpoints.

CONCLUSIONS

In conclusion, the CF's approach to EHM policy setting, implementation an. development has been technique specific. Individual techniques have often been implemented in a hit and miss fashion with no reference to the other techniques used on the same aircraft or other available techniques. The establishment of a comprehensive EHM program which coordinates the application of each technique thus permitting the strengths of one to offset the weakness of another is an important goal of the CF. Although development will continue on specific techniques, priority will be placed on the formulation of a general policy for EHM, the building of a center of expertise at AMDU and the development of the previously mentioned comprehensive EHM program.

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LIST OF SYMBOLS

ACM	Aircraft Condition Monitoring
AE	Atomic Emission
AECL	Atomic Energy of Canada Ltd
AETE	Aerospace Engineering Test Establishment
AMDU	Aerospace Maintenance Development Unit
CANDU	CANadian Deuterium Uranium
CDC Ltd	Computer Devices of Canada Ltd
CF	Canadian Forces
DMS	Data Management System
DND	Department of National Defence
ECM	Engine Condition Monitoring
EGT	Exhaust Gas Temperature
EHM	Engine Health Monitoring
ETF	Engine Test Facility
FDA	Filter Debris Analysis
FOD	Foreign Object Damage
GPA	Gas Path Analysis
IECMS	In-flight Engine Condition Monitoring System
ITT	Inlet Turbine Temperature
LEHM	Load and Engine Health Monitor
MPD	Magnetic Particule Detector
N_G	Gas Generator Speed
$N_{1,2}$	Low, High Pressure Compressor Speed
NRCC	National Research Council of Canada
NSA	New Shipborne Aircraft
OCM	On-Condition Maintenance
R&D	Research and Development
RTTS	Real Time Thrust recorder System
SAR	Search and Rescue
SOA	Spectrometric Oil Analysis
Tq	Engine Torque
UK	United Kingdom
US	United States (of America)
VA	Vibration Analysis
VM	Vibration Monitoring
W_F	Fuel Flow

Table 1 - CF Aircraft Engines and EHM Techniques

Techniques		F404	CT64-820-3	R1820-82MR5	JT3D-7	PT6A	CF34	T56	J-85	ALFM 502L-2C	CF700-2D-2	T400-CP-400	T53-L-13B	T-58-GE-8F	T-63-A-700B	C-20B	PW-120
Oil Monitoring	Spectrometric Oil Anal.	(1)	x		x	x			x	x		x	x	x	x	x	x
	Filter Visual Inspection	x	x	x	x	x			x			x	x	x	x	x	x
	Filter Debris Analysis	(2)	(2)									(3)	(3)				
	Magnetic Particle Detect.	x	x	x			x	x	x	x		x	x	x			x
Vibration	Vibration Monitoring	x	(4)		x		x		(4)	x							
	Vibration Analysis													(4)			
Performance Degradation	Gas Path Analysis	(5)			x	x						x		x	x	x	x
	Performance Runs	(5)	x		x			(6)	x	x	x	x	x	x	x	x	x
Other Techniques	Borescope Inspection	x		x	x	x	x	x	x	x					x	x	
	Hot Section Inspection	(7)					x	(8)	x	x	x	x	(9)	x			

(1) One third of the fleet on 20 hrs sampling frequency; remainder on 100 hrs
(2) Under development at Defence Research Establishment Pacific, Victoria, BC
(3) Carried out by contractor
(4) On test cell only
(5) Under development
(6) T56A-14LFE only
(7) Through boroscopic inspection
(8) T56A-7B and T56A-14LFE
(9) UN aircraft in Sinai only

Table 2 - Some SOAP Performance with CF Aircraft Engines and Gear Boxes

Aircraft, Engine and Gear Box Types	No. of Unsched. Removal Involving Oil-wetted Components	Prime reason for removal				Secondary Indication			Success Rate
		SOA	Filter	Mag. Plug	Other	SOA	Filter	Mag. Plug	(%)
CC-115 CT64-820-1	9	2	1	0	6	1	0	0	33
CH-135 T400-CP-400	2	0	0	1	1	0	0	0	0
CH-147 T55-L-11C	6	1	0	1	4	2	0	0	50
CH-113/-124 T58-GE-8B/F	17	5	0	0	12	3	1	0	47
CC-115 Speed Decreaser Gearbox	22	3	6	1	12	1	2	0	18
CH-135 Reduction Gearbox	10	2	2	1	5	0	0	2	20

Table 3 - Some Experiences with MFD's in CF Aircraft (1 Jan 85 - 31 Dec 87)

Aircraft and Engine Types	Cockpit Indica'n	Fuzz-busster	Engine Experience			Gearbox Experience		
			Occur-rence	False Alarm	Success Rate	Occur-rence	False Alarm	Success Rate
CP-140 T56-A-14LFE	yes	two proto-types	17	11	35%	31	11	65%
CH-113A T58-GE-8F	yes	no	nil	nil	n/a	2	2	0
CH-118 T53-L-13B	yes	no	1	nil	100%	nil	nil	n/a
CH-124 T58-GE-8F	yes	yes	nil	nil	n/a	19	8	57%
CH-147 T55-L-11CS	yes	half fleet modified	4	nil	100%	8	3	63%
CH-136 T63-A-700	yes	half fleet modified	8	3	63%	6	3	50%
CH-135 T400-CP-400	yes	One proto-type	16	13	19%	6	2	66%
CH-139 250-C20B	yes	yes	2	0	100%	0	0	n/a

DISCUSSION

G. XISTRIS

1. What type of training does the airforce provide to the vibration analysis personnel?

2. The EHM policy statement referred in your paper, is it intended for the promulgation to the airforce only or for all elements of the Canadian Forces?

Author's Reply:

1. No special training is provided to personnel in the use and interpretation of Vibration Monitoring (VM) data. The only guidance provided is that included in technical orders for each aircraft.

Training and Vibration Analysis (VA) is provided at two levels. Officers and non-commissioned officers attend a one week workshop in Advanced Dynamic Analysis provided by Scientific Atlanta. Technicians take one week course given by Aerospace Maintenance Development Unit specialists. The course cover VA policy and theory, operation of VA equipment and diagnosis.

2. The EHM policy referred to is intended to apply to the maintenance of aircraft gasturbine engines only and not to those operated by other elements of the Canadian Forces.

H. SARAVANAMUTTOO

What is the delay between the sampling and the transmission of the result of the SOAP analysis to the operator?

Author's Reply:

The turnaround time is very quick and never exceed 24 hours.

ON BOARD LIFE MONITORING SYSTEM TORNADO (OLMOS)

by

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1. Introduction

The "Onboard Life Monitoring System" of the GE Tornado was introduced mainly because of one reason, saving costs during the entire using phase of the Weapon System, by better utilization of the inherent life of airframe, structure and engine. Using the flight hour as a measurement for material usage, the disadvantage is obvious. The real material fatigue can not be measured or calculated without knowing the various material stress levels for airframe and engines. Therefore in military aviation it is very important to know about the individual fatigue history of aircraft to safe costs and improve flight safety.
The personnel situation in the service does not allow the introduction of new systems, that are intensive in manpower. Therefore it is very important that any "On condition Monitoring System" shall improve the "Trouble Shooting" and other maintenance routine work as well. To extract data from the Aircraft shall not increase the down time of the Aircraft and shall not lengthen the Operational Turn Around.
The main challenge therefore is the harmonization of On condition Maintenance principles with the personnel structure in the service and the existing maintenance and repair levels.

2. Technical Requirements

2.1 Technical Baseline

The Tornado Aircraft was already in existence, when the requirement for a "Maintenance Data Evaluation System" was finalized. The Crash Recorder System with the Data Acquisition Unit as the keycomponent was the baseline to start from. This System should be supplemented by a Maintenance Recorder, recording maintenance relevant data, which should be evaluated after flight, using a ground based computer.

2.2 Technical Innovation

The development of more powerful, faster and smaller electronic components was the main reason to take "On board processing" into consideration. The existing Crash Recorder System should be the basis for an "On board Life Monitoring System" .The new functions should be incorporated, and no additional Electronic box (LRU) should be installed in the Aircraft (beside tape recording devices, where provisions were already installed). The Data Acquisition Unit was dedicated to perform this requirement, and a detailed study should prove, that the required processing capacity could be installed in the existing Acquisition Unit on board the Aircraft. The result of the study seemed to be realistic and a joint working group was established to define and precise the functional requirements.

3. Functional Requirements OLMOS

3.1 Overall System Performance

The overall functional requirements of OLMOS can be structuralized basically into three categories:
On board functions (to be realized in Data Acquisition Unit)
Transfer functions (to be developed)
Ground functions (to be developed)
The on board part of OLMOS shall collect and process stress relevant data, determine life consumption of Engine and Structure, Monitor limit exceedances of aircraft structure, engine and other definable (free programmable) events. The results have to be stored in non volatile memories. Critical events shall be indicated after flight on the central maintenance panel. The noncritical results of lifing accounts should be extracted when time is available (preferable once a day), for off board trending and control.
A handheld terminal should extract the data from the Aircraft to transfer the data to a ground station. For the evaluation of events (quick look) the HHT should be able to display eventdata at the Aircraft. The operation of the HHT should be independent of A/C electrical power.
The groundstation should be a convenient evaluation facility and shall link the OLMOS to the base computer, so data can be distributed easily to other users and the lifing data

can be monitored in the logistic System.
The onboard recording on the existing Crashrecorder, as well as the recording on the optional Maintenancerecorder will be considered as OLMOS related functions.
The Data and Information flow from the Aircraft to the logistic ground based System and vice versa will be shown in the following flowdiagram.

3.2 OLMOS Functions in DAU 1c

3.2.1 Engine Life

The Engine of the Tornado Aircraft (Turbo Union RB 199) is validated and certified against cycles instead of flighthours. The main reason is the principle problem in military aviation, that the different missions will stress the engine differently. The Low Cycle Fatigue in rotating engineparts is becoming more and more significant, because of the higher temperature levels modern engine are designed to. Earlier studies indicated, that e.g. in formation flying the wingman will stress his engine up to two times higher, than the leader. In the famous U.S. Airforce Showformations the difference in accumulated cycles between Nr.1 A/C and Nr.8 A/C was even more significant. To count engine cycles, which are based on "Low Cycle Fatigue" is therefore the most important requirement of OLMOS. Other fatigue categories, like "Thermal Fatigue", "High Cycle Fatigue" or "Creep" were discussed during the development phase, the experts however believed, that for the RB 199 engine it might not be necessary. For future engine developments, especially when the temperaturelevels will be even more increased, these fatigue categories might become moore important and an even more complex on board processing might be required. For the Tornado however the LCF (low cycle fatigue) calculation was considered to be sufficient.

3.2.2 Engine Placarding

The Engine Performance is controlled by the Pilot during Run Up. This manual procedure does have some disadvantages. Even with well defined run up procedures there is quite a difference in crewhandling. The Tornado procedure requires a manual conversion of the gained snapshotdata into comparable "standard day" data. Not all of these data are available in the cockpit (e.g. air intake temperature), the result is not very precise, at least the gained data do not allow any trending. The requirement to snapshot the run up was added to OLMOS to prevent unnecessary engine run ups for adjustment purposes.

3.2.3 Structural Life

In Order to simplify the read out of structural stress data and to gain more accuracy, the requirement of structural life counting was added to OLMOS. The Tornado Aircraft was originally fitted with a simple accellerometer (G-counter), which did allow the counting of "G-categories". This feature already did allow an individual Airframe monitoring, however some important parameters (e.g. present weight, stores) were not available, the results were quite rough. The parameter were available in the existing system, the requirement to monitor structural life usage could be added to the OLMOS requirement without rewiring the Aircraft.

3.2.4 Event Monitoring

The main argument, to use a bulk storage device to collect in-flight data and evaluate these data after flight, was because of possible events and limit exceedances during the mission. Flight test engineers were using this method when ever new A/C were designed and tested. Day by day operation however does require a more comfortable tool. OLMOS does provide a programmable event monitor to allow the monitoring of limit exceedances, and assist in diagnostic if spurious failures or hard to find failures are assumed.

3.2.5 Logistic data Monitoring / Related Requirements

To allow the User an easy and carefree groundhandling of OLMOS data, additional data have to be added to minimize manual inputs at the groundstation. These data are e.g. flight hours, amount of landing gear (undercarrier) engagements, Tailnumber of the Aircraft etc.. All these requirements are leading to a complex airborne computer system. In order to meet state of the art standards consequential requirements have to added, mainly to improve the internal testability.

4. Logistic Requirements

4.1 General Requirements

The On Board Life Monitoring System has to be enbedded into the logistic system of the Air Force, and specially a very close match with the maintenance echelons has to take place. For the different Subsystems, like structure, engine, avionics, the integration of OLMOS has to follow different rules.

4.2 Handling at Aircraft

First level maintenance handling has to be relatively simple. There is no indication required for the Aircrew. There may be a different philosophy in handling similar Systems in commercial aviation, in the Airforce however it was decided to keep the monitoring of stress relevant data strictly in the hand of the maintenance personnel (the only exception is the run up check).
The line chief will have a failure indication at the CMP (Central Maintenance Panel), when the system reports a Hardware or sensor failure. The same indication will occur, when one of the programmable events were triggered during flight. The indication at the CMP can not be interpreted by the 1st level maintenance personnel, OLMOS (2nd level maintenance) specialists are required for further diagnosis. Using a special AGE (Hand Held Terminal), it is possible to interpret events or failures. The HHT also is used for data transfer between the Aircraft and the Groundstation.

4.3 Handling at Shop level

At shop level OLMOS may assist various specialists to perform "On Condition Maintenance". Mainly the following shops may be able to get better information and do a much better and more sufficient maintenance job:
- Engine maintenance (controlling lived items)
- Engine control (controlling operating parameters to adjust ECU)
- Avionic maintenance shops (shorten trouble shooting time)
- Structure and Engine maintenance (inspections after events)

The main evaluation task will be performed by the OLMOS Ground Station, in order to prevent bottle necks some of the Software has to run also on other computers. The shoplevel organization should not be changed by introducing OLMOS.

4.4 Handling at Material Command level

On Material Command level the individual Airframes are controlled to optimize retrofit packages for depot inspections. This task cannot be performed at winglevel, because additional evaluation at industry level is required.

4.5 Handling at Industry level

To assist the Logistic and Material Command some of the evaluations has to be done at industry level. Each individual Airframe will be controlled by tailnumber to optimize depot inspections. On top of this task the Ge firm IABG will do special evaluations on request, using the result of the event monitor or the maintenance recorder, which will be installed in 5-10% of the Aircraft. It is also an industry job to validate new OLMOS programs and carry out all type of software maintenance.

5. Consequential Requirements

5.1 Functions of the Hand Held Terminal

To meet the handling requirements on ground, and to allow stand alone operation (emergency operation) the HHT has to transfer data bidirectional from DAU to OGS and analyze failures and event. In the transfer mode the HHT has to store data of 10 Aircraft and the transfer operation should be carried out without using Aircraft power. A special designed batteries pack will be part of the HHT equipment.

5.2 Functions of OLMOS Ground Station

The main function of the ground station is the acquisition and control of the various DAU data. To allow easy distribution of data into the Logistic System the ground system has to be linked to the Base Computer. All data necessary to support engine changes will be provided from the Logistic System. A stand alone mode has to be possible (e.g. oversea operation).

5.3 Functions of Recorder Test Unit

As a consequential requirement to OLMOS, the update of the RTU (already existing) was required. For Testing the System and the Aircraft sensors, the RTU has to be updated, on top of this testrequirement, the RTU was designed to hold one complete dataset of Crashrecorderdata, and convert signals into physical units.

6. OLMOS System Layout

The System was introduced into service 1985 on a prototype basis. The principle design is shown in the following Blockdiagramm (Fig.2). The groundequipment which is not used on Aircraft is commercial type equipment the HHT, RTU and the Batteries pack is designed to military environmental specifications.

7. DATA Acquisition Unit Hardware/Software

The key element of the OLMOS is the on board processing facility DAU 1c. There is another paper presented in the afternoon, where in more detail the onboard software is presented (J. Broede, MTU). With the next diagrams I would like to draw your attention on the embedded design for the engine calculation module. The Hardware for this SW Module could be installed on one circuitboard for each engine.

8. Conclusion

The development of OLMOS proved, that On Board Monitoring is possible, and the received data can be used in the Logistic System. The Tornado OLMOS technology is using state of the art Hardware and structured Software. OLMOS is a System which serves engine, structure and functional equipment as well, the level of integration is high, but due to the structured Softwareapproach the system can be handled. The Software was developed by four companies, and in the using phase the same companies are sharing the SW maintenance. High integrated Systems definitely do need a very close management on both sides, the government and the industry, however OLMOS proves that even commercial and proprietary aspects can be worked out.

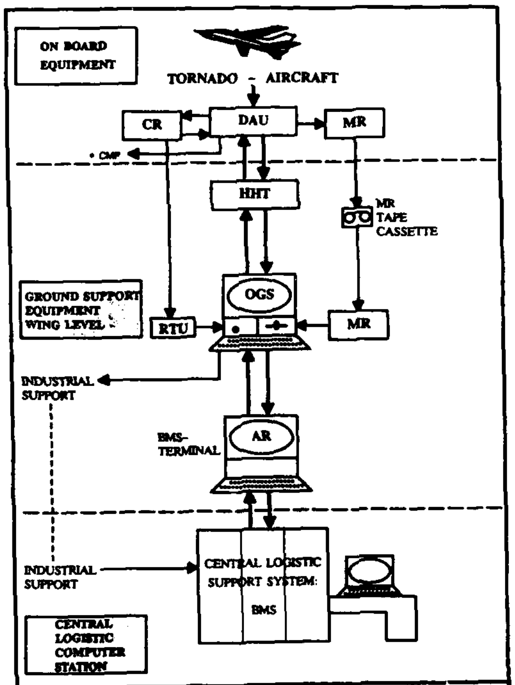

Fig.: 1 OLMOS LOGISTIC SUPPORT SYSTEM

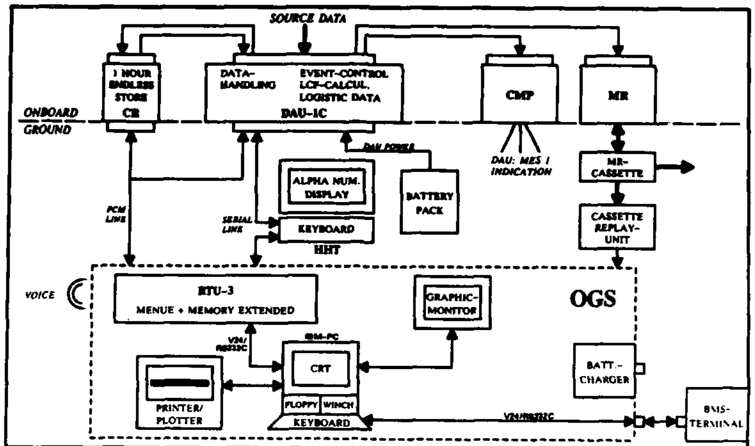

Fig.: 2 **EQUIPMENT BLOCKDIAGRAM** TORNADO

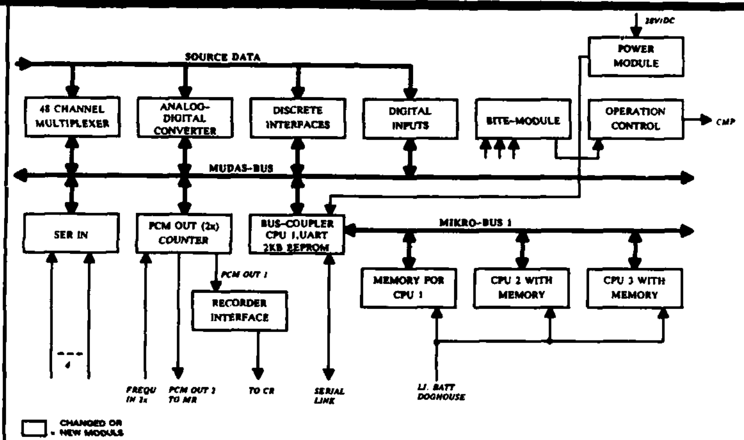

Fig.: 3 **BLOCKDIAGRAM OF THE DAU-1C** TORNADO

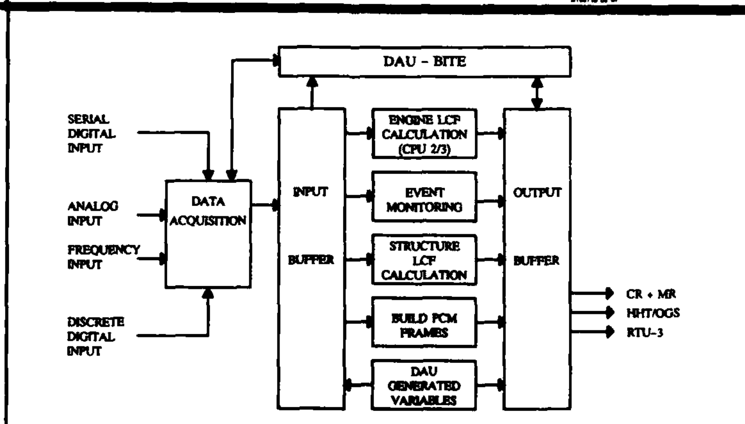

Fig.: 4 **DAU-1C SOFTWARE STRUCTURE** TORNADO

DISCUSSION

R. DYSON

Vibration systems are praised and criticized. Please provide your rationale for the decision not to include vibration monitoring.

Author's Reply:

OLMOS does include a vibration monitoring, however it is a strict "vibration" monitoring. There is no frequency analysis performed within "OLMOS".

J.L.HOUILLON

Le système OLMOS n'est pas opérationnel aujourdhui, d'où les trois questions suivantes:

1. Quand le système sera-t-il opérationnel dans la Luftwaffe?
2. Comment sera initialisé l'endommagement des pièces critiques des moteurs en service depuis plusieures années?
3. Quelles pièces sont suivies?

Author's Reply:

1. The first production systems were introduced into service in 4/87. The existing TORNADO'S will be retrofitted. The complete fleet will be operationnal in 1992.

2. All "NO-OLMOS" engines will be monitored by flight-hours. The "group A" parts will have individual β-factors assigned. The monitoring will be performed by flighthour and β-factor. An engine converted from a "flighthour controlled" engine to an "OLMOS controlled" engine will pick up the consumed life gained by the present procedure.

3. All rotary "group A" parts of the engine.

INFORMATION MANAGEMENT SYSTEMS FOR ON-BOARD MONITORING SYSTEMS

by

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SUMMARY

"With the advent of micro-processors" is a phase which has heralded a host of advances in aircraft mounted equipment. It promises to yield rich dividends for the hard pressed maintenance engineer by providing detailed information on equipment performance to enable defects to be accurately and rapidly diagnosed. Latest developments in the propulsion field show the potential of being able to anticipate certain types of defect and thus achieve true on-condition maintenance in these cases. The aim of this paper is to highlight the vitally important role played by maintenance information management systems in storing, analysing and displaying the data captured by on-board monitoring systems and to make recommendations for a code of practice for the successful implementation of such systems.

INTRODUCTION

1.0 Increasingly, military aircraft are being designed to incorporate on-board monitoring systems. For instance, it is now RAF policy for all new aircraft to be fitted with an integrated flight data recorder (IFDR). Unfortunately, what has tended to be neglected has been the requirement to manipulate and manage this information in a way that provides clear, unambiguous advice in a readily understandable form. To date, the trend has been to view the problem primarily from the airborne side with attention only focussing on the potential users requirements very late in the day.

1.1 The Section in which I work is the Engine Usage, Condition and Maintenance Management Systems (EUCAMS) Project Office in the UK MOD Procurement Executive. It used to be called Engine Health Monitoring but this title fails to adequately describe the range of activities covered. Some of the developments we have been responsible for are the Engine Usage Monitoring System (EUMS), and Low Cycle Fatigue Counter (LCFC), Air Staff Target (AST) 603, about which you will be hearing elsewhere, and the Engine Monitoring System (EMS) fitted to the Harrier GR Mk 5. We have also developed the Harrier Information Management System (HIMS) to support the EMS and are developing a similar system for the Tucano. Finally, we are involved in the process of defining the requirements for the Integrated Monitoring and Recording System (IMRS) and the Ground Exploitation System (GES) for the European Fighter Aircraft (EFA) - but that requires a paper in its own right. I will briefly describe the various information management systems using our experiences on the Harrier and Tucano systems to illustrate important points.

1.2 The future trend, as exemplified by the Tucano and EFA, is to integrate the engine, airframe and systems monitoring function into either a physical or virtual system. Hence, airframe fatigue consumption calculation can be enhanced by introducing recording the readings of strain gauges strategically positioned on the airframe. Avionics and some mechanical systems will also benefit from being constantly monitored to improve the diagnosis of defects and, more importantly, transient defects.

2.0 BACKGROUND

2.1 EUMS

2.1.1 The Plessey Avionics EUMS is fitted to a percentage of aircraft in each of the UK fast jet fleets and to a number of helicopters and transport aircraft. EUMS continuously records a limited number of engine parameters, primarily shaft speeds and JPT, onto a standard audio cassette format. The cassette, together with a proforma giving sortie details is sent to Rolls Royce Bristol (RRB) where the data is analysed and stored on a computer (a DEC PDP 11/70). This analysis is fairly complex and beyond the capabilities to be found on the average Service unit. The data output gives LCF consumed per flight which can be tagged with a Sortie Pattern Code (SPC) and Squadron identity. It is then possible to place the LCF cycles/hr exchange rate in context. On some engine types, the analysis has shown that it has been possible to halve the originally estimated exchange rate ie effectively double the component's life, which can represent a large financial saving. On other engine types, EUMS has highlighted greater than assumed engine usage and, hence, "life" has had to be reduced. However, the greater knowledge of actual usage is an important contribution to flight safety. Its got to be good!

2.1.2 The big problem with EUMS is "data drag". It can take up to a month between a flight and processing a cassette at RRB. If data is corrupted and the cause is equipment malfunction, then, by the time the defect has been rectified, a lot of data will have been lost. The EUMS results cannot be used on their own as they only reflect a small percentage of fleet usage, hence, various statistical techniques need to be used to overcome any bias if the results were to be applied to the whole fleet. So the time taken for a meaningful output to be made available rules out using EUMS data for 1st or 2nd line use.

2.2 LOW CYCLE FATIGUE COUNTER (LCFC)

2.2.1 The Smiths Industries LCFC was made possible by "the advent of the micro processor". Similar inputs to EUMS are fed to the aircraft mounted LCFC which then continuously computes LCF usage by running an appropriate algorithm in its micro-processor. The original LCFC displayed results on 4 electro mechanical counters which are normally read at the end of the day's flying and recorded in the aircraft documentation. This is the system used on the Red Arrows Hawks and is the only fleet fit of LCFCs. The system is analogous to reading airframe fatigue meters, although, in this case the numbers directly represent life consumed.

2.3 AST 603

2.3.1 AST 603 spawned a quite ambitious and advanced trial of engine monitoring techniques. Whilst it would be true to say that the project suffered more than its fair share of problems, it also enabled the way ahead to be defined. The trial, at an RAF advanced flying training school, comprised 12 Hawk aircraft, fitted with an expanded EUMS fit, and a ground station, similar to that at RRB, to process the cassettes. An RAF team of 3 ran the system.

2.3.2 The on-station computer acted as the information management system but required a high degree of knowledge to operate it. In the latter stages of the project, a much more "user friendly" system was designed called the Prototype Information Management System (PIMS). Two companies, SCICON and Stewart Hughes, combined to produce and demonstrate this system which was heavily based on the USAF's Maintenance Information Management System (MIMS) but tailored to meet the RAF's requirements.

3.0 HARRIER GR MK 5

3.1 The Harrier GR Mk 5 will be the first RAF aircraft to be fleet fitted with an EMS. The PIMS experience was very valuable in focussing thoughts to define the requirements for a system to support the Harrier EMS. The original idea was to manage the EMS data on the Station Engineering Management Aid (SEMA), a micro-computer based centralised engineering database. However, SEMA implementation at RAF Wittering, the first Harrier GR Mk 5 unit, was not planned until 1 year after the aircraft entered service. Thus was born the Harrier Information Management System (HIMS) as a stand alone system but with the ability to interface with SEMA in due course.

3.2 EMS

3.2.1 A brief description of the Harrier EMS is appropriate. Firstly, there is the aircraft mounted equipment, the Engine Monitoring Unit (EMU), and, secondly, there is the ground based equipment, the Data Retrieval Unit (DRU). The EMU does all the processing to provide the functions described in para 3.2.2 below whilst the DRU is used to download the data and feed it into HIMS. The DRU is also used to re-set data stores in the EMU following an engine or EMU change. To cope with the Harrier's deployed role, the DRU is designed to download its data to a cassette recorder so that the data may be transferred to HIMS back at base. Fig 1 gives a simplified overview of the system.

3.2.2 The major features of the EMU are as follows:

a. It runs 6 LCF algorithms in real time and stores the results in a "per flight" and a cumulative consumption store.

b. It runs 2 algorithms for determining the life of HP Turbine Stage 1 and Stage 2 blades and stores results as per sub-para a above.

c. It carries out exceedance detection of a wide range of parameters such as overspeeds, overtemps etc, and records maximum parameter value, time spent above the limit and time into flight at which the exceedance occurred.

d. Following exceedance detection, EMS records the entire raw data stream for the duration of the incident, including a short period before and after the exceedance, and stores this data in solid state memory. The EMS is able to provide data prior to an exceedance because data is held in a circular buffer able to store up to 60 seconds of data.

e. Over a period of 6 flights, EMS records and stores that engine/airframe combination's vibration signature and uses this data to trigger a vibration maintenance warning before a vibration exceedance is recorded. EMS also monitors vibration levels associated with the highest engine speed at take off and each 15 minutes thereafter.

f. On the Harrier, a check is carried out which is similar to the Power Performance Index for helicopters. The object of the check is to assure that the aircraft and engine combination will produce a certain standard of performance. To obtain a feel for just the engine performance, it is necessary to carry out a separate engine performance snapshot when the engine compressor air is not being bled off to control the aircraft below wing borne speeds. EMS is planned to automatically capture hover performance and a take off parameter snapshot for ground analysis in due course.

3.3 HIMS

3.3.1 Development of HIMS was started when the Harrier's in-service date was only 21 months away. The EMS had been in development for some 30 months prior to that. The original philosophy had been to read data from the EMS as and when necessary (at that stage only exceedance summaries were being logged) in much the same way as for the LCFC. However, as the EMS design progressed, advances in memory capacity of non volatile random access memory (NVRAM) devices permitted the introduction of raw data recording and storage. Direct calculation of LCF consumption allowed the change from the traditional system of "lifing" the engine in hours to lifing in LCF cycles. Now, the Pegasus has 36 Group A parts which, in theory, could each consume LCF at different rates. The EMU only runs algorithms for 6 Group A components. These components are the most highly stressed features in each spool/shaft and the combustion chamber outer casing. The remaining Group A parts are related to these 6 by a read across factor which is currently set at unity. Some sort of ground based storage and display system was clearly needed to support this functionality and this formed the basis for the requirements for HIMS.

3.3.2 HIMS inputs are as follows:

a. EMU data is loaded via the DRU for on-base operations.

b. EMU data is loaded via a cassette for off-base operations.

c. The following data has to be entered manually:

i. Sortie details, hours flown and sortie pattern code, from the aircraft documents.

ii. Removal/installation of engines/components.

iii. Database corrections.

3.3.3 Following the introduction of SEMA, HIMS will obtain the data in paras 4.3.2.c.i and 4.3.2.c.ii by electronic transfer from SEMA.

3.3.4 The main HIMS functions may be described as follows:

a. Maintains a record of LCF consumption of all 36 Pegasus Group A parts by using read across factors from the 6 LCF algorithms running in the EMU.

b. Maintains a record of HP Turbine blade usage.

c. Maintains a record of exceedances recorded in the EMU.

d. Displays raw incident data graphically.

e. Displays a summary of engine life remaining in hours.

f. Displays a summary of rate of usage between different engines.

g. Produces data to re-set EMU data stores.

h. Transfers data to and receives data from SEMA.

It is beyond the scope of this paper to describe all these functions fully, so I will only describe a few of the outputs below.

3.3.5 One of the most useful outputs from HIMS will be the ability to investigate engine defects without having to rely implicitly on aircrew reports. This is not a slur on aircrew but a recognition that they are likely to be rather too busy flying the aircraft following an engine malfunction to pay other than passing interest in how parameters are changing during a malfunction. Maintenance engineers will be presented with a summary of the incident ie maximum value reached, duration above limit and the time into flight at which it occurred as well as being able to "view" the incident by plotting out the relevant parameters either on a VDU or onto hard copy and correlating what actually happened with the advice in the engine manual. Provided the EMU is functional, no longer will the words "When I looked into the cockpit the JPT was falling through 850°..." be greeted by "What temperature did it reach?". Accurate data will be readily available.

3.3.6 Another useful output will be that of engine life remaining in hours. Having said that we want to get away from lifing engines in hours why come back to it? Very simply, hours remaining are what matter when operating aircraft, so converting back from cycles to hours gives a basis for managing the engine. However, as this hours remaining figure is derived by dividing a cycles/hour exchange rate into the component with the lowest cycles remaining figure, it could decrease at a slower or faster rate than the aircraft flying hours depending on the severity of engine usage. For example, when aircraft are being used on an armament practice camp, the range is usually closer than usual. Transit time to and from the range is, therefore, much lower than when at base. As LCF consumption is either very low or zero during transit, for every hour spent flying, proportionately, the engine is consuming much more LCF than would normally be the case. However, this increased complexity in determining engine life is automatically taken care of within HIMS.

3.3.7 Another example which has a use both in-service and at the engine manufacturer, is the ability for the first time to display the difference in the rate of engine life usage between engines on a squadron and also between pilots. Whilst I am not suggesting that in the Service a check should be kept on engine usage by individual pilots, it may be a useful output when evaluating different operating profiles. At 4th line, this information will prove invaluable when assessing the amount of scatter that the manufacturer is likely to expect when the aircraft is flown by different pilots on the same sortie pattern. This data can then be used to modify the "assumptions" used in lifing calculations.

3.4 FUTURE ENHANCEMENTS

3.4.1 Although originally envisaged, the EMS currently does not have a facility to automatically capture data to calculate hover performance on the Harrier. To those unfamiliar with Harrier operation, this procedure is carried out to check the overall performance of the engine/airframe combination. It is analogous to the helicopter power performance index check. The Harrier procedure requires the services of experienced aircrew as very accurate hovering is required. Ideally, there should be no wind so that the use of the reaction jet controls can be minimised. Inevitably, this is rarely the case and so for a number of reasons a hover performance check may have to be reflown. I would expect the software for the automatic capture and calculation of hover performance to be available in late '88. HIMS will take on this data and store it against the particular engine/airframe combination.

3.4.2 Another function which has been delayed is the capture of a snapshot of engine parameters at a repeatable point in the flight envelope. Such a point has been identified as occurring shortly after take off when the aircraft is in full wing borne flight. The snapshot window has been defined as occurring approximately 7 seconds after the aircraft is airborne and the nozzles are fully aft. 10 parameters will then be recorded over a 6 second period and either averaged or all 6 values stored. This snapshot data will be downloaded to HIMS where a Rolls Royce provided analysis routine will be used to determine the engine's performance. This could be particularly relevant where a hover performance was below specification but the snapshot data analysis indicated that the engine was above the minimum acceptable power. This would eliminate the engine as being the prime suspect and would immediately direct the fault finding to the airframe. Conversely, the indication of a deteriorating engine from this analysis could trigger either an engine inspection or an unscheduled hover performance check. Again, by providing early warning of an engine's deterioration, maintenance personnel may be able to reduce the impact of an engine change on a squadron's programme. Furthermore, selecting aircraft to go on exercises where maximum performance is required will become relatively easy. No doubt aircrew will pay particular attention to these outputs to bid for the jet with the best performance!

4.0 TUCANO T MK1

4.1 The Tucano on-board system, called the Airborne Integration Monitoring System (AIMS), comprises a Data Acquisition and Processing Unit (DAPU) and an Accident Data Recorder (ADR). The DAPU, which is analogous to the Harrier EMU, is downloaded to a Data Extraction Unit (DEU) which in turn will download into the Tucano Information Management System (TIMS). The DAPU carries out engine lifing, but in a simpler form than that used in the Harrier EMU, and also replaces the traditional fatigue meter, or more correctly the counting accelerometer. The DAPU also has an exceedance detection and logging facility but does not collect raw data following an exceedance. Finally, a performance snapshot is taken on the first occasion in each sortie when the aircraft climbs through 5000 feet.

4.2 The major differences in TIMS compared with HIMS, is the ability to handle airframe fatigue data. The "g" counts are stored and converted to fatigue index (FI) readings using a simple fatigue algorithm. The raw "g" counts are still passed back to MACE for the full rigorous FI calculation. To overcome the problem of "the original aircraft with 3 different wings, 2 different fuselages and 1 different tailplane" the history of each of these major components is tracked within TIMS automatically. It is, therefore, a simple matter to determine the true life of a wing, say, even when it has been used on several different aircraft.

5.0 LESSONS LEARNED

SYSTEMS APPROACH

5.1 The most obvious lesson to be learned from the experience with HIMS and TIMS is the reiteration of the use of the systems approach to introducing new technology. This is to use the word "system" in its widest form by which I mean the inclusion, or consideration, of any relevant factor. By its very nature, the "system" starts by the customer considering the performance, readiness requirement, ie aircraft availability, and life cycle costs he requires from the aircraft. From this can be defined the engineering philosophy required which, in turn, defines the type of information which must be acquired on-board to support the appropriate ground based engineering functions.

5.2 The importance of the ground station cannot be stressed too highly and considerable effort should be expended in defining its requirements. These requirements should then drive the definition of the airborne system. Of course, it could be that existing or projected technology cannot support the required functions ie it may not be feasible to collect some data, in which case a compromise between what is required and what is technically feasible will be necessary.

5.3 It is important at this stage to recognise that it is essential to have some means of uniquely tagging information gathered. The least ambiguous way is to use time tagging which implies a real time clock (RTC) somewhere in the monitoring system. For advanced aircraft designs using data buses, a single RTC in the aircraft will suffice. For less complex aircraft, or in the retrofit case, it is essential to have a RTC in the monitoring equipment even if this means having to accept the penalty of changing a battery every 3 to 5 years.

INTEGRATION WITH OTHER SYSTEMS

5.4 Many military air arms these days have a computerised engineering database. Some operators will be tempted to include the functions of the IMS into their existing facilities. Whilst this may be possible, a more attractive solution is to design a distributed processing system and define either the data transfers required or, better still, utilise an Open System Architecture. This implies use of operating systems such as UNIX or PICK. The great advantage of following this route is that the same software can run on any hardware which can run UNIX or PICK. This is a very important consideration as software costs far outweigh hardware costs these days and it is likely that hardware will require replacement every 5 to 10 years.

FUNCTIONAL REQUIREMENT SPECIFICATIONS

5.5 Having laid the foundations of a system, it is then time to begin producing the functional requirement specification (FRS). It is vitally important to get the FRS as accurate as possible. The penalty for inaccuracy and ambiguity is a very expensive rework of the software at a later stage. Producing a FRS is an activity that must involve the end-user in a considerable amount of effort. Otherwise, there is the danger of an avalanche of modifications being required, at great expense, as soon as the system enters service as the user finds that the software doesn't work in the way he wanted, or expected, it to.

5.6 It is at this stage that all the interface requirements should be identified. Some interfaces will be satisfied with merely a transfer of data using some form of magnetic media. Other interfaces may require direct on-line data transfer. There may be conflicting operational requirements between systems with some only updating databases in batch processes and others relying on real time updates. This implies some form of "data drag" and, hence, the 2 databases will only be in synchronisation once or twice a day. It is most unlikely that all data held in distributed databases needs to be transferred between them. Rather, those data fields whose transfer is essential should be identified, and they should conform to a standard format. The use of standard Data Dictionaries within the ranges of systems being linked will greatly simplify this process.

5.7 Another form of "data drag" is caused when aircraft operate away from base and, for various reasons, the paper records take some time to return to the host unit. This can give rise to several problems:

a. Some aircraft sortie details will not be available for, say, up to 3 months.

b. A monitored/lifed item has been changed on the aircraft and neither the on-board system nor the ground system is updated with the change.

c. A monitored/lifed item has been changed and the on-board system is updated but the ground system is not.

5.8 For the first case, allowance needs to be made for "dummy" or estimated details to be entered to allow the database to function until the real details arrive. The database then needs to be "rolled back" to the area to be corrected, and, having input the correct details, the database must then be "rolled forward" and carry out any necessary changes resulting from the input of the real data.

5.9 For the second case, the same "rolling back", correcting and "rolling forward" of the database is required. However, an additional requirement is to reflect the changes in lifed/monitored components removed from and fitted to the aircraft. This is to enable the correct allocation of life consumed by the old and new parts. The RTC is invaluable in sorting out this type of problem, always assuming that the correct time has been used on the aircraft work sheets which recorded the component change.

5.10 In the third case, the ground station software should trap the error as there will be a discontinuity in the life usage readings of the affected component.

5.11 When raw data is collected to assist in the diagnosis of incidents then, there is further scope for expensive errors to be made. The manner in which the basic data frame is composed and handled should be unambiguously stated. For instance, if a data frame comprises a number of sub-frames, both the on-board system and the ground system should handle the data either by frame number of by sub-frame number. An obvious statement but one which should not be left unstated.

5.12 Equally, once the aircraft is in service, it may be necessary to change the data frame format to permit the capture of additional parameters or to increase the sampling rate of a particular parameter. This should be allowed for within the design of both air and ground systems. A possible solution is for the airborne system to contain the frame format standard in a byte in the data frame and for the ground station to read this byte before implementing the appropriate decode sequence for that particular data frame format. This will enable incident data with different frame formats to be automatically decoded correctly.

SOFTWARE CONSIDERATIONS

5.13 A recent alternative to a rigorous FRS is to "prototype" the system. Use of modern fourth generation language (4GL) packages allow the rapid creation of a "prototype" system which can be shown to the user for comment. Proceeding in an iterative process leads eventually to the creation of the FRS. It is difficult to say which of the 2 systems is the better other than when first creating a ground station the prototyping option can offer advantages by showing the software in action. This can trigger thoughts on how to use the system which would not have come to light until some operating experience had been gained with the system. Additionally, interfaces will be more easily identified as the system is run.

5.14 The use of a modern 4GL Relational Database Management System (RDBMS) can have a most beneficial effect on the speed of software implementation and hence on the overall cost of the development. It is important to evaluate the available RDBMSs to ensure that the most appropriate one is chosen for the task. This will depend on a number of factors such as the size of the database, the amount of data processing envisaged, the speed of response required, the type of queries likely to be instigated and the ability of the package to interface with other software packages. Of particular importance is the type of query likely to be used. Very often it is not until a system has been running for some time that it becomes clear that a particular query function, which would be very useful, was not specified at the start. An example could be the aftermath of a turbine disc failure where a life reduction is required pending the resolution of the problem. The question the engine fleet manager most wants answered is "How many engines are at risk and what effect would a small variation in the life cleared have on my operations?" Now, a flexible and well designed system could be easily modified to cope with such a query whereas a less flexibly constructed system would merely increase the frustration of the hard pressed manager by being unable to provide such data without resorting to manually sifting through a host of outputs which contain the answer somewhere in them.

CHOICE OF HARDWARE

5.15 The reader will note that the choice of hardware is left until last. This is entirely deliberate and serves to show how the influence of hardware has waned with the advent of Open Systems Architecture (OSA). The choice of hardware then is dependent on the following factors:

a. Will the hardware support OSA?

b. Will the selected RDBMS run on the hardware?

c. How fast will the hardware run when subject of a recognised benchmark?

d. Is there a recognised interface package to allow the chosen hardware to interface with other existing systems?

e. Does the hardware support colour graphics?

5.16 Having addressed the above points satisfactorily the hardware may be procured and the software development can start in earnest.

6.0 CONCLUSIONS

6.1 When designing an aircraft monitoring system, the design starts with the consideration of the whole system. This means considering how it is intended to maintain the aircraft, what level of aircraft availability is required and the life cycle costs envisaged by the aircraft operator. Failure to do so will result in a situation arising whereby it will not be possible to obtain the optimum advantage from the investment in the monitoring system. Indeed, in the worst scenario, it is possible to find that, unless considerable sums of money are invested, the monitoring system becomes virtually unmanageable.

7.0 RECOMMENDATIONS

7.1 During the development of information management systems for use in military aircraft with monitoring systems it has been found that the following "code of practice" can yield very great benefits in terms of maximising the expected benefits:

a. Adopt a "systems approach" when analysing the requirements for a monitoring system.

b. Specify a real time clock in the airborne system to time tag all relevant data.

c. Determine the extent to which integration with other ADP systems is required.

d. Consider the use of Open System Architecture.

e. Rigorously identify the functional requirements, particularly the interfaces which will be required. Alternatively, consider "prototyping" the system.

f. Evaluate and choose the most suitable database management system bearing in mind the considerable advantages offered by fourth generation language packages. Aim for maximum flexibility in the database.

g. Evaluate and choose the most suitable hardware to run the chosen software aiming to meet the requirements for speed of operation with the chosen software, interface requirements with other hardware and VDU attributes.

7.2 Adherence to the above code does not automatically guarantee success but at least the major problems will have been addressed.

The views expressed are those of the author and do not necessarily represent the policy of the Ministry of Defence.

HIMS OVERVIEW

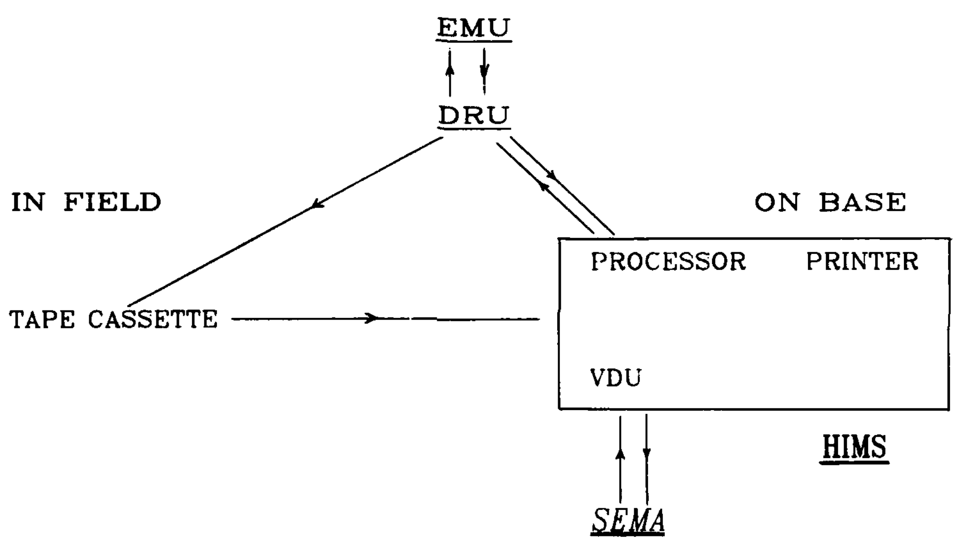

FIG 1

DISCUSSION

C.M. O'CONNOR

What measures exist to validate data transferred to the HIMS and what procedures are there to secure it from unauthorised access.

Author's Reply:

Firstly, during data transfer from the aircraft to the Data Retrieval Unit, Manchester II protocol is used to ensure that no data corruption occurs even when this operation takes place in a high Electromagnetic environment. When transferring data from the DRU to HIMS there is no need for data validation. Once the data is on HIMS, the system checks the airframe and engine number with that listed on the database and warns the operator of any error. Currently no other data validation is carried out. However should in-service operation indicate that further validation is required, appropriate validation checks will be introduced later.

Security is maintained by use of passwords.

M.J.FLEMING

How is data retrieval managed whilst the aircraft spends prolonged periods away from home care?

Author's Reply:

When the HARRIER is operated away from its base, after downloading data to the DRU, data is transferred to a cassette tape. Data integrity is ensured by a write, read, verify sequence and by use of data buffers. The cassettes are then transferred to base and read into HIMS.

If the aircraft are deployed to another base it is possible to position a spare HIMS computer system and transfer data by means of floppy discs.

D.E. COLBOURNE

We have heard earlier of the great usefulness of vibration monitoring- but of its reputation for unreliability- does your off-aircraft analysis system have any benefits to offer?

Author's Reply:

We have planned to carry out vibration analysis within HIMS. However we found that the data captured did not link shaft speed with vibration amplitude uniquely. Thus it is not possible at the moment to utilise the data to the extent originally envisaged.

CF-18 ENGINE PERFORMANCE MONITORING

by

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SUMMARY

The Canadian Forces have adopted a conditional maintenance concept for the engines of the CF-18 fighter aircraft. In support of this concept, advanced engine performance monitoring procedures are being developed to track the general performance level of each engine and identify problematic engine components. The procedures are based on take-off ground roll data recorded by the aircraft In-Flight Engine Condition Monitoring System and steady-state data obtained from automated Engine Test Facilities. The development and field evaluation of these procedures is described. A discussion of future development work and related research activities is also included.

NOMENCLATURE

A_8 - exhaust nozzle area

CVG - compressor variable geometry position

FVG - fan variable geometry position

F_g - gross thrust

MFC - main fuel control

N - rotor speed

N_{des} - design point rotor speed

N_1 - fan rotor speed

N_2 - compressor rotor speed

P_1 - engine inlet pressure

P_{S3} - compressor delivery pressure

P_{56} - exhaust gas pressure

PR - pressure ratio

PR_{des} - design point pressure ratio

PLA - power lever angle

Q - turbine flow parameter, $W\sqrt{T}/P$

Q_{des} - design point turbine flow parameter

T_1 - engine inlet temperature

T_{56} - exhaust gas temperature

W_1 - engine airflow

W_{fm} - main fuel flow

θ_1 - inlet temperature correction factor $T_1/288$ K

δ_1 - inlet pressure correction factor, $P_1/1$ bar

INTRODUCTION

The General Electric F404-GE-400 engines of the CF-18 are the first Canadian military engines to be maintained under a formal "on-condition" maintenance program. Under this program, maintenance actions are dictated largely by direct or indirect measurements of actual engine condition; hence, advanced condition monitoring and fault isolation capabilities are required to ensure that engine and aircraft availability targets are met.

The F404 is a low bypass, twin-spool turbofan engine with a mixed flow exhaust and afterburning. The engine is typical of modern military gas turbines, employing variable fan and high pressure compressor geometry to obtain a high compression ratio and a variable area exhaust nozzle to optimize engine performance over a wide operating range. The layout of the F404 is presented in Figure 1 which also defines the engine station numbering used for performance analysis.

Operational F404 engine condition monitoring is provided by the aircraft's In-Flight Engine Condition Monitoring System (IECMS). The IECMS continuously monitors several different engine and aircraft performance parameters, evaluates engine component life usage indices, activates cockpit cautions and sets maintenance codes whenever an engine operating limit is exceeded, and automatically records engine performance data on a removable tape cartridge for post-flight analysis [1]. Each CF-18 main operating base is also equipped with a modern Engine Test Facility (ETF), capable of both on-wing and off-wing engine performance verification testing.

In 1985, the Canadian Forces (CF) contracted with GasTOPS Ltd. to develop engine performance trending and troubleshooting procedures based on the information available from the CF-18 IECMS and ETF. To-date, software has been developed which enables engine maintenance technicians to access, display, analyze and print the various data recordings provided by the IECMS, to track the performance of individual engines based on engine health indices derived from the IECMS take-off recordings and to identify specific engine problems using steady-state engine performance data recorded in the ETF.

This paper describes the development and in-service evaluation of the CF-18 engine performance monitoring procedures. The direction of future development work is also discussed.

OPERATIONAL PERFORMANCE MONITORING

The CF-18 IECMS records F404 engine performance data automatically during the ground roll of each aircraft take-off and whenever an engine operating limit (fan speed, compressor speed, exhaust gas temperature, oil pressure or vibration) is exceeded. Additionally, a pilot record button feature enables engine performance data to be captured on an as required basis. The exceedance and pilot-activated recordings are comprised of 5 seconds of pre-event and 35 seconds of post-event data. The take-off recordings begin when the engine power lever is advanced to the take-off power setting, end when the aircraft lifts off and are typically 6 to 10 seconds in duration. Table 1 summarizes the major parameters which are recorded by the IECMS and the frequency of each recording.

The development of operational CF-18 engine performance monitoring procedures has centred on the take-off recordings. In general, these recordings capture the dynamic response of the engine to a rapid throttle movement from idle to the take-off power setting. Figures 2(a) and 2(b) illustrate two representative parameter versus time traces, fuel flow (W_{fm}) and compressor rotor speed (N_2), obtained from an IECMS take-off recording. It is evident from the figures that the engine is in a transient state throughout the take-off ground roll. To make use of the take-off data for engine performance monitoring purposes it is therefore necessary to relate engine condition to the dynamic behaviour of the engine as exhibited by the take-off recordings.

The use of transient data for engine performance monitoring has received relatively little attention by monitoring system developers. At the present time, the dynamic behaviour of gas turbines (and in particular complex engines such as the F404) under degraded conditions is not well understood and the requirements of an airborne measurement system suitable for transient performance monitoring have yet to be established. In the case of the CF-18 IECMS, it is therefore reasonable to assume that the IECMS take-off recordings have been included because of their perceived usefulness, rather than on the basis of a proven performance monitoring capability.

This situation clearly complicates the task of developing reliable performance monitoring procedures based on the CF-18 take-off recordings. For example, the data capture algorithm used by the IECMS does not account for any variability in the starting conditions of the transient; however, depending on how a take-off is executed, the starting engine speed can vary between ground idle and approximately 90% N_1. Because of the variable geometry features of the engine, the dynamic response of the engine will also be dependent on ambient temperature. The accuracy of the transient measurements must be considered as well. For instance, the parameter versus time plots of Figure 2 indicate that data must be filtered or smoothed to eliminate signal noise and sampling rate problems. The data smoothing techniques presently employed are summarized in Table 2.

In spite of the difficulties described above, a number of relatively simple "engine health indices" have been derived from the CF-18 engine take-off recordings and are presently under evaluation. For example;

1. <u>Fuel Ratio Units</u>: During a rapid acceleration from ground idle to take-off, the main fuel control (MFC) provides fuel to the engine according to a predefined fuel ratio unit (W_{fm}/P_{S3}) schedule. This schedule is affected somewhat by ambient temperature, but is independent of the starting speed of the transient. Hence, it is reasonably repeatable from one take-off to another. Examination of the W_{fm}/P_{S3} versus N_2 relationships for a large number of take-offs indicates that the fuel ratio unit curves may be useful in identifying problematic fuel control components. Figure 3 shows two fuel ratio unit curves, one taken before and the other after an MFC removal from an engine

which experienced a flameout on startup. The overfuelling which occurred prior to the flameout incident is clearly evident. For field evaluation purposes, the fuel ratio unit values at 81% and 87% N_2 are presently being monitored.

2. <u>Rotor Acceleration Times</u>: Immediately following a rapid throttle advance to the take-off power setting, the variable exhaust nozzle of the F404 moves to a completely closed position and remains closed until the exhaust gas temperature limit of the engine is approached. It has been determined that the fan and compressor rotor acceleration times during the interval when the nozzle is closed are quite consistent, irregardless of the starting conditions of the transient. Furthermore, as indicated in Figure 4, the rotor acceleration times are also sensitive to fuel control adjustments. The usefulness of the acceleration times as indicators of additional engine problems is presently being evaluated.

3. <u>Compressor Delivery Pressure Rise Time</u>: Figures 5(a) and 5(b) show the compressor delivery pressure traces for the left and right hand engines of an aircraft which experienced severe blade damage to the HP compressor of its left engine. The divergence of the left and right traces following the damage is clearly visible. As a mean of detecting cold end gas path problems, the difference between left and right hand engine P_{S3} rise times (time to reach 250 psi) is presently being evaluated. By comparing left and right hand engine values, take-off to take-off variations are minimized. Figure 6 presents a number of data points taken from a single aircraft over a period of 3 months. The changes in relative engine performance following each engine removal are quite pronounced. It is felt that the magnitude of performance changes due to engine condition degradation will be similar to or greater than the engine-to-engine variations shown in Figure 6; hence, engine performance trends should be detectable.

The analysis of CF-18 engine take-off data has resulted in benefits to other CF-18 Engine Health Monitoring programs as well. For instance, it has been determined that N_2 signal noise can cause erroneous values of the N_2 low cycle fatigue counts to be recorded by the IECMS. Strictly speaking, the left and right hand engine partial N_2 counts for a given aircraft should be similar or identical. However, a mission-by-mission analysis of CF-18 engine life usage data and take-off performance recordings has revealed that one engine can accumulate partial N2 cycle counts at a significantly higher rate than the other (by as much as a factor of 8) as a result of a noisy N_2 signal.

<u>TEST CELL DIAGNOSTICS</u>

The highly modular design of the F404-GE-400 has enabled the Canadian Forces to establish an in-depth repair capability for these engines in the field. In support of these repair activities, modern Engine Test Facilities have been constructed at each CF-18 main operating base. Each ETF is capable of comprehensive engine functional and performance verification testing for both installed and uninstalled engine configurations. Data acquisition and processing is accomplished by a computer-based system which interactively leads the operator through the required test schedules, displays the test results and stores the test data on magnetic disk for future reference. The test schedules and performance specifications provided by the manufacturer are used to ensure that each engine is capable of meeting minimum performance requirements. In the event that an engine fails to meet these requirements, however, it is often difficult to pinpoint the cause of a performance deterioration.

The Engine Laboratory of the National Research Council of Canada and GasTOPS Ltd. have demonstrated that component-based thermodynamic engine models provide a systematic means of investigating performance-related gas turbine engine problems [2, 3]. The Engine Laboratory has successfully developed these models for a variety of military gas turbines including the F404-GE-400 engine. "Component-based" implies that the overall engine model is comprised of individual component performance models. For the F404 engine this amounts to separate models for the fan, HP compressor, combustor, HP turbine, LP turbine, bypass duct, mixing duct, propelling nozzle and variable geometry control systems. If suitable performance characteristics for these components can be estimated, engine performance over a wide range of operating conditions can be predicted. Furthermore, having established a component-based engine model, the influence of specific modes of component degradation on overall engine performance can be investigated by appropriately modifying the individual component characteristics.

A major obstacle to the development of component-based engine models is the lack of available component data. These data are usually proprietary to the engine manufacturer and, with the scant information which is normally provided, the estimation of suitable component characteristics remains a difficult task. For the F404 engine, adequate representations of the turbine and nozzle characteristics were obtained using relative scaling techniques such as the turbine flow and efficiency correlations shown in Figures 7(a) and 7(b). These techniques are inadequate, however, for the variable geometry fan and HP compressor of the F404. For these components a more sophisticated performance estimation method was developed whereby idealized stage performance characteristics were inferred from known operating data and a meanline stage-stacking procedure was used to estimate overall fan/compressor performance [4]. Figure 8 presents the estimated pressure ratio versus flow characteristics of the F404 fan. From the figure it is clearly evident that the variable geometry system has a pronounced effect on fan performance.

The predictions of the F404 engine model are compared to data provided by the National Research Council in Figures 9(a) and 9(b). As indicated in these figures, the simulated performance predictions show remarkably good agreement with the test data. The engine model is thus a valid thermodynamic representation of F404-GE-400. It is capable of predicting engine performance at the overall and component levels over a wide range of operating conditions under both nominal and degraded component conditions and has been used extensively in the development of the F404 performance monitoring procedures.

The use of the engine simulation for fault isolation purposes is depicted in Figure 10. Within a specific data capture window, the data acquisition system of the ETF records the required steady-state performance parameters. The subsequent processing of these data includes data smoothing and validity checks, correction for non-standard engine inlet conditions, comparison of measured performance parameters to baseline values and evaluation of performance deviations (engine fault signature). Fault isolation is accomplished by an algorithm which compares the engine fault signature to a library of known or simulated fault signatures and produces a list of most probable faults.

The scatter in the performance data used for fault isolation can be greatly reduced by limiting data capture to a specific "window" of operation. For a mixed flow turbofan such as the F404, the position of the variable exhaust nozzle has a significant effect on overall engine performance. For this reason, the data used for F404 fault isolation are recorded at a part power setting within the "cruise flat" region of exhaust nozzle area schedule, as indicated in Figure 11. It is also important to select a data capture window such that the performance deviations due to an engine fault can be readily measured. Figure 12 shows the estimated variation in F404 airflow due to a progressive reduction in HP turbine efficiency. It is evident that the airflow deviations are larger and more consistent in the mid-power operating range. Once again, this behaviour can be attributed to the influence of the variable exhaust nozzle on F404 performance.

The second major step in the fault isolation process is to compare the measured performance data to baseline or expected performance curves. Strictly speaking, the relationship between any pair of measured or calculated performance parameters, corrected to standard engine inlet conditions, may be used as a baseline. However, it is advantageous to limit the number of baseline pairs to the minimum required for effective fault isolation. A detailed investigation of F404 performance under nominal and degraded conditions was conducted using the engine model. Based on the criterion of minimum performance variation with engine inlet temperature (i.e. minimum influence of the variable geometry systems) and maximum sensitivity to engine component deterioration, the following baselines were selected:

1. $W_1\sqrt{\theta_1}/\delta_1$ vs. $N_1/\sqrt{\theta_1}$
2. $N_2/\sqrt{\theta_1}$ vs. $N_1/\sqrt{\theta_1}$
3. F_g/δ_1 vs. $N_2/\sqrt{\theta_1}$
4. $W_{fm}/\sqrt{\theta_1}\delta_1$ vs. $N_2/\sqrt{\theta_1}$
5. P_{S3}/P_1 vs. $N_2/\sqrt{\theta_1}$
6. T_{56}/θ_1 vs. P_{56}/P_1
7. $N_2/\sqrt{\theta}$ vs. P_{56}/P_1

The engine airflow (W_1) and thrust (F_g) measurements are available only in the uninstalled test configuration.

Figures 13(a) and 13(b) illustrate how the selection of a specific baseline can reduce data scatter caused by the engine variable geometry system characteristics. It is evident from the figures that corrected thrust (F_g/δ_1) correlates much better with corrected compressor speed ($N_2/\sqrt{\theta_1}$) than with corrected fan speed ($N_1/\sqrt{\theta_1}$).

The analysis of ETF data for a number of serviceable F404 engines indicates that a considerable variation in engine performance can occur as a result of the tolerances allowed on the setup of the variable geometry systems. For example, Figures 14(a) and 14(b) illustrate the typical scatter obtained for HP compressor variable geometry position and engine thrust measurement data. Because of this data scatter, corrections for each of the measured variable geometry positions (FVG, CVG and A_8) must be applied to the baselines noted above. The magnitudes of these corrections were determined using the engine model predictions in conjunction with field measurements. The application of these corrections results in a reduction in data scatter by a factor of approximately 2 to 3.

Having established a suitable set of baseline curves and measured performance deviations away from these curves, fault isolation is accomplished by comparing the deviations to a "library" of estimated deviations for specific engine faults. For the most part, the present F404 fault library has been derived from the engine model previously described. Figure 15 summarizes several faults which have been simulated and their anticipated effects on F404 performance in a fault matrix format. A probabilistic fault isolation algorithm has also been developed based on the assumptions that the model predictions represent the mean or expected values of the performance deviations and the actual field data will be distributed normally about this mean. In this manner, the measured performance deviations are used to assign a probability value to each candidate fault.

A preliminary evaluation of the steady-state fault isolation procedures has been conducted using data recorded by the IECMS during special ground runs performed every 25 flying hours. A control group of 8 engines was used and the performance deviations for each engine were tracked against flying hours for a period of approximately 18 months. Figures 16(a) and 16(b) show two typical trend plots for one of the control group engines. Superimposed on the plots are the significant maintenance actions which occurred during the evaluation period. It is evident from these plots that the performance measurements are quite repeatable and that distinct performance shifts can occur as a result of maintenance. For the most part, the observed engine performance changes could be attributed to readjustment of the variable geometry systems following repair. In one instance, however, an engine which experienced foreign object damage exhibited a fault signature very similar to the engine model predictions.

Evaluation of the fault isolation procedures using ETF data has only recently begun. Software has been developed which enables field technicians to assess the general condition of an engine and, if desired, display the engine fault signature. Analysis of the fault signatures is conducted by GasTOPS Ltd. and results to-date indicate that a number of common engine problems can be detected with a reasonable level of confidence. For example, Figure 17 shows a fault signature obtained from an engine immediately following a flameout in the test cell. Included in the figure for comparison is the predicted fault signature for an HP compressor variable geometry misadjustment, which proved to be the problem upon subsequent troubleshooting. A second example is given in Figure 18. In this case the measured fault signature for an engine which experienced severe HP compressor damage is compared to the model prediction for a 5% reduction in HP compressor efficiency. It is noteworthy that, with the exception of fan and nozzle problems, the model studies indicate that the F404 can sustain considerable damage to its major components and still pass the Engine Pressure Ratio performance verification test. This reinforces the need for an enhanced performance verification capability.

FUTURE WORK

The CF-18 engine performance monitoring procedures described in this paper are still undergoing field evaluations and their reliability is as yet unknown. It is evident that further development of both the operational performance monitoring and test cell diagnostic procedures will be required before they can be fully integrated into the day-to-day activities of the field maintenance personnel. In support of these developments, a number of basic research activities have also been identified.

Of fundamental importance to the operational performance monitoring program, is an improved understanding of F404 dynamic behaviour under both healthy and degraded engine conditions. The Engine Laboratory of the NRC is presently assessing the feasibility of developing a dynamic model of the F404-GE-400. This model will be used in conjunction with test cell experiments to investigate the effects of common F404 faults on the transient performance characteristics of the engine. The Canadian Forces have dedicated a special "ground runner" engine to the project. Damaged components will be implanted by the overhaul contractor and testing is expected to begin early in 1989.

In conjunction with the ground runner engine tests, an evaluation of the measurement system requirements for transient performance data analysis will also be conducted. A prototype data acquisition system has been developed by the NRC for F404 performance testing and will be installed in the overhaul contractor's test cell. If possible, performance data recorded by the NRC measurement system will be compared directly to similar data obtained from the aircraft Maintenance Signal Data Recording System (MSDRS). From this evaluation, potential improvements to the MSDRS will be identified.

As previously noted, a major impediment to using the take-off recordings for performance monitoring is the variability in these recordings introduced by the way different pilots handle the aircraft. As an alternative to the take-off recordings, special ground runs have been considered, for both transient and steady-state performance analysis. The present data handling features of the IECMS (i.e. cartridge tape data storage) make such ground runs impractical on a regular basis. However, the Canadian Forces is presently investigating the possibility of a mobile engine test unit which would access engine performance data directly from the aircraft multiplex bus. A special purpose interface between the Engine Test Facility computer and the aircraft data bus has already been developed for installed engine testing.

Future development of the test cell diagnostic procedures will focus on improvements to F404 fault library. In addition to field data analysis, the NRC Engine Laboratory has an ongoing research program aimed at quantifying the effects of common engine problems on component performance characteristics. The basic approach to the research program involves physically imbedding faults into an engine and comparing experimental performance deviations to theoretical models of these faults. The primary test vehicle for this work at the present time is an Allison T56 turboshaft engine. T56 engine instrumentation provides for data collection at the overall engine, component and individual compressor stage levels. The stage level measurements enable the results obtained from T56 testing to be generalized and subsequently applied to other engines such as the F404. A General Electric J85-CAN-15 engine and the F404 ground runner previously mentioned are also available for experimental investigations. Using the ground runner engine, the Engine Laboratory intends to correlate performance measurements taken in each of the CF-18 Engine Test Facilities to reference measurements taken in an NRC cell. At the same time, two additional F404 sensors (HP compressor inlet and exit temperature) which enhance the fault isolation capability of the test cell diagnostic procedures will be qualified. Current test plans for the J85-CAN-15 engine include fuel control unit and variable geometry system fault studies. Finally, the Engine Laboratory is also evaluating the potential of a knowledge-based or expert system approach to fault diagnosis as a means of integrating the F404 fault library data with other engine condition data sources such as oil debris analysis and vibration analysis.

CONCLUSIONS

The CF-18 engine performance monitoring procedures described in this paper show considerable promise for assessing the general health of the F404 and identifying specific component problems. The development of these methods, to a large extent, has been made possible by the availability of a comprehensive thermodynamic model of the engine, capable of investigating the effects of engine degradation in a systematic manner. Further substantiation and refinement of the performance monitoring procedures is necessary before they can be fully integrated with existing field maintenance activities. In support of this work, fundamental research in the areas of transient data acquisition and analysis and gas turbine performance analysis and testing under degraded component conditions is planned.

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1. P.M. Doane and W.R. Kinley, "F/A-18A Inflight Engine Condition Monitoring System (IECMS)", AIAA-83-1237, 1983.
2. R.J. Dupuis, H.I.H. Saravanamuttoo and D.M. Rudnitski, "Modelling of Component Faults and Application to On-Condition Health Monitoring", ASME 86-GT-153, 1986.
3. H.I.H. Saravanamuttoo and B.D. MacIsaac, "Thermodynamic Models for Pipeline Gas Turbine Diagnostics", Trans. of the ASME, Vol. 105, Series A, pp. 875-84, 1983.
4. D.E. Muir and H.I.H. Saravanamuttoo, "Health Monitoring of Variable Geometry Gas Turbines for the Canadian Navy", Paper presented at the ASME IGTI Conference, Amsterdam, 1988.

Parameter	Recording Frequency
Pressure Altitude (PALT)	10 Hz
Mach Number (MN)	10 Hz
Angle of Attack (AOA)	10 Hz
Normal Acceleration (AN)	1 Hz
Total Temperature (T_0)	10 Hz
Engine Inlet Temperature (T_1)	10 Hz
Fan Speed (N_1)	10 Hz
Compressor Speed (N_2)	10 Hz
Exhaust Gas Temperature (T_{56})	10 Hz
Exhaust Gas Pressure (P_{56})	10 Hz
Compressor Exit Pressure (P_{S3})	10 Hz
Main Fuel Flow (W_{fm})	10 Hz
Power Lever Angle (PLA)	10 Hz
Nozzle Position (A_8)	10 Hz
Oil Pressure (EOP)	1 Hz
Vibration (V1)	1 Hz
Fuel Temperature (TF)	1 Hz
Anti-Ice Valve Position (AIVP)	1 Hz
Bleed Air Door Position (BADP)	1 Hz

Table 1 - Parameters Recorded by the IECMS

Parameter	Smoothing Technique
N_1	Exponential Curve Fit
N_2	Exponential Curve Fit
W_{fm}	Spike/Flats Removal Generation of Missing Data Points 2 Point Moving Average
P_{S3}	2 Point Moving Average
T_{56}	2 Point Moving Average
P_{56}	2 Point Moving Average

Table 2 - IECMS Take-off Data Smoothing

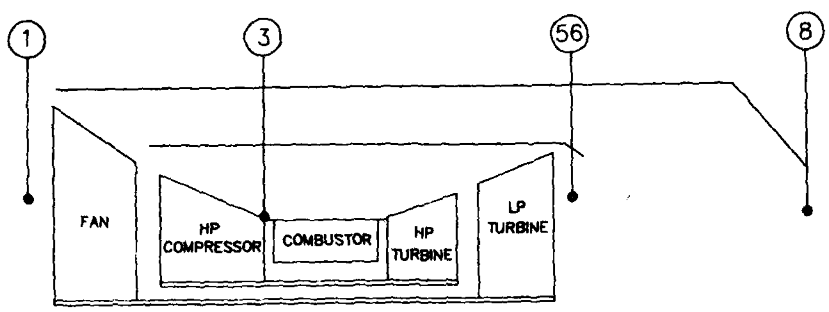

Figure 1 - F404-GE-400 Engine Layout

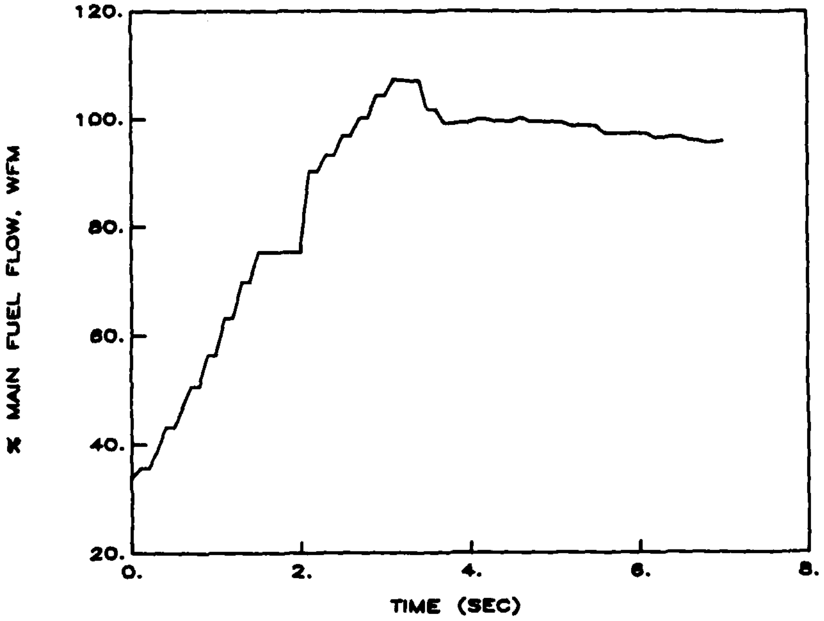

Figure 2(a) - Typical IECMS Take-off Data Recording

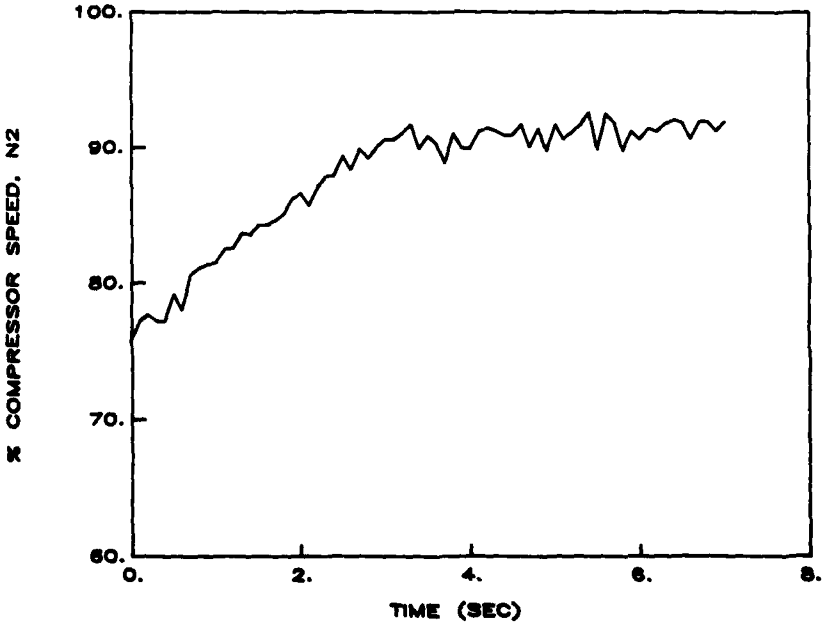

Figure 2(b) - Typical IECMS Take-off Data Recording

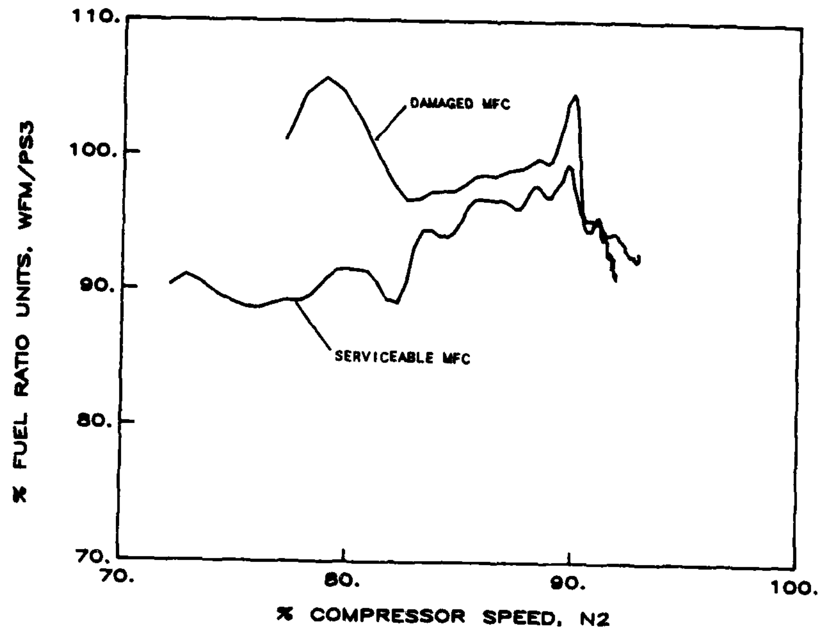

Figure 3 - Fuel Ratio Unit Traces Taken Before and After an MFC Failure

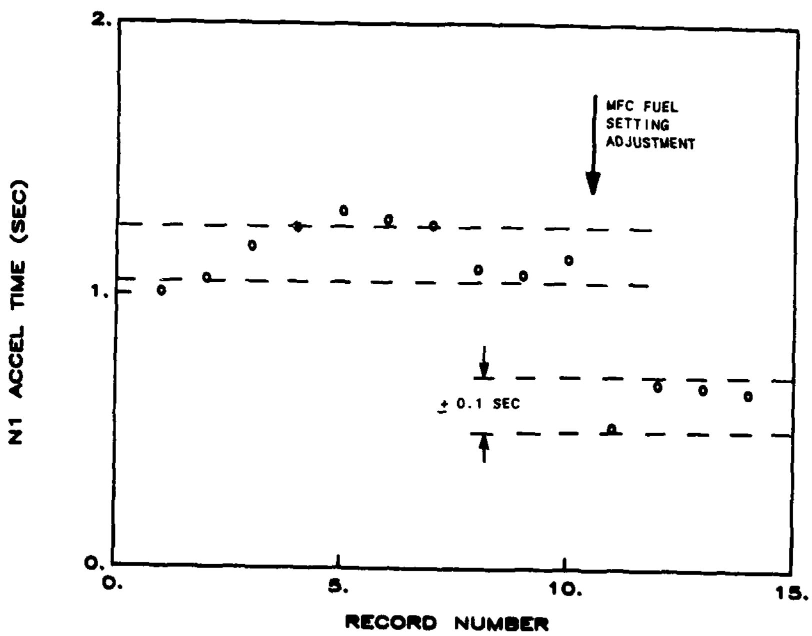

Figure 4 - Trend Plot of Fan Rotor Acceleration Times

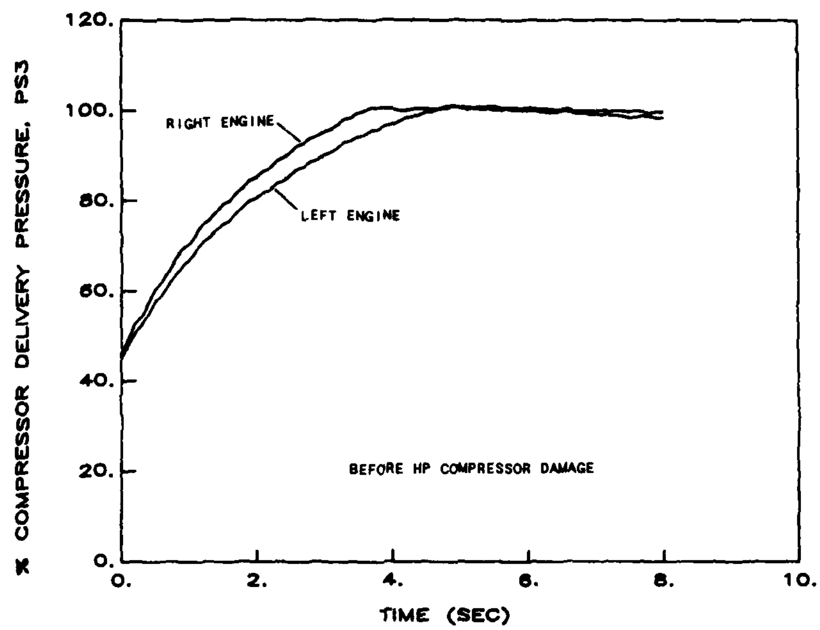

Figure 5(a) - Compressor Delivery Pressure Trace - Before HP Compressor Damage

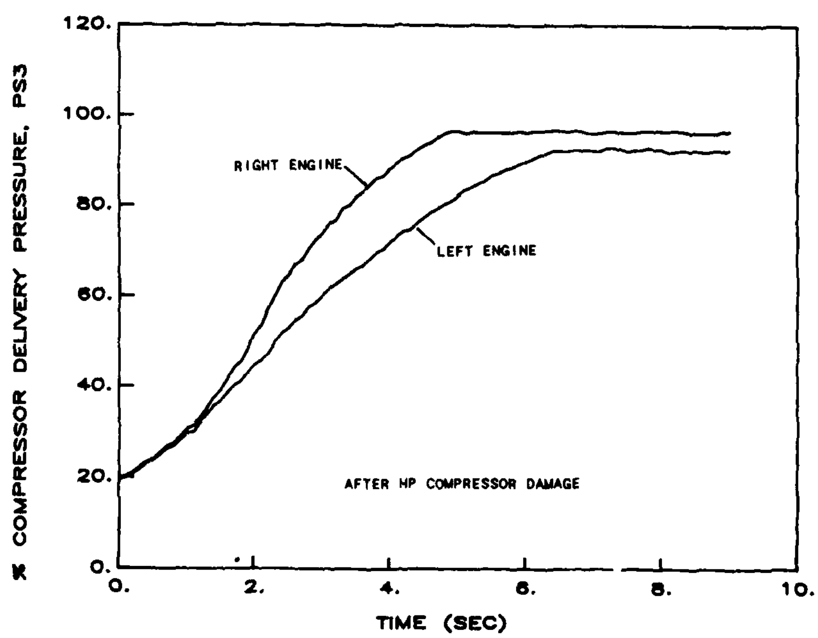

Figure 5(b) - Compressor Delivery Pressure Trace - After HP Compressor Damage

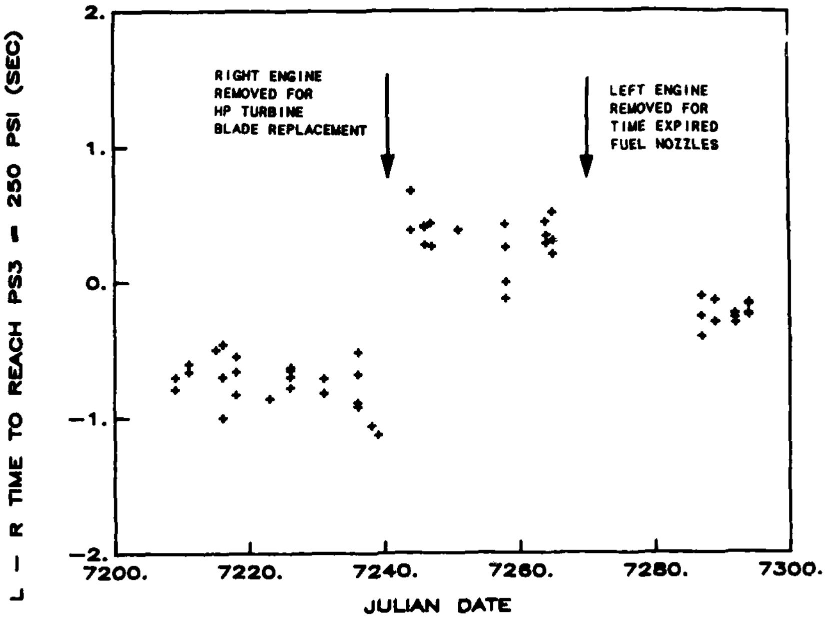

Figure 6 - Trend Plot of Left-Right Engine Compressor Delivery Pressure Rise Times

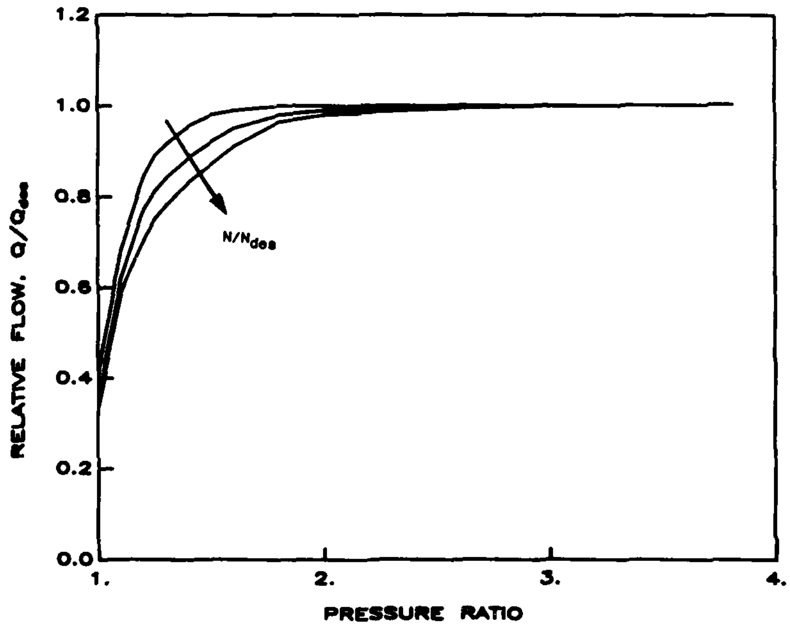

Figure 7(a) - Scaled Turbine Performance Characteristic

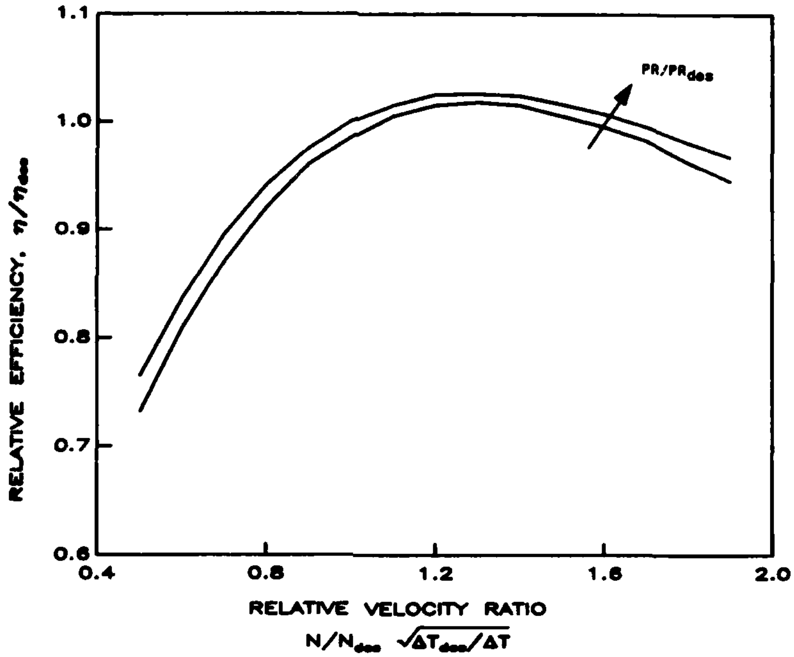

Figure 7(b) - Scaled Turbine Performance Characteristic

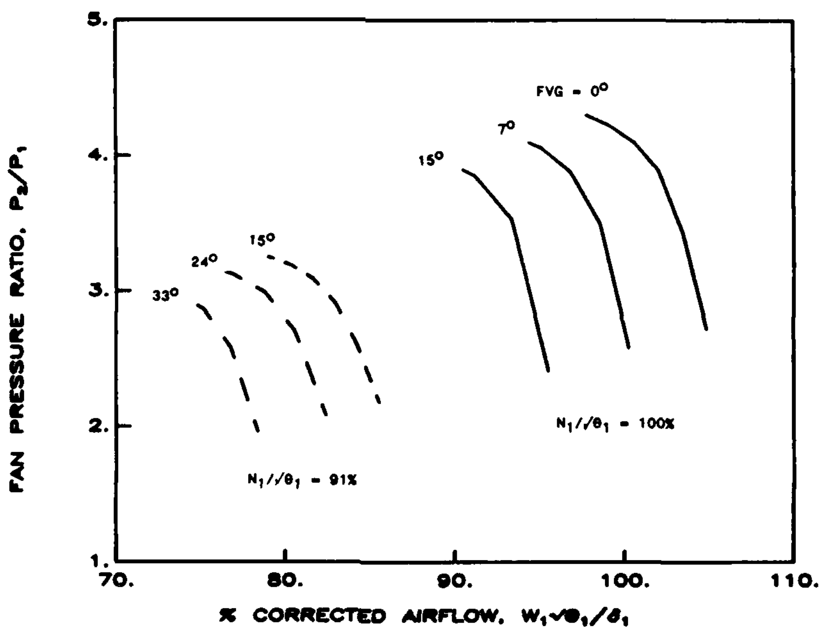

Figure 8 - Estimated F404-GE-400 Fan Performance

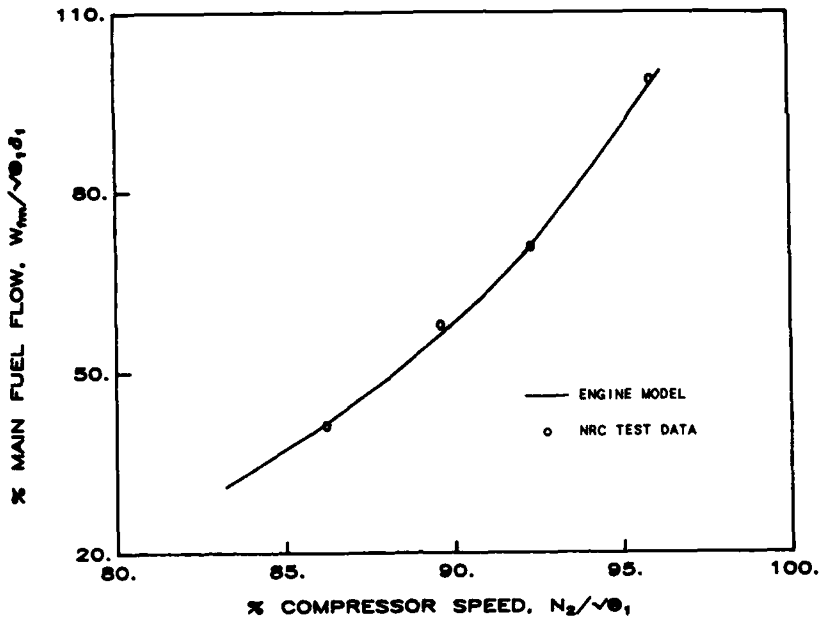

Figure 9(a) - Engine Model Validation

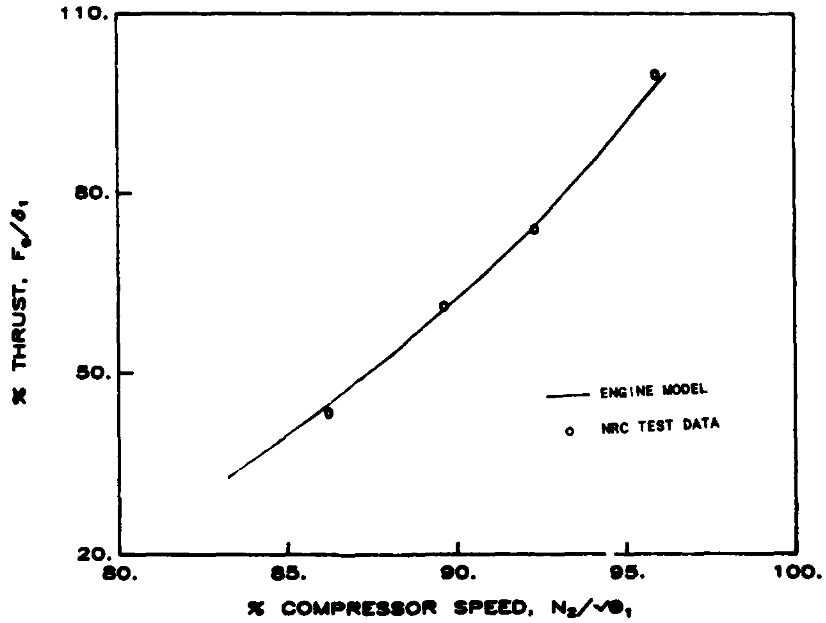

Figure 9(b) - Engine Model Validation

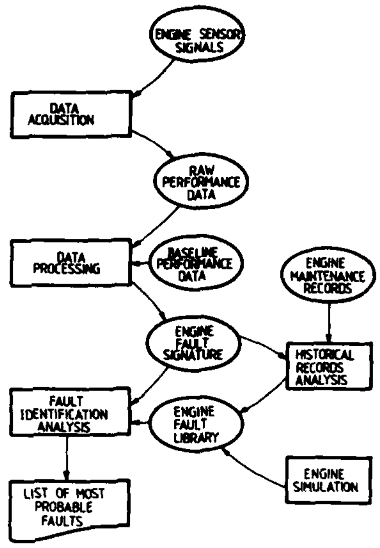

Figure 10 - Proposed use of Engine Model for Fault Isolation

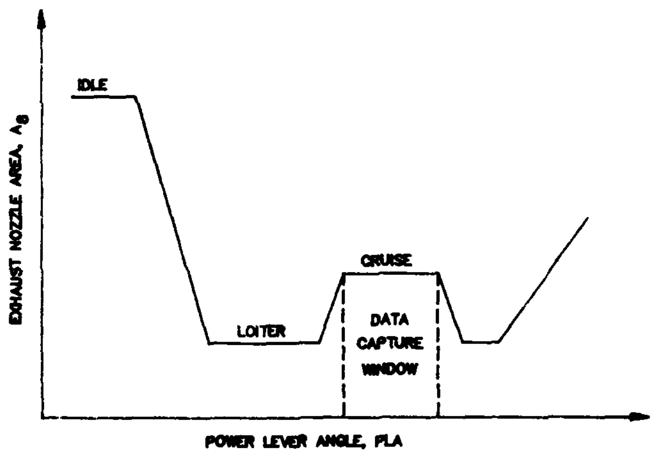

Figure 11 - Variable Exhaust Nozzle Area Schedule

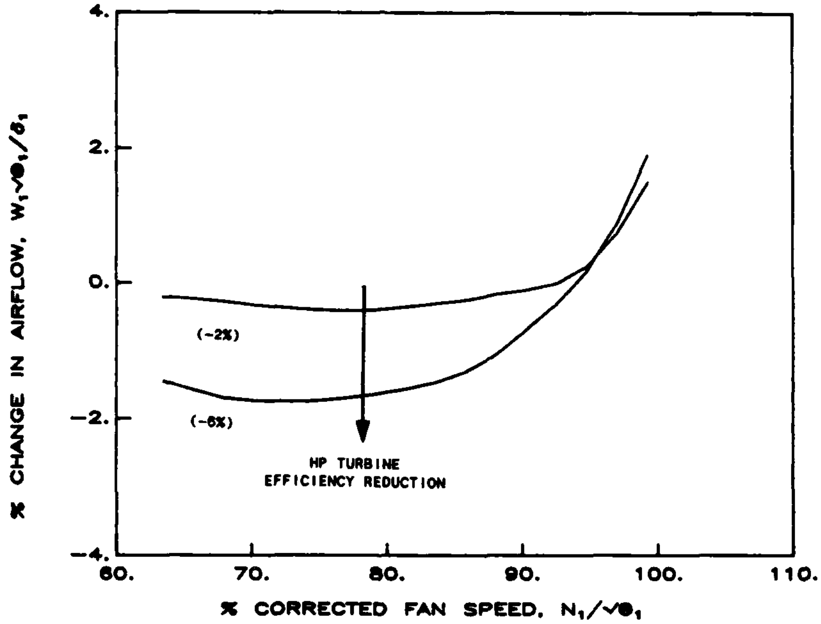

Figure 12 - Influence of HP Turbine Efficiency Degradation on F404 Airflow

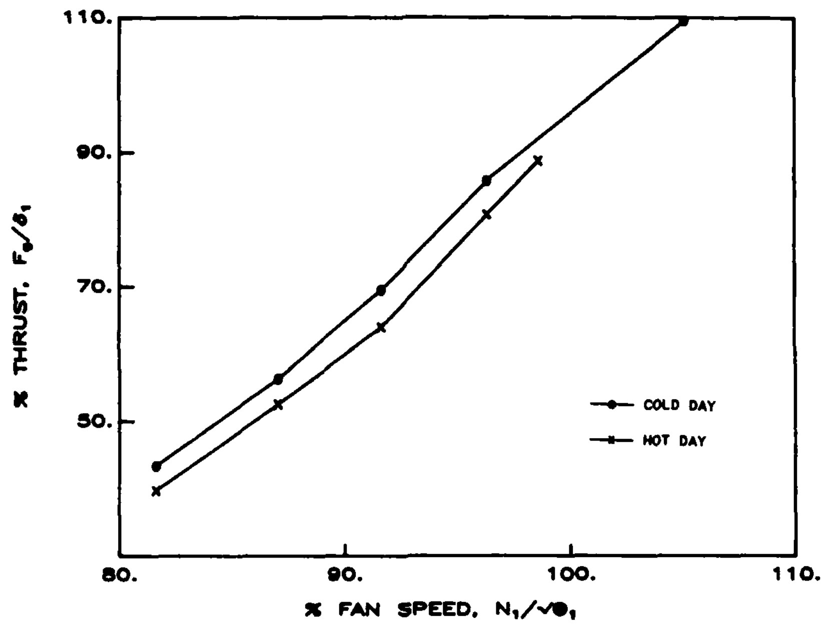

Figure 13(a) - Baseline Selection for Minimum Data Scatter

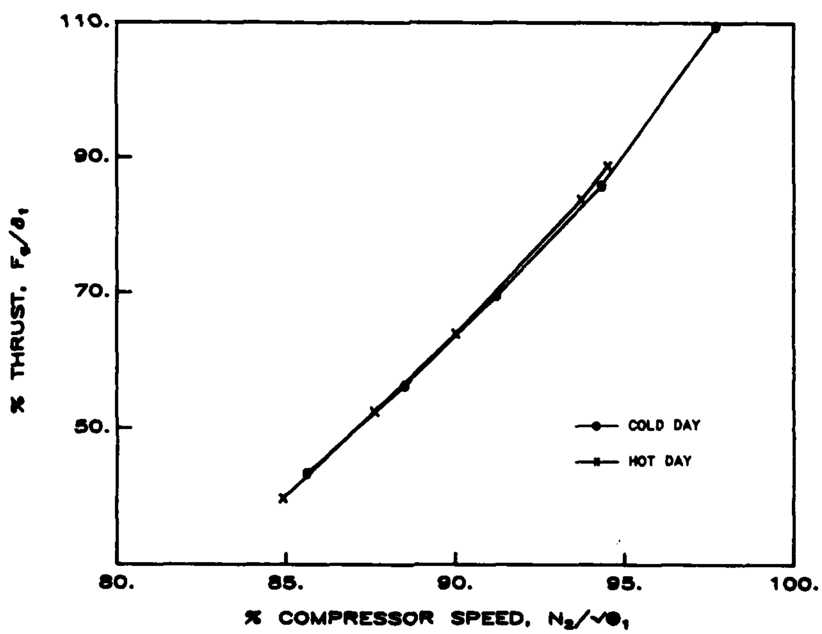

Figure 13(b) - Baseline Selection for Minimum Data Scatter

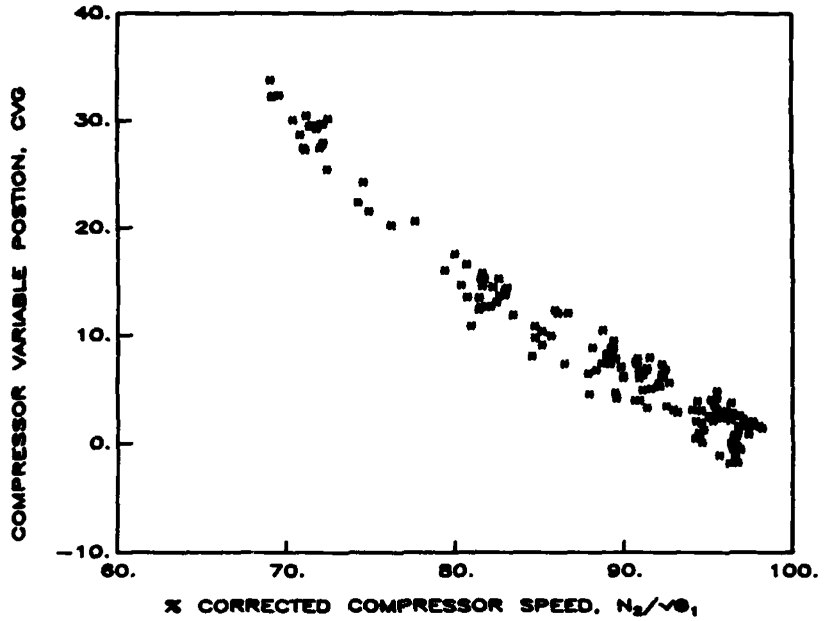

Figure 14(a) - Typical Performance Data Scatter for Serviceable Engines

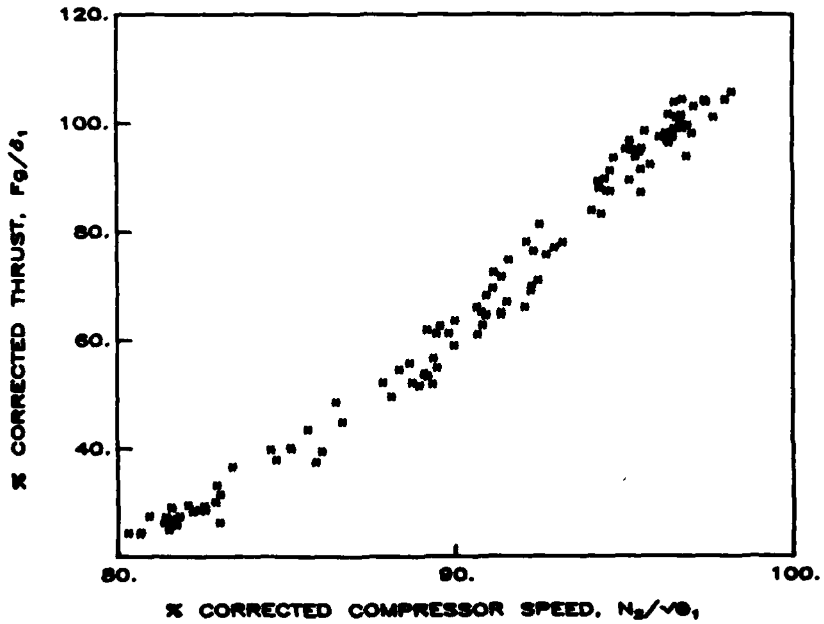

Figure 14(b) - Typical Performance Data Scatter for Serviceable Engines

Fault	Baseline $W_1\sqrt{\theta_1}/\delta_1$ vs. $N_1/\sqrt{\theta_1}$	$N_2/\sqrt{\theta_1}$ vs. $N_1/\sqrt{\theta_1}$	F_g/δ_1 vs. $N_2/\sqrt{\theta_1}$	$W_{fm}/\sqrt{\theta_1}\delta_1$ vs. $N_2/\sqrt{\theta_1}$	P_{S3}/P_1 vs. $N_2/\sqrt{\theta_1}$	T_{56}/θ_1 vs. P_{56}/P_1	$N_2/\sqrt{\theta_1}$ vs. P_{56}/P_1
1. Fan Flow/Efficiency Degradation	↓	↓	↓	↓	↓	↑	↑
2. HP Compressor Flow/ Efficiency Degradation	—	↑	↓	↓	↓	↑	↑
3. HP Turbine Efficiency Degradation	↓	↓	↑	↑	↑	↑	↓
4. LP Turbine Efficiency Degradation	—	↑	↓	—	—	↑	—
5. Fan Variable Geometry Above Limits	↓	↑	—	—	—	—	—
6. Compressor Variable Geometry Above Limits	—	↓	↑	↑	↑	↓	↓

↑ positive deviation
↓ negative deviation
— no appreciable deviation

Figure 15 - F404-GE-400 Engine Performance Fault Matrix

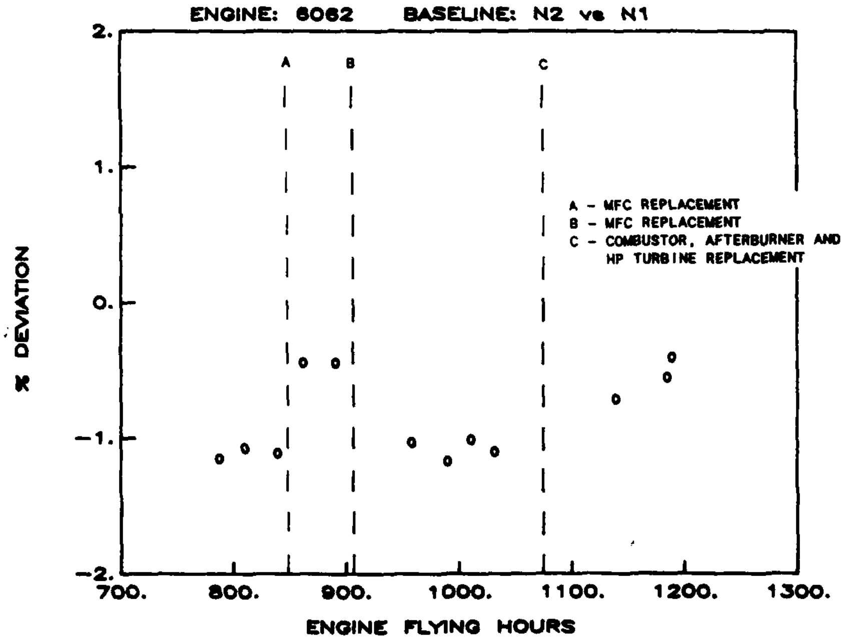

Figure 16(a) - IECMS Data Trend Plot for Steady-State Ground Runs

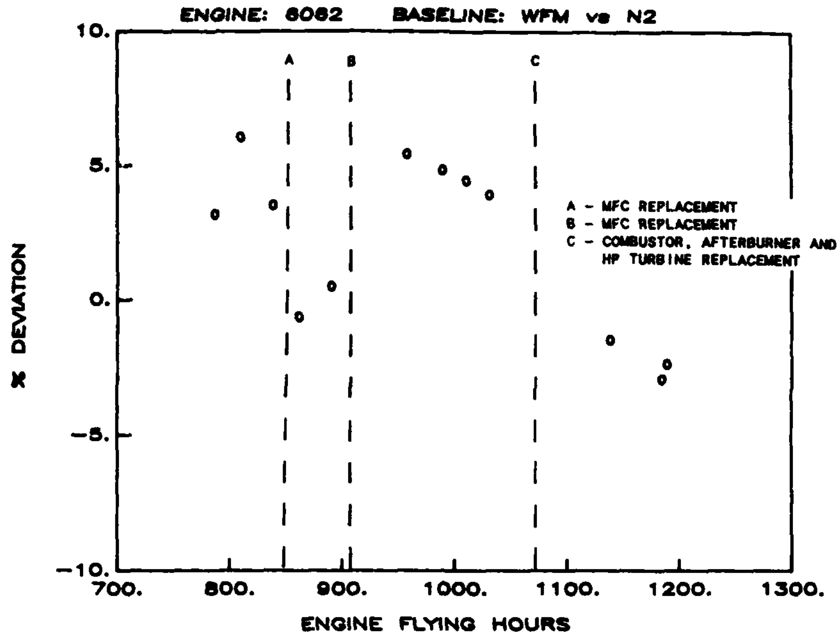

Figure 16(b) - IECMS Data Trend Plot for Steady-State Ground Runs

Engine S/N: 6060
Date: 14/11/86
Fault: Test Cell Flameout

Baseline	Measured Performance Deviation	Simulated Performance Deviation for 6° CVG Shift
$\frac{W_1\sqrt{\theta_1}}{\delta_1}$ vs $\frac{N_1}{\sqrt{\theta_1}}$	-0.3%	0.0%
$\frac{N_2}{\sqrt{\theta_1}}$ vs $\frac{N_1}{\sqrt{\theta_1}}$	-1.0%	-1.5%
$\frac{F_g}{\delta_1}$ vs $\frac{N_2}{\sqrt{\theta_1}}$	12.6%	11.7%
$\frac{W_{fm}}{\sqrt{\theta_1}\delta_1}$ vs $\frac{N_2}{\sqrt{\theta_1}}$	13.6%	11.1%
$\frac{P_{S3}}{P_1}$ vs $\frac{N_2}{\sqrt{\theta_1}}$	7.9%	8.1%
$\frac{T_{56}}{\theta_1}$ vs $\frac{P_{56}}{P_1}$	0.3%	-0.5%
$\frac{N_2}{\sqrt{\theta_1}}$ vs $\frac{P_{56}}{P_1}$	-1.9%	-1.5%

Figure 17 - Comparison of Fault Signature with Engine Model Prediction - CVG Fault

Engine S/N: 6076
Date: 30/04/84
Fault: HP Compressor Blade Damage

Baseline	Measured Performance Deviation	Simulated Performance Deviation for 5% Reduction in HP Compressor Efficiency
$\frac{W_1\sqrt{\theta_1}}{\delta_1}$ vs $\frac{N_1}{\sqrt{\theta_1}}$	0.3%	-0.6%
$\frac{N_2}{\sqrt{\theta_1}}$ vs $\frac{N_1}{\sqrt{\theta_1}}$	-0.7%	-0.5%
$\frac{F_g}{\delta_1}$ vs $\frac{N_2}{\sqrt{\theta_1}}$	12.2%	6.0%
$\frac{W_{fm}}{\sqrt{\theta_1}\delta_1}$ vs $\frac{N_2}{\sqrt{\theta_1}}$	8.0%	9.6%
$\frac{P_{S3}}{P_1}$ vs $\frac{N_2}{\sqrt{\theta_1}}$	8.2%	9.6%
$\frac{T_{56}}{\theta_1}$ vs $\frac{P_{56}}{P_1}$	2.9%	5.3%
$\frac{N_2}{\sqrt{\theta_1}}$ vs $\frac{P_{56}}{P_1}$	-1.8%	-0.7%

Figure 18 - Comparison of Fault Signature with Engine Model Prediction - HP Compressor Fault

DISCUSSION

M. BEAUREGARD

Is the IECMS only activated on take-off? Was it never considered worthwhile getting stabilized data at "50000ft"?

What do you do about installation effects in your model?

Author's Reply:

The IECMS records engine performance data each take-off and whenever a parameter limit exeedance is detected. The take-off recording was developped initially to serve as a go / no-go indicator for carrier based take-offs and has subsequently been used for performance monitoring purposes. A multi-role tactical aircraft such as the F-18 does not have a repeatable in-flight operating condition where stabilized engine performance date can be obtained.

Most of the data analyzed to date has been obtained from the test cell or from the IECMS take-off recordings (MachN° less than .35), hence intake compressibility can be ignored. The steady state engine model includes a relatively simple intake pressure loss model. The pressure loss is assumed to be proportional to flow squared.

B-1B CITS ENGINE MONITORING

by

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and

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ABSTRACT

The Central Integrated Test System (CITS) is a real-time test system which continually monitors the performance of the 34 principal systems, onboard the B-1B aircraft, including the four General Electric F101 turbofan engines. CITS consists of an onboard computer, four Data Acquisition Units, a data converstion unit, a printer, a magnetic tape recorder, and a control and display panel. Approximately 19,000 parameters are available for recording and display purposes. CITS performs the following functions:

- Provides real-time information to the aircrew in the event of a system malfunction which permits immediate evaluation of mission capability.
- Records data when faults occur, enabling fault analysis by ground personnel and automatic preparation of the appropriate work orders.
- Provides trend data and other special engine recordings for use in ground-based diagnostic systems.
- Minimizes the need for ground support equipment.

The Engine Diagnostic algorithm was designed in close coordination with General Electric. Information obtained from early test cell runs was utilized in the original logic design. Many modifications have been made as a result of flight test experience, but the overall test sequence has remained unchanged.

The Engine Diagnostic software utilizes approximately 100 parameters per engine. The test logic is exercised four times per second and a fault is declared if a failure condition occurs for six consecutive passes. Every effort is made to ensure that a single failure will result in only one fault code out of 154 possible codes per engine.

The B-1B Engine Diagnostic program is the most advanced flying test algorithm. Its inherent complexities are due to calculations of test limits based on aircraft flight mode, environmental conditions, and engine control schedules. These limits are then compared to actual engine readings, and if established limits are exceeded, a fault code is annunciated.

INTRODUCTION

Supportability was given a high degree of emphasis in planning for the B-1B because this new concept aircraft would operate from dispersal bases with limited ground support resources. As a result, the B-1B has significant self-sufficiency features not generally found on other aircraft. These features are possible because Auxiliary Power Units (APU's) were incorporated into the aircraft design to provide self-contained power for ground operations. The APU's provide the motive forces to generate electrical and hydraulic power required for alert reaction and ground maintenance operations. In addition, the APU's provide high-pressure bleed air used by the aircrafts environmental control system to cool onboard equipment and condition the crews air supply during ground operations. The other major element to providing self-sufficiency was to provide the aircraft with an onboard Central Integrated Test System (CITS).

CITS is an onboard fault detection/fault isolation system that automatically and continually tests the operation of all major B-1B systems, in flight and on the ground, and detects and isolates faults to the Line Replaceable Unit (LRU) level (see Figure 1). In flight, failed modes of operation are detected and displayed to the crew in Near-English language messages to aid in making mission-oriented decisions and in planning alternate courses of action during the flight. Detected faults, both in flight and on the ground, are automatically isolated and isolation codes referred to as CITS Maintenance Codes (CMC's) are printed on paper tape and magnetically recorded. This allows unscheduled ground maintenance to start immediately upon aircraft recovery, without the need to acquire and hookup operational support equipment.

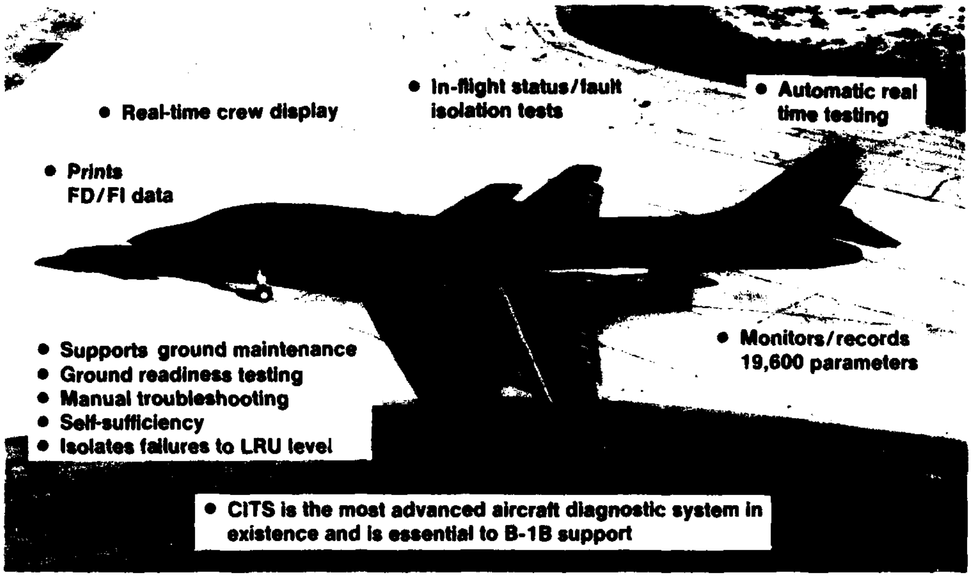


Figure 1. B-1B Central Integrated Test System (CITS)

SYSTEM DESCRIPTION

The CITS consists of a digital computer with a memory capacity of 256K 16 bit words, four Data Acquisition Units (DAU's) for interfacing with aircraft systems to transmit and receive test signal data, a Data Conversion Unit (DCU) to interface the communication and traffic control system to transmit and receive test signal data, a Control and Display Panel (CCD) for operator interface, an Airborne Printer (AP) to provide a paper copy of in-flight and ground test failure data, and a CITS Maintenance Recorder (CMR) which provides magnetic storage of B-1B failure data for further in-depth analysis of the detected failure using ground data processing (see Figure 2). A MIL-STD-1553 data bus system connects the CITS hardware to the CITS computer and the CITS computer to the avionics computer complex to accommodate the display, printing, and recording of the offensive avionics and defensive avionics testing results (see Figure 3).

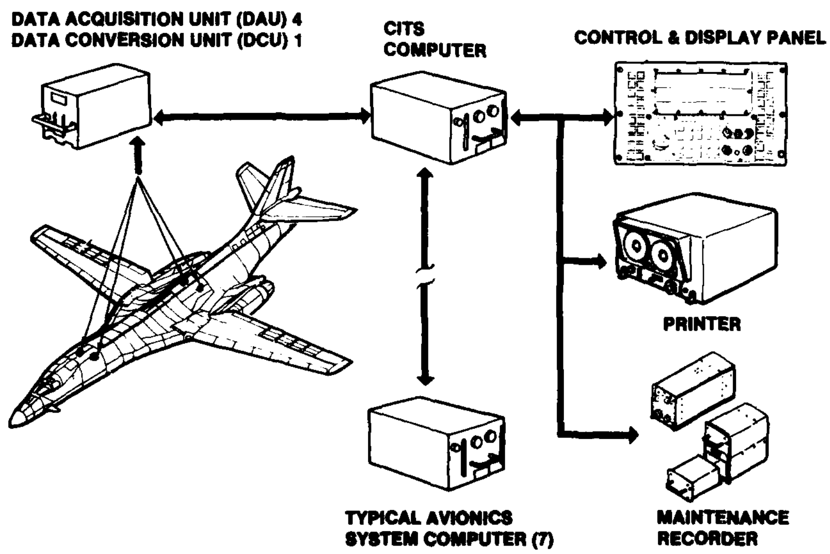


Figure 2. CITS Major Equipment

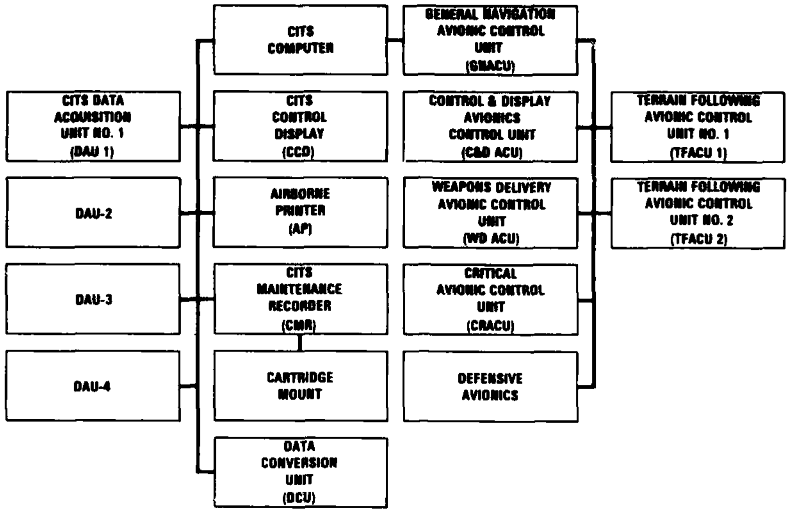


Figure 3. Integrated B-1B Test System

The onboard test functions for the B-1B are accomplished through the efforts of the B-1B Associate Contractors, with Rockwell designated as lead contractor for total system development and integration. The offensive Avionics Contractor, Boeing Military Aircraft Company (BMAC), is responsible for the testing of the Offensive Radar System, the Avionics Controls and Display System, the Stores Management System, the Inertial Navigation System and the Terrain-Following and Avoidance System. These test functions are resident in each of the associated avionic computers and terrain-following computers. Each of these computers (6) performs the testing of its related systems and reports test status of the CITS control and display panel, airborne printer, and maintenance recorder via the Avionics computer complex to the CITS computer interface.

The Defensive Avionics Contractor, AIL Division of Eaton Industries, is responsible for the testing of the Electronic Countermeasures System, the R. F. Surveillance System and the Tail Warning Function. These test functions are resident in the Defensive Avionic Computer. This computer tests its related systems and reports test status to the CITS (CCD, AP, and CMR) through the Boeing computer complex to the CITS computer interface. The B-1B Weapon System Contractor, Rockwell is responsible for providing the testing for the avionics and aircraft systems. This testing includes the Automatic Flight Control System; Stabilization Control and Augmentation System Pitch, Roll and Yaw; Flaps/Slats System; Speedbrake Spoiler System; Structural Mode Control System; Wing Sweep System; Integrated Propulsion System; Landing and Deceleration System; Electrical Multiplex System; Aircraft Structural Data Collection System; Communication and Traffic Control System; Fuel Management Systems; Environmental Control Systems; and the CITS self-test functions. These test functions are resident in the CITS computer and test status is reported on the CCD, AP, and CMR (see Figure 4). The engine manufacturer, General Electric (GE), is responsible for developing engine test and trending requirements and providing them to Rockwell for incorporation into the integrated propulsion system test functions.

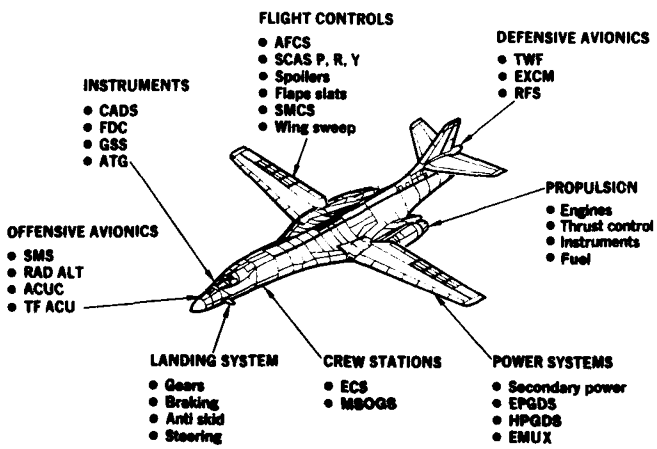


Figure 4. Systems Monitored/Analyzed by CITS

The CITS testing functions are essentially automatic with a minimum of operator action required. All test logic, failure messages, and failure codes are predetermined and fixed within the various resident-stored software programs, thus eliminating the need for the operator to interpret results or make decisions as part of the normal testing process.

SYSTEM CAPABILITIES

The major objective of the Central Integrated Test System is to detect a minimum of 95 percent of all the B-1B weapon system faults. Definition of a fault is any failure which causes a system to operate in a degraded state, thus requiring maintenance action in order to return the aircraft to full mission capability.

The second objective is to isolate the cause of a fault to a Line Replaceable Unit (LRU) for at least 65 percent of all detected faults and to isolate at least 95 percent of all remaining detected faults into groups of four or less LRU's.

The third objective is to minimize false indications to a maximum of 2 percent. Definition of a false indication is to declare a fault condition that doesn't exist, to fail to declare a fault condition that does exist, or to incorrectly isolate a detected fault.

The remaining objectives are to minimize the need for flight line support equipment and to reduce the B-1B life cycle costs. Because of the B-1B support concept, and the fact that support resources which duplicate CITS capabilities are not being procured, CITS will be essential in supporting the B-1B.

OPERATIONAL USAGE

During aircraft operation the CITS is continually and automatically monitoring all B-1B systems and reporting the health of these systems to the crew (see Figure 5). Detected aircraft weapon system faults are displayed to the crew and recorded for maintenance action when the aircraft returns to base. Optional CITS modes of operation have been provided to the operators which will allow interrogation of the test systems to obtain more detailed failure and operational information. The operator may select the parameter monitor mode of operation and through keyboard entries, access specific test parameters, up to three at a time, and observe the actual signal values in real time. This mode or operation is selectable in flight and on the ground and provides access to, and display of, approximately 10,000 aircraft signals. Another optional CITS mode available to the aircrew is the in-flight fault isolation mode in which the fault isolation codes (CMC's) for detected failure are displayed on the CCD. This mode is designed for use when an aircraft is to be recovered at an austere base. By selection of this mode, the operator can access the fault isolation codes and transmit them by radio communications to the planned recovery base. The recovery team can then be prepared to recover the aircraft and have replacement LRU's available when the aircraft lands (see Figure 6). When the aircraft is recovered at a main operating base, the crew chief removes the CITS printer tape and maintenance recorder cartridges. The removed cartridges are then taken to the CITS Ground Processor (CGP) where the data is stripped and processed. Failure data will be extracted and provided on a display terminal in the debriefing area where flight crew observed failures and anomalies can be noted and compared to the CITS detected failures.

CITS-detected failures that are isolated to a single LRU will result in a work order being generated by the Ground Processing System to remove and replace the LRU and retest the system using the CITS Ground Readiness test. CITS-detected failures that are isolated to an ambiguity of two or more LRU's will result in a work order being generated to perform additional fault isolation tests on the aircraft to further isolate the failure to a single LRU utilizing Technical Orders (T.O.'s). These

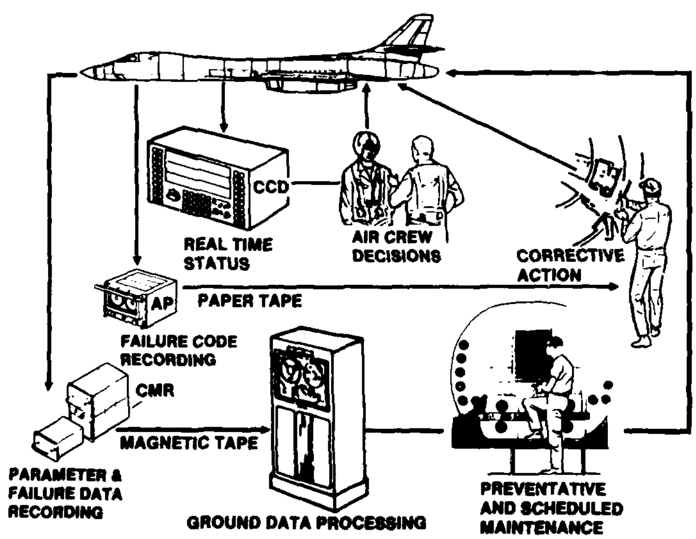


Figure 5. Central Integrated Test System (CITS)

Technical Orders will utilize the CITS capabilities of Ground Readiness and parameter monitoring and will introduce operational support equipment after all CITS resources have been utilized including the ground processing of the failure snapshots at the time of failure. After the failure has been isolated and repaired, system operation will be verified using the CITS Ground Readiness Test. Flight Crew anomaly observations for CITS tested systems that did not have a related CITS output will result in the generation of a work order to conduct the CITS Ground Readiness tests to verify the failure or reverify system operation.

Flight crew failure observations for systems not tested by CITS will result in the generation of a work order to fault isolate the problem using CITS in the parameter monitor mode of operation and or with operational support equipment.

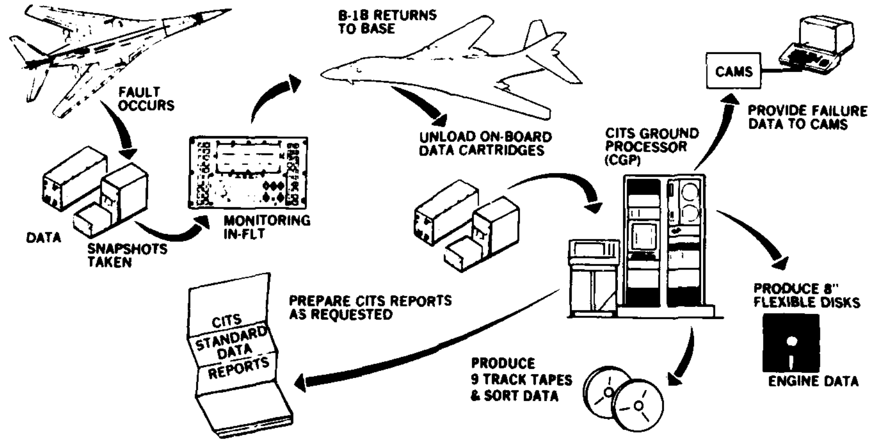
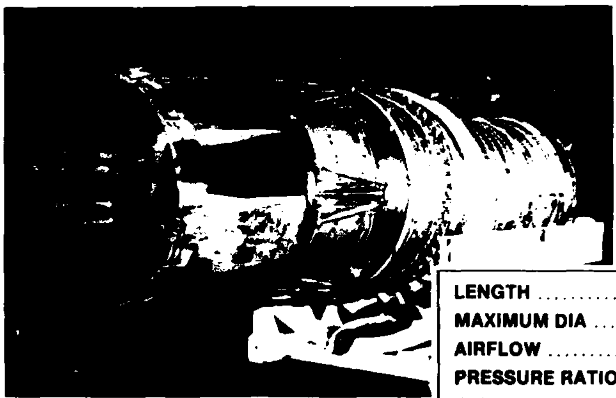


Figure 6. CITS System Data Flow

At the conclusion of the Rockwell CITS Maturation effort, a joint Air Force/Rockwell CITS evaluation was conducted at Ellsworth AFB to measure the performance of the CITS. All CITS-indicated failures and crew-indicated failures were analyzed and dispositioned as to the cause of the failure indication. The result of this evaluation indicated that the Rockwell CITS had less than one false indication per flight.

ENGINE TEST APPROACH

The B-1B aircraft is powered by four GE F101 engines. These engines are of the augmented, mixed flow, turbofan type with aerodynamically coupled low and high pressure sections and a variable area exhaust nozzle (see Figure 8).



LENGTH	180.7 IN.
MAXIMUM DIA	55.2 IN.
AIRFLOW	352 LB/SEC
PRESSURE RATIO	26.5
BYPASS RATIO	2.01
TEMP CLASS	2600° F
THRUST CLASS	30,000 LB
WEIGHT CLASS	4,450 LB

Figure 7. F101-GE-102 Turbofan Engine

The test approach for the F101 Engine Diagnostic algorithm was the result of a closely coordinated effort between GE and Rockwell. Several areas required thorough study before the test approach could be determined:

- Complete understanding of engine operation and functions.
- Thorough knowledge regarding which signal parameters were easily accessible and those which were also necessary but might require additional instrumentation.
- Understanding of the various modes of engine operation.
- Identification of the parameters necessary for useful trending data and the appropriate flight modes for trend point capture.
- Identification of the failure modes associated with unacceptable engine operation.

To simplify the analysis of the Engine subsystem, the engine components were divided into eight major systems:

- Control System
- Main Engine Fuel System
- Augmenter Fuel System
- Electrical System
- Ignition System
- Lubrication System
- Exhaust Nozzle System
- Basic Engine

The failure modes which CITS could detect and isolate were determined for each system. Accordingly, tests were designed for each system and integrated into a logical sequence. The original test approach was designed to detect engine failures which were defined as either a 10 percent power loss or as an event leading to pilot corrective action to reduce power. As the program progressed, failed sensors and failed signal processors were also fault isolated in order to prevent false failure indications for engine LRU's and to assist maintenance personnel in the field.

TEST PARAMETERS

Engine parameters which were selected for use in testing are shown in Table 1. Most of these parameters are also used for cockpit indications and engine control. All parameters in Table 1 are also recorded for engine trending purposes. The data flow from the engines to the CITS computer is shown in Figure 8.

Table 1

B-1B ENGINE PARAMETERS

CORE SPEED	ANTI-ICE VALVE POSITION
FAN SPEED	VIBRATION (3)
FAN DISCHARGE PRESSURE	TORQUE MOTOR CURRENTS (4)
FAN INLET TEMPERATURE	AUGMENTER INITIATION SWITCH
NOZZLE AREA (2)	FLAME DETECTOR SENSOR
TURBINE BLADE TEMPERATURE	AUGMENTER FUEL VALVE POSITION
INLET PRESSURE	STATUS WORDS (4)
COMPRESSOR DISCHARGE PRESSURE	OIL PRESSURE
DUCT PRESSURE RATIO	OIL TEMPERATURE
INLET GUIDE VANE (IGV) POSITION	OIL QUANTITY
POWER LEVER ANGLE	CORE FUEL FLOW

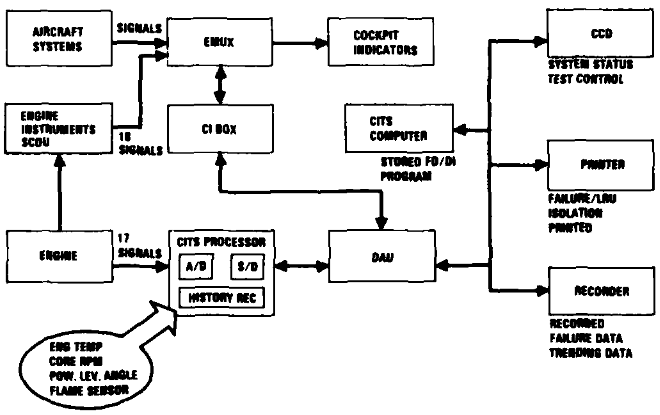


Figure 8. CITS/Engine Interface Typical 4 Engines

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Ex. 1034, p. 85

Other parameters outside of the engine are also required for monitoring. These are necessary to determine operating mode and environmental conditions. Examples of some of these parameters are listed in Table 2.

Table 2

B-1B ENGINE RELATED PARAMETERS

MACH	AIRFRAME FUEL FLOW
AMBIENT PRESSURE	THROTTLE POSITION
IGNITION SWITCH POSITION	CIRCUIT BREAKER STATUS
START SWITCH POSITION	RELAY STATUS
SPEED LOCKUP SWITCH POSITION	FUEL TEMPERATURE
FUEL SHUT-OFF VALVE POSITION	INLET LIP POSITION

LOGIC DESIGN

Information obtained from early test cell engine runs was utilized to provide test limits in the original logic design. Three basic operating modes were selected for testing.

- Start-Up Cycle
- Transient State
- Steady State

The Engine Start Cycle portion of the test involves testing certain conditions such as: ignition, hot start, hung start, and slow start.

The Transient State portion of the test is applicable when engine parameters are at constant unrest. This may include signal and sensor integrity, oil pressure and temperature, vibration, compressor stall, turbine blade temperature, augmenter control, and rapid power loss.

The Steady State portion of the test is applicable when engine parameters are observed to be steady. This may include nozzle control, augmenter control, inlet guide vane position, fan speed, and speed ratio. Various engine control schedules are computed at this time. Figure 9 displays an example of a typical engine schedule, turbine blade temperature versus fan inlet temperature.

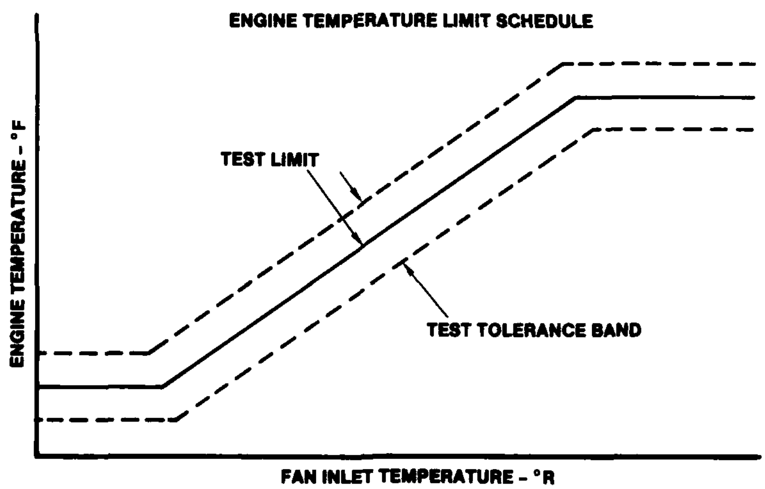

Figure 9. A Simplified Engine Control Schedule

When the engines are perceived to be in a steady state condition, different tests are performed depending on whether the aircraft is on the ground or airborne. While on the ground, a ground thrust test occurs. While airborne, an engine-to-engine comparison is performed for fan speed, augmenter fuel flow, and fan pressure ratio. A torque motor signal validity test is performed in either case. See Figure 10 for a block diagram of the logic flow.

Preconditions, which include relay statuses, circuit breaker statuses, and various switch settings, are examined at the beginning of the test to prevent false failure indications. Counter and flag initializations and frequently used computations are also performed at this time. Engine parameters are sampled and the test logic is exercised at a rate of 4 times per second.

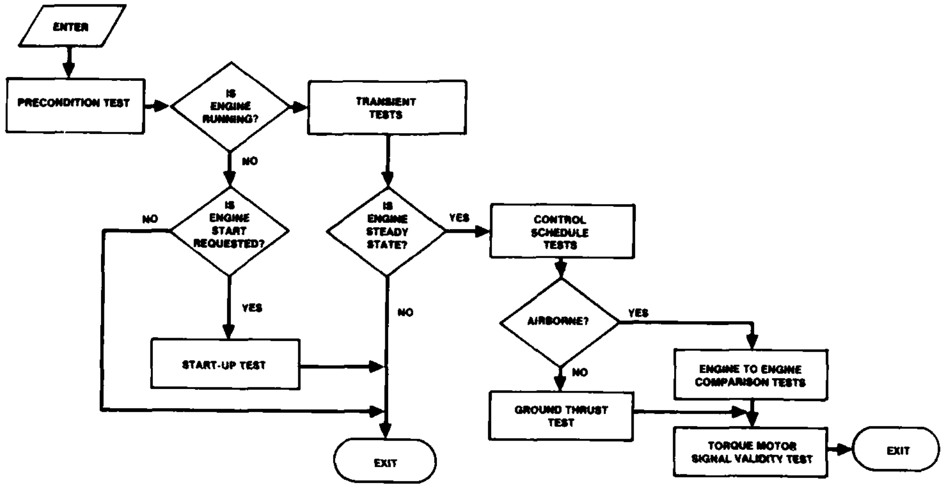

Figure 10. F101 Engine Test Logic Flow

A typical test sequence, whether it is a transient, steady state, or any other type of test consists of the following steps:

- A validity check of the signals to be used in the test is performed. A valid signal parameter is within its normal range and the sensor appears to be behaving normally. If the signal validity check fails, the test is bypassed.
- Environmental conditions are determined, if necessary. For example, in the augmenter control test, compressor discharge pressure must be above a certain limit before the test can be performed. If compressor pressure is below this limit, the engine is outside of the test envelope and the test is bypassed.
- Switch positions are interrogated for correct configuration, if required for the test.
- Actual engine readings are compared against previously established limits plus or minus a tolerance. Test limits are determined by the hardware design, such as minimum allowable oil quantity. In the case of control schedule tests, the appropriate input parameter(s) are used to compute the scheduled value for the tested parameter, allowing for environmental conditions and aircraft flight mode. (For example, the scheduled turbine blade temperature is computed using the actual fan inlet temperature. See Figure 9). When an actual reading exceeds the reference, a fault has been detected and a failure code is annunciated.
- If more than one LRU is suspect, fault isolation is performed using failure mode information for the individual LRU's. Ideally, a failure can be isolated to a single LRU by the CITS logic. When this is not possible, additional data analysis and troubleshooting must be done by ground crews. See Figure 11 for a block diagram of a typical test sequence.

CITS ENGINE DIAGNOSTICS IN THE REAL WORLD

When the CITS was initially installed on the B-1B aircraft, false failure indications plagued the entire system, especially the engine diagnostic area. Hundreds of hours had been spent in laboratory testing and design reviews prior to release. However, the engine diagnostic algorithm is very complex and engine performance depends entirely upon environmental conditions and pilot discretion, which makes thorough testing extremely difficult. Each area of the test exhibited deficiencies which had to be corrected to eliminate the false indications.

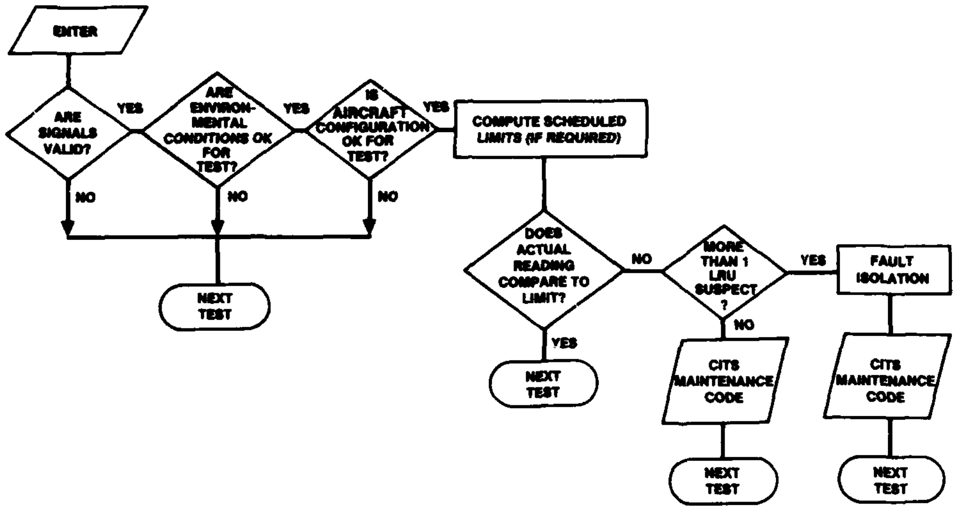

Figure 11. A Typical Sequence

START-UP CYCLE

In the start-up cycle test, one of the first deficiencies to appear was the inability of the test logic to distinguish between an engine start problem and an aircraft ignition circuit problem, something which frustrated maintenance personnel in the field. Fault isolation of the aircraft ignition circuitry was added to solve this problem. Also, hot start limits were adjusted upward to provide more realistic levels where maintenance action would be required.

TRANSIENT STATE

In the Transient State test, several types of problems were encountered. Engine signal processor failures could not be distinguished from CITS interface hardware failures, so CITS hardware self-test parameters were added to the logic prior to testing the signal processor.

The Power Lever Angle (PLA) is a key parameter in the test logic because it defines the engine power setting. Failures of the PLA transducer were undetected thereby triggering many false alarms in the engine control schedule logic. The failure mode for the PLA tranducer was defined and logic was designed to isolate this failure without creating false alarms in another CITS System, the Engine Thrust Control System

A failure mode for the exhaust nozzle is tested in the Transient test. This false failure occurred when transitory movements of the nozzle created the right conditions to set the failure code. A software timer was placed in the logic to correct this problem. The timer approach was also used when switches, such as the anti-ice switch, changed state to allow for hardware response time and when transient out-of-limit parameters, such as low oil pressure, caused false alarms during certain airborne maneuvers.

Another key parameter to engine diagnostics is the corrected fan speed. Sometimes, the fan speed parameter would fail in a degraded manner which was not detected by the logic causing false alarms in the engine control schedule tests. A comparison of the fan speed parameter from two sources corrected this problem.

Differentiation between sensor malfunction, signal processor malfunction, and an actual LRU failure was sometimes difficult. For instance, an out-of-limit vibration parameter might require troubleshooting to isolate the three possibilities (depending upon pilot reported anomalies). When a signal parameter failed in a degraded fashion, fault isolation was especially difficult. Field experience with the actual failure rates of the involved components has been the only answer to this problem.

The fault filter for CITS subsystems was orginally a 3 pass filter. Early field experience with the engine test seemed to indicate that this filter (which would declare a fault in little more than 0.5 seconds) was resulting in false failures during transient situations. Changing the fault filter to 6 passes seemed to be a reasonable solution to this problem. After all, a hard failure would surely last at least 1.25 seconds.

This approach worked well, except in one very important area, compressor stalls. During stalls, many parameters change rapidly. As a result, many different logic paths are taken during the failure, and the 6 pass filter requirement is sometimes not met before the core speed drops below the minimal tested level. The end result is that no CMC appears and a loss of failure data occurs. An investigation is being conducted to determine if the fault filter should be set to 3 passes for these types of codes.

Augmenter light-off time is tested in the transient state. This was a common false failure until appropriate preconditions and timers were added depending upon which area of the flight envelope the aircraft was in.

Rapid power loss was an early false alarm. This appeared when the engines were turned on because certain counters and flags were not properly initialized when CITS was powered up.

STEADY STATE

A small, but very critical code error in the steady state logic caused many control schedule false alarms. With the complex and comprehensive logic required in engine diagnostics, it is unrealistic to expect that every logic path can be tested prior to release. Infrequent software errors are expected to appear as more logic paths are exercised in the future.

Unanticipated hardware failure modes resulted in nondetection of some nozzle control schedule faults. Field reports of undetected stalls resulted in additional logic to correct this deficiency.

The IGV control schedule test was modified primarily in the area of test limits and tolerances. Limits which were valid in the test cell were not appropriate to everyday field operation and resulted in false failure indications. The tolerances were adjusted to account for environmental conditions and errors inherent in signal transmission hardware.

In the engine-to-engine thrust comparison test, fan inlet pressure is used in the relative thrust calculations. During some unusual in-flight maneuvers, this parameter would vary across the four engines and produce false engine comparison failures between the outboard engines. This problem was solved by averaging the four fan inlet pressures and requiring that they each be within a small range of the average prior to using that engine in the thrust comparison. Fault isolation of the fan inlet pressure and fan discharge sensors was also necessary to prevent false thrust comparison faults.

Augmenter fuel flow comparison was discovered to be unreliable at the minimal flow levels. Therefore, a minimum level of fuel flow was established as a precondition to that engine being used in the comparison test.

Obviously, many modifications have been made to the test logic and software coding since the initial release. The coordination of these changes by Rockwell and GE was facilitated by regularly scheduled meetings which were attended by GE engineering, Rockwell engineering, and military maintenance personnel. The maintenance personnel provided valuable insight into the areas where CITS was doing well and where it could be improved from a practical standpoint. Feedback from the field regarding failure codes exhibited and actual maintenance performed is essential to the verification of this type of program.

Successful fault detection and isolation has occurred in all areas of the logic. Table 3 contains a list of the types of engine failures which have been detected by the CITS Engine Diagnostic test during the past 3 years of B-1B service.

It must be remembered that some engine problems cannot be detected by the CITS. These include metal fatigue, hydraulic leaks, clogged filters, and loose cables or connectors.

Table 3

ENGINE FAILURES DETECTED BY CITS

LOW OIL QUANTITY	RAPID POWER LOSS
HOT STARTS	NOZZLE OFF SCHEDULE
SLOW STARTS	IGV OFF SCHEDULE
LOW OIL PRESSURE	FAN SPEED OFF SCHEDULE
HIGH OIL TEMPERATURE	FAN SPEED MISCOMPARE
HIGH VIBRATION	SIGNAL VALIDITY
COMPRESSOR STALL	INLET TEMPERATURE SENSOR
HIGH TURBINE TEMPERATURE	ELECTRONIC CONTROLS
SLOW AUGMENTER LIGHT	FAN SPEED SENSOR

SPECIAL ENGINE RECORDINGS

In addition to fault detection and isolation, CITS records specified parameters at a rate of 4 per second during certain out-of-limit conditions such as: high turbine temperature, fan or core overspeed, high thrust, augmenter fuel flow miscompare, and rapid power loss. This data has proven to be extremely valuable when analyzing severe engine failures such as compressor stalls.

Trend data is also acquired each flight at take-off and during climb and cruise when the correct conditions are met. Engine start and stop times are recorded, as well as engine serial numbers, to facilitate accurate trending of each engine in ground-based diagnostic systems.

CURRENT STATUS

A month-long evaluation was conducted at an operational B-1B base to determine the reliability and usefulness of the CITS. Pilot reported anomalies and failure codes were tracked on 13 aircraft for 33 flights. Seven unique engine fault codes occurred on five aircraft during eight of 33 flights (one code repeated on two flights). Data analysis revealed that five codes could be isolated to a single LRU. The remaining two codes required troubleshooting to resolve an ambiguity between two or more

LRU's. Three types of LRU's were isolated including two AFT controls, a signal conditioner, and a fuel valve control. There were no undetected engine failures. This results in an average of 0.05 failure codes per engine per flight. One failure indication isolated the incorrect LRU.

The Engine Diagnostic algorithm has evolved into an extremely useful tool for engine maintenance. At the time of writing, two potential false alarms existed which are scheduled for correction this year. Potential false alarm refers to a code which does not appear on every flight, but it could appear depending upon environmental conditions. Another area is being investigated for improved fault detection of high turbine temperature at sub-idle core speeds.

CONCLUSION

The substantial amount of engine condition monitoring experience gathered during the early years of B-1B deployment has resulted in many modifications to the original test design. Hopefully, this experience will allow future systems to be designed and implemented on multi-engine aircraft with fewer initial problems. The issues which need to be considered and resolved when designing an engine monitoring system fall into the following areas:

- Design the engine hardware with monitoring in mind. This includes providing the appropriate test points and providing the most reliable sensors possible. Because perfect sensors do not exist at this time, a method should be provided to differentiate between sensor malfunction, signal conditioner/processor malfunction, and actual LRU failure.

- Determine the minimum complexity of the algorithm necessary to perform the test function. An extremely complex algorithm is expensive to design and implement. It also consumes a large amount of computer time in a real-time system. The B-1B engine test may or may not be more complex than necessary, but this will only be determined by continued evaluation over years in the field.

- Provide the most effective means of communication between the personnel involved in the test design, test implementation, and the users in the field. Expertise from many areas is required when designing the test logic. Engine hardware design, performance, and controls information is vital to the algorithm design. This design must be correctly transmitted to the software programmer. Evaluation of the final product requires consistent input from maintenance personnel in the field. Formal written interface documents and regularly scheduled meetings between the interested parties are essential to the success of an engine monitoring program. This is particularly important in a fully integrated test system.

With computer technology rapidly advancing to decrease computer size while increasing memory capacity, engine monitoring will become more sophisticated. The long-term goal should be automatic fault isolation to a single LRU requiring a minimum of human intervention.

DISCUSSION

H. MAY

You are recording the turbine blade temperature. How do you determine this temperature?

Author's Reply:

Turbine blade temperature is determined with the use of a General Electric developed pyrometer which has an accuracy of + or - 10 to 15 °F at the limiting temperature of 1750°F.

D.E. COLBOURNE

Do you use the same capture rate in steady state and transient phases of engine operation?

Author's Reply:

Data recording rate is determined by the purpose of the recording, not whether it is transient or steady-state. The data capture rates are as follows:

1. Fault dode recording- 3 aircraft data "snapshots" total:
   - At time of fault declaration
   - 30 seconds after fault
   - 60 seconds after fault
2. Trend data capture at take-off, climb or cruise- 8 trend data recordings total at 1/4 second intervals.
3. Trend data capture for certain faults, such as rapid power loss- 20 trend data recordings total at 1/4 second intervals.
4. Special recordings are done at a rate of 1/4 second intervals for as long as the condition lasts, such as a high turbine temperature. These recordings consist of a very limited number of parameters.

ENGINE LIFE CONSUMPTION MONITORING PROGRAM FOR RB199 INTEGRATED IN THE ON-BOARD LIFE MONITORING SYSTEM

by
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SUMMARY

The On-Board Life Monitoring System (OLMOS) of the GE Tornado consists of on-board equipment (Data Acquisition Unit DAU) where the majority of the data processing is carried out, and of ground equipment (OLMOS Ground Station OGS, connected to the Central Logistic Support System BMS) where the majority of the data management tasks are carried out.

The Engine Life Consumption Monitoring Program (ELCMP) is part of OLMOS. Its main task is LCF life consumption calculation, which consists of data acquisition and data checking, calculation of temperatures and stresses, as well as damage assessment. A general view of the calculation path within ELCMP is given, and the hardware structure of the system is presented. Some advantages of individual and complete engine monitoring are pointed out.

1. INTRODUCTION

The On-Board Life Monitoring System (OLMOS) is a system for monitoring the life consumption of the Tornado aircraft in the German Air Force.

The requirements of the German Air Force for this system and its functional structure are presented in /1, 2/. The monitoring tasks carried out by OLMOS are the following:

- engine life consumption monitoring
- structure life calculation
- structure limit exceedance monitoring
- event monitoring
- logistic data monitoring.

Basic requirements are individual monitoring of each aircraft and each engine by means of on-board data processing, on-board result storage, and on-board bookkeeping of the state of engine life consumption.

The Engine Life Consumption Monitoring Program (ELCMP) is that part of OLMOS which covers the monitoring procedures for the Turbo Union RB199 engine installed in the Tornado aircraft. ELCMP contains as primary tasks

- LCF life consumption calculation of group A parts
- performance trending
- diagnosis and statistics

during engine running, which are carried out on-board in real time.

Result storage as well as data transfer is done by means of a set of accounts. There are two types of accounts. The first are accumulating accounts. They have to be set to an initial value before the system operates. In particular, after any maintenance action (e.g. replacement of an engine) these accounts have to be updated before further engine operation. Their values after an engine run are the sum of the value at the beginning of this run and the results obtained during this actual run.

The second type of accounts are overwritten during every engine run. They contain only results of the most recent engine run. These nonaccumulating accounts are updated only when the engine run exceeds a certain time threshold. This provides against information loss in case of mishandling of the system.

The accounts contain the actual state of engine life consumption. The comparison with the approved values is made on ground. For this purpose the accounts are milked frequently, and the data are transferred to the OLMOS Ground Station (OGS) and the Central Logistic Support System (BMS), where the comparison is made and required maintenance steps are initiated.

2. STRUCTURE OF OLMOS

The OLMOS system includes

- on-board functions, such as data acquisition, data processing, and result storage
- transfer functions, such as data transfer between aircraft and ground station and quick-look of the results.
- ground functions, such as data management, data display and data update.

The respective tasks are carried out in dedicated equipment as shown in Fig. 1.

The on-board equipment consists of the Data Acquisition Unit (DAU), which acquires the data from the different sources, processes the data, and stores the results. The DAU also provides data for recording at Crash Recorder (CR) and Maintenance Recorder (MR). In case of faulty DAU operation, it initiates a DAU-fail indication on the Central Maintenance Panel (CMP).

Data are transferred between aircraft and ground station by means of a Hand Held Terminal (HHT), which is a portable, battery-powered piece of equipment. The battery serves as power supply for the DAU during the data transfer process, too, so that for this purpose powering of the aircraft is not necessary. The HHT is designed to collect and transfer data of up to 12 aircraft. Furthermore it serves to display data for quick-look purposes or in the event of the ground station not being available.

The OLMOS ground station has the task of data management and data display for all aircraft of an air base. This includes the abilities of data update in consequence of maintenance actions. Additionally, the OGS is connected with the Central Logistic Support System.

Further details of the structure of OLMOS were published at the 14th International AIMS Symposium /3/.

3. SAFE AND ECONOMIC ENGINE LIFE USAGE

Aircraft engines contain a number of parts which cannot be operated for unlimited periods. These parts have to be retired before life limit exceedance. When the life limit of a part is reached depends on its life potential and the operational usage.

Group A parts are parts of an engine whose failing could jeopardize the aircraft. The life of the group A parts of the RB199 engine is limited by Low Cycle Fatigue (LCF). Such a part has reached its life limit after a certain number of load cycles, which is defined during engine development and design. When the limit number of cycles is reached, the respective part has to be retired. If not, the probability of failure will rise rapidly.

To assure safe and economic usage of the life potential of the RB199 engine, is the most important objective of the ELCMP within OLMOS. This is achieved by means of individual and complete engine life usage monitoring. Individual usage monitoring has clear advantages compared with the usual general life usage monitoring method.

Fig. 2 shows life-consumption distribution curves versus the ratio of real life consumption to calculated life consumption, where calculated life consumption is calculated either individually by OLMOS or generally by cyclic exchange rates (ß-factors) and flight time. The advantage of individual - and of course complete - life usage monitoring is proved by the considerably smaller scatter band in the distribution curve of individual life monitoring compared with general life monitoring.

Based on individual and complete actual usage monitoring, safety increases because the risk of exceeding the approved life limit is smaller than when general monitoring is used.

On the other hand, individual and complete usage monitoring means that for each component of the engine the life consumption is calculated and compared with the approved life, and so each individual component can be used until its approved life is consumed. Consequently, as a result of more efficient use of the life potential, individual monitoring means an improvement in economy because no component will be retired earlier than necessary.

From Fig. 2 it also can be seen that the cyclic exchange rate must be conservative with respect to safety, and therefore it is not very economic. But, if it were more economic the distribution curve for general monitoring would shift to higher ratios and the objective of safety would be violated.

4. MONITORING CONTROL PARAMETERS

Individual and complete engine usage monitoring is carried out using ELCMP, which is operated within the DAU. To control the monitoring calculations a set of monitoring control parameters is employed. This parameter set contains the most important constants of the algorithms.

Minor changes and refinements to the algorithms can easily be adapted by simply changing the monitoring control paramenter set, leaving the ELCMP-software unchanged.

5. ENGINE IDENTIFICATION

To avoid data confusion, engine identification

- with respect to the individual engine and

- with respect to the engine configuration

is necessary.

Identification is effected by means of an engine identification code (see Fig. 3).

The individual engine is identified by its serial number.

Engine configuration identification is necessary because the engine configuration has an influence on LCF calculation and performance trending. All steps within the calculation path may be affected by modifications in engine design. The number and location of monitored areas may change with the engine configuration, too. Consequently, for different configurations different algorithms or different parameters may be valid. The actual configuration is identified by a configuration combination number, an engine variant code, and a number of group A part codes.

The engine identification code serves to control all the possible options within ELCMP. It also contains a software revision number for identifying the required software version. If the software version in question does not meet the requirements, monitoring calculations are not possible. ELCMP checks whether the requirement is met. If the result is negative, the monitoring calculations will not be carried out, and a respective diagnosis account will be flagged.

Every software version will be compatible with earlier engine configurations, so that the latest software version will meet all requirements.

6. CALCUALTION AND PROCESSING STRUCTURE

The whole calculation and monitoring process of ELCMP is orientated on an engine running history, as shown in Fig. 4. It is divided into three parts, which are separated by particular criteria.

The first or initial part begins with DAU power-up. After power-up, a built-in test is carried out and the monitoring control parameter set is loaded into the processor. Afterwards, the input data are checked to ascertain if the start criterion has been reached.

The start criterion is reached when the engine speed rises to idle. Then the main part of the monitoring process, consisting of plausibility checks of the input data and of life consumption calculations, and including the performance trending procedure, commences.

All steps of the main part of the monitoring process are repeated every 0.5 seconds. The process is finished when the end criterion is detected. The end criterion is defined by engine shutdown while the aircraft is on the ground.

After the end criterion has been reached, the final part of the monitoring procedure is carried out. That means the LCF calculation is completed, and the results are checked, and - if the check is satisfactory - stored in the respective accounts.

7. POWER DOWN DURING THE FINAL MONITORING PART

The final part of the monitoring process requires some time, where the DAU still must be powered. If the power breaks down during this final calculation, the processor status will be saved. The final calculation will be continued and completed either when the DAU is powered again or when the HHT is connected. In both cases correct LCF results will be obtained and added to the accounts, provided the result check does not fail.

8. PLAUSIBILITY CHECKS AND DATA CORRECTION

Input data are those data which describe the actual flight and engine condition. They are received from different sources and collected within the DAU. The set of input data used for engine monitoring is updated every 0.5 seconds.

The input data are converted to their physical value and checked for plausibility, where checks of range, rate of change and model checks are employed. The rate of data faults is counted by a separate counter for each signal. If the number of faults exceeds an accepted limit the current monitoring process will be terminated.

Data which are found to be implausible are substituted wherever possible. Substitutes are calculated either by a functional relationship to other plausible data or by interpolation within the time domain. If correction is not logical, the whole input data set is substituted by the previous one.

9. ENGINGE LIFE USAGE MONITORING

The engine life usage monitoring procedure consists of the same steps as the engine life design procedure. These steps are

- performance calculation (gas temperatures and pressures)
- calculation of temperature distributions for the components
- stress calculation for all critical areas
- damage assessment for each critical area with respect to stress and temperature history.

For the purpose of engine life usage monitoring, mathematical models are employed for all these steps. These algorithms have been specially developed (/4, 5/) in such a way that they are accurate enough to match the results of the design procedure within accepted limits and that they are simple enough to be implemented in an on-board real-time microprocessor system such as OLMOS.

LCF life usage monitoring requires coverage of the complete engine running temperature and stress history for each of the monitored areas, which number more than 40 with the RB199 engine. This demands that in the main calculation process each of these steps must be repeated in every 0.5-second time-increment.

In particular, the steps of the LCF monitoring procedure are carried out as follows.

9.1 PERFORMANCE CALCULATION

The performance calculation consists of the estimation of temperatures and pressures in the gas path and the cooling air paths.

9.2 TEMPERATURE CALCULATION

The metal-temperature distribution of thermally highly-loaded components is calculated.

The initial temperature estimation is achieved by using the ambient temperature.

For the main calculation the temperature distribution is calculated at the end of each time increment using the temperature distribution at the beginning of this increment and the performance data and speeds during this increment.

The temperature distribution of the shutdown peak is calculated using the temperature distribution and the performance data and speeds of the last main calculation increment.

The metal-temperature distribution of thermally lowly-loaded components is assumed to be constant.

9.3 STRESS CALCULATION

Total stresses are calculated for each monitored area, summing centrifugal stresses, thermal stresses and additional stresses.

Centrifugal stresses are related to the squared speed. Thermal stresses are derived from the actual temperature distribution of the component (which includes initial temperatures and shutdown temperatures, respectively). Additional stresses cover stresses from gas pressure, bolt clamping, etc.

Calculating the total stresses time increment by time increment, stress histories arise step by step for all monitored areas.

9.4 EXTRACTION OF STRESS CYCLES

Stress cycles are extracted from the stress histories using a rainflow algorithm. The rainflow algorithm allows most of the subcycles to be found during the main calculation process. But the main cycle is always gained during the final calculation process when the actual engine run is finished. The corresponding temperatures are also acquired. Each cycle is characterized by its lower stress value, its upper stress value, and the corresponding temperatures.

9.5 DAMAGE ASSESSMENT

Fatigue per cycle is calculated immediately when a cycle is found. This increment of fatigue is calculated with respect to stress range and mean stress as well as temperature and matrial's properties. So each cycle produces a fatigue increment, which all are summed up during a particular engine run, separately for each monitored area.

The fatigue sum over this particular engine run is completed during the final calculation process. All fatigue results are checked for plausibility with respect to flight time as well as to the number of faults detected by the input data check. If that check fails, the results will be rejected and appropiate diagnosis accounts will be set. If the fatigue results pass the plausibility check they will be added to the stored LCF accounts.

10. PERFORMANCE TREND MONITORING

For performance trend monitoring an automatic placard check is carried out. It is carried out a maximum of once per engine run.

Placard conditions are met when, for the first time within an engine run, the pilot's throttle is set to Max Dry and the low pressure spool speed exceeds a given level. After allowing a few seconds for the engine conditions to stabilize, average values of

- low-pressure spool speed,
- high-pressure spool speed,
- turbine blade temperature,
- air intake temperature

are registered. Speeds and turbine blade temperature are normalized to ISA conditions using the air intake temperature. These corrected values are stored. A status code is also stored, containing the information whether the placard procedure has begun, or whether it has finished correctly or incorrectly. Furthermore, it discriminates between flights and engine ground runs.

Trending results of five engine runs are stored for each aircraft engine within the DAU. When actual trending data are stored, the oldest data are overwritten.

Trending results and trending status are transferred via HHT to the OGS, which provides the option to store and display up to 50 trending results for each engine. The results of speeds and turbine blade temperature are shown in relation to reference values which depend on settings of the engine control unit. They are obtained from engine setting runs and are updated within the OGS via keyboard.

The engine performance trend can be judged using these trending displays.

11. DIAGNOSIS AND STATISTICS

Some status codes are stored in accounts such as LCF calculation status, trending status as well as several diagnostic times and numbers. These accounts are transferred via HHT to the OGS by the milking procedure, too. In case of failure, these accounts provide information for diagnosis purposes.

Flight and engine data are checked as mentioned above. For each signal a separate counter is provided. If any data do not pass the check, the respective counter is incremented.

Plausibility checks of the LCF results are carried out, where plausibility is checked with respect to the flight time and the number of input data faults provided by the data check. The check result is stored in a LCF calculation status code. In case of failure it contains information about the conditions which caused the failing of the check. If the result check fails the period without valid LCF results will be accumulated and stored. This value will be used in the OGS for data corrections.

The number of engine runs and the number of valid LCF accumulations is counted. Several important periods of time are measured such as engine running time, engine flight time, warming up and cooling down periods, as well as periods of limit exceedance of some input signals.

All these results are useful to support troubleshooting in case of ELCMP failure.

12. SOFTWARE DEVELOPMENT AND INTEGRATION WITHIN HARDWARE

The ELCMP software is designed as a fully modular structure. This provides the software for module interchangeability, necessary for adaptation to future engine configuration modifications.

The microprocessor software code was developed as shown in Fig. 5. The source code was written in FORTRAN 77-language for most of the modules, and then transferred into C-language. Other modules were developed in C-language directly. The source was then compiled on the development system for the target system and loaded into the microprocessor within the DAU.

The software was verified initially on the development system. Final verification was made on the target system under real-time conditions.

The hardware configuration is shown in Fig. 6. The ELCMP software is installed in processor system 2 for the LH engine and in processor system 3 for the RH engine. Both systems operate independently of each other.

The two systems are identical with regard to both hardware and software. Both systems are connected with system 1 by a bidirectional bus. With respect to ELCMP, system 1 has the tasks to condition the flight and engine data for system 2 and 3, to handle the monitoring control parameters which are stored in EEPROMs within system 1, and to control the data transfer.

13. RESULTS

OLMOS has been in operational service service since 1987, and first results are now available.

Some of these provisional results are given in Fig. 7. The frequency distribution of the fatigue ratio is shown, where fatigue ratio means fatigue calculated with ELCMP over fatigue calculated with ß-factors. These figures are given for three selected representative monitored areas.

They show completely different shapes of the distribution curves. But the curves have in common that they cover a wide range of ratios. That fact proves the ß-factors being not adequate for life monitioring of military aircraft engines, because the ß-factors do not cover all the infuences of

- mission type and variations in mission mix
- air base
- difference in handling of LH and RH engine
- climate and weather
- individual pilot's behaviour,

which are naturally covered by an on-board monitoring system such as OLMOS.

The distribution curves have also in common that their mean values - marked by the dashed lines - are more or less smaller than unity. This shows that the overall life consumption individually calculated by ELCMP is smaller than generally calculated with ß-factors, although the basic lifing concept is the same. This means that individual parts will remain in service for longer periods, reducing the cost of replacement and spare parts.

14. REFERENCES

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/3/	U. Schulz	OLMOS: Hardware Equipment On-Board and Ground 14th International Symposium AIMS, Friedrichshafen, 1987
/4/	G.E. Breitkopf T.M. Speer	In-Flight Evaluation of LCF Life Consumption of Critical Rotor Components Subjected to High Transient Thermal Stress AGARD Conference Proceedings, Lisse, 1984
/5/	T.M. Edmunds R.A. Lawrence	Monitoring Engine Thermal Stresses AGARD Conference Proceedings, Lisse, 1984

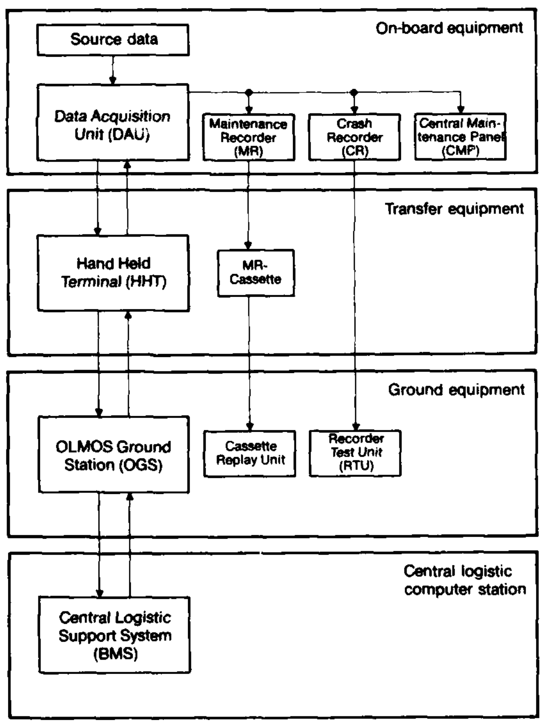

Fig. 1 Structure of OLMOS

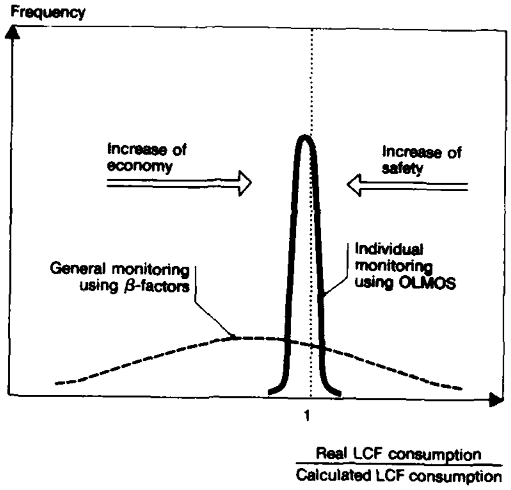

Fig. 2 Distribution of LCF Consumption due to Operational Usage

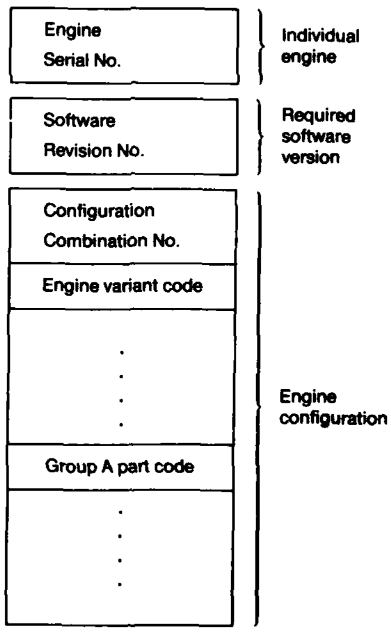

Fig. 3 Engine Identification Code

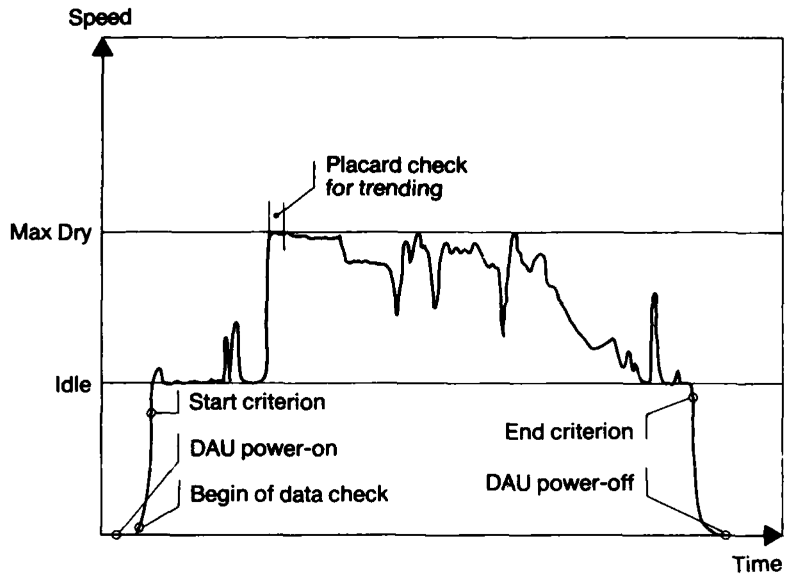

Fig. 4 General Pattern of an Engine Running History

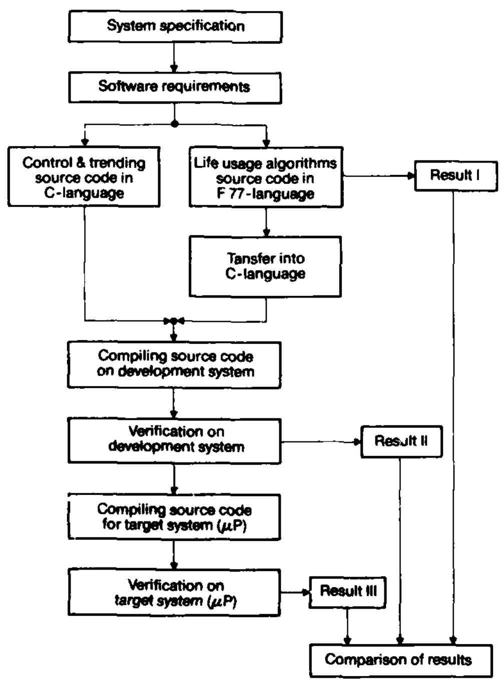

Fig. 5 Development of the Microprocessor Code

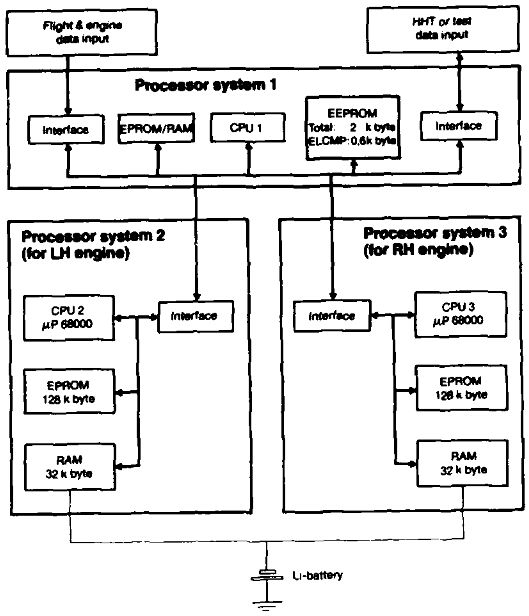

Fig. 6 Hardware Configuration

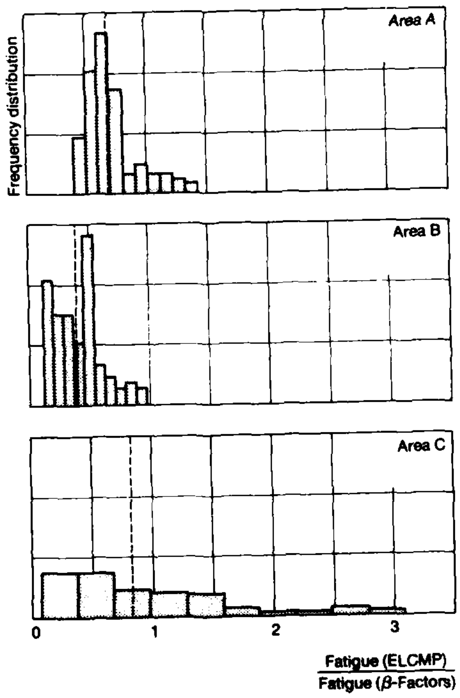

Fig. 7 Comparison of LCF Results Obtained by Individual and General Monitoring

DISCUSSION

Keith C. HOBBS

Your paper states that data found to be implausible is substituted, wherever possible, by calculation from other plausible data with a functional relationship or by substitution of complete previous data set. Do you have any figures on frequency of substitutions, perhaps a ball park percentage?

Author's Reply:

The reliability of the signals is in general very high. The number of signals faults is less than 0.1%, except one signal where a hardware problem of the sensor exists. The correction of that faulty signal leads to a slight overestimation of the calculated life consumption. Accumulated periods of data faults, which do not exceed 2% of the engine running time, do not influence significantly the monitoring results.

G.D.XISTRIS

What fatigue model is used to estimate LCF damage and how reliable are the results obtained?

Author's Reply:

LCF damage is accumulated linearly.

The results are in line with the basic design policy. The algorithms within OLMOS are derived with adequate accuracy from those used for engine design and so the results reflect the reliability of the design procedure. Verification is done by a sampling program.

RECENT UK TRIALS IN ENGINE HEALTH MONITORING - FEEDBACK AND FEEDFORWARD

by

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SUMMARY

Engine health monitoring effectiveness had to be quantified prior to large scale commitment by the UK Services. This paper describes some of the activities undertaken in Air Staff Target 603, a programme set up to assess that effectiveness. Also described are some of the incidental lessons learned from this and other related health monitoring exercises.

1. Introduction. Air Staff Target 603 was to demonstrate the effectiveness of engine health monitoring procedures. The physical embodiment and demonstration occurred in conjunction with several other related exercises. Perhaps inevitably, the general historical perception of all of these has combined into a single entity - namely AST 603. This paper describes the specific project but inescapably refers to those other activities which were instrumental in the decisions of the UK Services to adopt their current health monitoring policies.

In the late 1970s many longstanding questions regarding the cost effectiveness of engine health monitoring techniques were unanswered. The advent of modular engines and the exchange of modules between engines had renewed doubts both about the effectiveness of existing safety margins for life critical parts and about the economics of existing maintenance and provisioning practices. Naturally, there was a great reluctance to alter methods without strong evidence that changes were necessary, and of the types of change that should be made. As the potential savings that might accrue were believed to be significant, it was decided to collect in-flight and repair data in a methodical manner so that maintenance information could be correlated to usage. If successful, it was hoped that a wide range of pointers to improvements in design, operation, and maintenance philosophies would be gained.

Subsequently, 12 Hawk aircraft at RAF Valley were modified to collect relevant engine, aircraft and ambient data throughout flight. The data was stored on audio cassettes that were analysed on a Ground Data Processing Unit (GDPU) at RAF Valley. From this stored data life consumption and performance calculations were made. The trial also used manually recorded maintenance data from normal service documentation produced during module strip at RAF St Athan. Several novel experimental mechanical condition monitoring techniques were also trialled. Data from all of the above was then used to relate failure modes to appropriate detection methods.

During the trial some disappointments and difficulties were encountered, reducing the impact that the programme might have had. Notwithstanding the setbacks the trial may be judged a success, especially when viewed in conjunction with other contemporary trials and studies. The outcome is that it is now the policy of all 3 UK Services to fit health monitoring equipment to all new aircraft entering service. Increasingly, these are whole aircraft monitoring systems rather than engine systems, and are fleetwide rather than sample fits, with a large element of onboard life usage calculation.

2. Objectives of the Trial. The overall objective was to prove the cost effectiveness of Engine Condition Monitoring (ECM) when used in conjunction with comprehensive On Condition Maintenance (OCM). The formally specified objectives were:

a. to determine the extent of the correlations which exist between engine health and variations in measurable engine operating parameters on the Adour Mk 151 engine;

b. to devise a practical method for presenting the correlations in forms which could be used for maintenance purposes, to reduce the costs of owner-ship, to improve aircraft and engine availability and flight safety, and in particular to show how these correlations could best be used to support a policy of on-condition maintenance for aero-engines;

c. to indicate the individual costs of development, production and operation of all the elements of the data collection and processing equipment used to provide and present those correlations;

d. to show how cost savings have been, could have been, or would be obtained by applying those correlations, and to quantify those savings;

e. to show how improvements in aircraft and engine availability and flight safety have been, could have been, or would be obtained by applying those correlations and to assess the benefits thereof, quantifying them wherever possible;

f. to devise the procedures for the transfer of information and data between the RAF, DG Eng (PE) and Industry to obtain executive action to achieve those benefits;

g. to recommend preferred combinations of EHM techniques, including the information transfer procedures, to maximise the savings of improvements or both;

h. to consider the extent to which the conclusions of the trial are relevant to aircraft/aero-engine combinations in general and to indicate what additional work would be necessary to validate and to quantify the benefits for particular cases;

i. to examine the in-service management structure which would be necessary to integrate such a system into the RAF's maintenance organisation at all levels and lines of servicing.

These objectives led to a programme that lasted from October 1981 to early 1985 (some four and a half years), and involved a considerable number of people from both MOD and Industry.

3. AST603 Contemporary Projects and Equipments. The first digital engine monitoring system for the UK Services was known as the Engine Usage Monitoring System (EUMS1). Introduced in 1975 this was essentially a system that recorded data for later analysis on the ground in the Ground Data Processing Station (GDPS) managed by Rolls Royce, Bristol. The data captured and analysed with this system substantiated the case for further developments.

The first development was EUMS2 which also performed Low Cycle Fatigue (LCF) life usage calculations in real time. These results were displayed at first line, with bulk data for further analysis being returned to the GDPS. At about the same time a dedicated Low Cycle Fatigue Counter (LCFC) was also developed. This accepted engine spool speed data from a variety of standard aircraft transducers, executed life usage algorithms in real time and displayed the results at the end of each flight.

EUMS1 and 2 are still in use on a wide variety of aircraft. The LCFC is now used only on the Hawk. It was once intended for fit to the Tornado but was cancelled to provide short term cost savings necessary during the financial moratorium of the early 1980s.

In 1984 an extensive study of the cost effectiveness of different levels of engine monitoring on the Adour Mk 151 engine (Hawk) and RB199 (Tornado) was completed. This was heavily dependent on data from the EUMS1 and LCFC equipments and analysis programmes.

4. Project Organisation. The project organisation was surprisingly simple in view of the ambitious objectives. Putting the MOD bodies to one side (the RAF and the Procurement Executive) six companies were involved of which five were contracted directly by MOD(PE). A seventh company was directly contracted to produce software for the Prototype Information Management System which was a follow-on task.

MOD(Air) was responsible for in-service management, whilst the Central Servicing and Software Development Establishment (CSDE) were responsible for all day-to-day in-service activities, which were considerable and encompassed operation of the GDPU facility, collection of strip data, software development and correlation of diagnostic cause and effect data. MOD(PE) were responsible for managing the industrial aspects of the project.

The companies involved were:

Rolls Royce plc - the engine manufacturer who was responsible for specification of the functional requirements ie: the lifing algorithms, performance diagnosis, definition of the engine measurements, the engine modifications, design of the CSDE GDPU, and running the Ground Data Processing Station at Bristol. They naturally, were also responsible for engine related advice to all of the participants.

British Aerospace plc - the aircraft manufacturer provided the aircraft modifications and sensors.

Flight Data Company Ltd - assisted CSDE and Rolls Royce in the analysis and interpretation of in-flight data.

Plessey Avionics Ltd - were responsible for the Engine Usage Monitoring System and its associated replay facility to pass data to the GDPU.

Scicon Ltd - were responsible for producing the software for the Prototype Information Management System (PIMS), which was a follow-up activity.

Stewart Hughes Ltd - produced the expert system software for performance analysis and diagnosis based on small change matrix data from Rolls Royce. They were also subcontractors to Scicon for the PIMS.

Vinten Ltd (then Davall) - supplied the airborne recording equipment, which was already standard equipment in service, as part of the Engine Usage Monitoring System (EUMS).

The Rolls Royce, Plessey and Vinten equipment was already in use in a related Low Cycle Fatigue (LCF) life consumption monitoring exercise, as the EUMS Mk 1 programme.

5. The Trial. Twelve Hawk T Mk 1 training aircraft at RAF Valley were instrumented. It was considered essential that the trial did not cause any disruption to the flying programme of either these or any of the other 60 similar aircraft at RAF Valley. Due to the short turnround time for the aircraft it was necessary to be able to replay and analyse cassette data within 10 minutes - the minimum period between successive flights - so that the crew could be briefed on any engine deterioration detected. With a typical flying time of 30 hours per month it was anticipated that some 15 000 sorties would be flown during the trial. The data from these flights was to be calibrated and stored on magnetic tape and the GDPU was sized accordingly.

In case of breakdown, the similar Ground Data Processing Station (GDPS) at Rolls Royce Bristol was to provide the necessary support. This equipment was similar to and in addition to the system already installed at Rolls Royce for the EUMS1 and 2 data collected from other aircraft. It was used for programme support, to prepare specifications and computer programs for analysis of data, and to develop software to overcome unforeseen problems.

The functional elements of the engine monitoring system were essentially:

Life usage monitoring - low cycle fatigue, thermal fatigue and creep,

Mechanical condition monitoring - vibration, turbine cooling air temperature, oil debris monitoring etc,

Performance monitoring - trending and diagnosis,

Limit exceedance monitoring - speeds and temperatures.

Other failure detection techniques were later trialled or tested as an extension to AST603. These included gas path particle analysis, based on capturing particles on carbon "targets"; use of conductive wire and paint to detect cracking of static parts; and vibration analysis.

5.1 Life Usage. The low cycle fatigue life usage calculation on rotating components illustrated the potential for lifing based on cyclic use rather than engine running or flying hours. Two life expired HP compressor spools were individually given extended lives due to this monitoring, thus demonstrating the conceptual benefits of individual engine life management. It was also shown that high data capture rates were essential if such techniques were to be used in a routine manner. Only 70% of the ideal data capture rate was achieved. Reasons for data losses were:

Failure of ground/aircrew to fit a cassette.

Cassette/recorder failure.

Data channel faults ie sensors or wiring.

The minimum acceptable data capture rate for individual engine life management was estimated to be 95%. Reinforcement was also given to the already recognised need to calculate usage data in real-time on-board the aircraft so that data losses, ground system processing times and overheads could be reduced.

Creep life consumption calculation was intended to monitor HP turbine blade life. Due to lack of data quality and impending work on other turbine lifing programmes no useful demonstration was achieved.

Thermal fatigue was the most difficult usage measure to develop. An early algorithm was proved to be unsatisfactory, and a new algorithm was withheld until the method involved had been more thoroughly demonstrated on rigs.

5.2 Mechanical Condition The mechanical condition monitoring objective was to prove whether methods other than magnetic chip detection, boroscopy, simple broad band vibration analysis and oil consumption could be effectively applied in a Service environment. A very wide range of techniques was examined in relation to mechanical problems observed on the Adour during the trial. Of these, 3 techniques were selected as applicable during the timescale of the trial. These were:

Gas-path particle detection and analysis. Carbon pads installed in the jet pipe were used to catch metallic particles generated within the engine. These were removed at 25 hourly intervals and analysed at Rolls Royce Bristol. The work continued beyond the trial, but was not a success, due to difficulties in selecting a pad material that could withstand the environment and yet still be soft enough to allow impingeing particles to embed themselves. Pad contamination from other sources was also a problem.

Detection of cracked compressor stator vanes was attempted as this is an occasional problem in this engine and necessitates a periodic Eddy Current inspection. A reliable detection device would, it was considered, significantly reduce the servicing workload. The technique selected was to "paint" a continuous conductor along each vane so that any loss of continuity would indicate vane cracking. Checks could be made either at intervals, or continuously using the onboard data recorder. Although the modification was not approved during the trial, it was subsequently tested on the ex-AST603 aircraft but found to give a high false alarm rate due to paint damage and unreliable connectors.

Vibration signature monitoring was attempted, by measuring total levels. However, the digital sampling technique used precluded detailed analysis, and the particular method used was not a complete success. Nonetheless, it provided a usable vibration signature which could have formed the basis of a production system. It also provided information on the variation of vibration levels with altitude. Other programmes of work have investigated these techniques much more thoroughly with respect to both airborne and ground based equipments. In general, work is now proceeding down 2 main routes: dynamic generation of Campbell "Spoke" diagrams and for transmissions and gearboxes complex serial averaging techniques are employed. Expert system approaches to the analysis are also being explored.

5.3 Performance Trending and Diagnosis. Performance trending and diagnosis was undertaken to establish whether correlations between the physical condition of the engine and its performance could be achieved. To this end 15 aircraft and engine parameters (measurements) were recorded. The GDPU was then used to extract a 5 second sample of data which was taken from each sortie at 2 specific flight windows. These were at take-off and during climb.

The data was corrected and presented as trend deltas, defined as the difference between the measured and theoretical values based on a datum (fleet average) engine. During the trial it became evident that no significant performance deterioration was occurring. This was attributed to the simple fact that the engine had a robust thermodynamic cycle that rendered it somewhat insensitive to small changes in component efficiency. This meant that most engine removals were due to life expiry of components or other maintenance considerations.

Early attempts were unsuccessful due to a combination of unsatisfactory instrumentation and errors in software. These were unrelated but made fault diagnosis difficult. Consequently it took some 2 years to achieve a satisfactory standard of data.

The diagnostic technique to be applied to the performance trends was initially as problematical as the trending itself. Based on a small change matrix approach which shows the expected changes in trended measurements for a one per cent change in say efficiency, throat capacity or some other engine parameter. This was visualised via "Star Charts" which provided a graphical representation of the changes. These were fairly effective when only a single component deteriorated, but multiple component deterioration resulted in confusion for the interpreter. The final approach was to use "Expert System" techniques to relate trend plots to actual defects discovered during inspection. This proved to be a breakthrough in assisting interpretation.

Unfortunately the trial finished after only twelve months of the executive phase during which the fully implemented system was trialled, and before a conclusive demonstration of the power of this approach was achieved. Originally, an executive phase of three years duration had been envisaged. It should be stated, however, that a correct diagnosis was made for the last 2 engines rejected.

In addition to the above the CSDE team independently established a GO/NO GO parametric thrust measuring technique using exhaust duct pressures and NL. This was demonstrated on the RAF Un-installed Engine Test Facility to be capable of indicating thrust within 2% under test bed conditions. AST603 data was inadequate for this purpose, due to instrumentation and data inadequacies.

5.4 Limit Exceedance Monitoring. Limit exceedance monitoring provides an indication of abnormal engine operation that is potentially damaging. Three types of exceedance were monitored:

Standard fixed limits - N_H, N_L, TGT, vibration and turbine cooling air temperature.

Time limits - TGT.

Individual engine limits - vibration.

Used primarily to confirm pilots' reports the exceedance alert system proved its worth, and extended knowledge of the behaviour of the engine throughout its envelope. An example was the discovery that the vibration signature changed significantly at altitude, indicating the need to capture adequate vibration data in the air to allow analysis on the ground.

5.5 Cost Analysis. One objective was to show how maintenance cost savings could be made by using engine health monitoring. The AST603 aircraft engine operating costs were to be compared with a control group of aircraft. Because of difficulties in determining complete costs due to external constraints, only the following were considered:

Direct manhour costs at first and second line,

Direct manhour costs at module overhaul (3rd line),

Repair parts cost at module overhaul,

Consumables at second line.

All other costs were excluded. Cost data was extremely limited. The following simplifying assumptions were made:

All trades attracted the same rates,

Supervisors were Chief Technicians or Sergeants,

Civilians attracted Service rates,

Spares were costed at 1 April 1984 rates.

There were 19 "occurrences" in the AST603 group and 21 in the control group. However the total costs of the AST603 group were some 15% higher than that of the control group.

The EHM techniques were not all proven or in place at the time of the cost analysis. More importantly the duration was too short to smooth out distor tions due to an unrelated engineering campaign and the associated discovery and correction of secondary damage. Purely by chance, the effect was greater upon the AST603 engines.

During the course of the AST603 trial the parallel EUMS 1 programme achieved new cyclic exchange rates for the Adour Mk 151 engines. This effectively removed the opportunity for AST603 to achieve the same thing and claim the associated cost benefits. The exchange rates changed by a factor of 2.3 cycles per hour. This generated an estimated saving of £45M over 20 years.

Despite the difficulties,, this and other trials provided sufficient evidence to prove the cost effectiveness of engine health monitoring such that EHM is now recognised as cost effective within the UK.

6. Results of the Trial - Feedback. The objectives were to assess the technical and economic viability of engine health monitoring. A summary of the extent to which the objectives were met is given below, and may be compared with the sub-paragraphs of Section 2 corresponding to those below:

a. The extent of the correlations which existed between engine health and deterioration was not fully established, but the potential was clearly demonstrated. It was possible from assessment of the trend plots to identify a deteriorating module and assign a probability or confidence factor to the analysis. This was achieved by use of 'expert system' techniques, which were a powerful software development tool.

b. A practical method for presenting the correlations in a usable form was demonstrated via the expert system display.

c. The individual costs of development, production and operation of the EHM system relating to non RAF activities were well documented.

d. Cost savings due to EHM were inconclusive during the one year cost measurement phase, due largely to the short trial period, and to the fact that not all elements of the EHM system were fully functional at the time.

e. Improvements in availability and flight safety were not directly demonstrated. However considerable use was made of the data during diagnosis of reported defects. These included reported thrust pulsing, cockpit captions lit, vibration levels, surges and flameouts. Additionally, the EHM recorder survived 2 crashes and provided vital evidence to the Board of Inquiry. In one case the Accident Data Recorder was not functioning and in the other it was destroyed. In both cases the AST603 recorder broke away on impact.

f&i) The procedures that already existed for transfer of information between the RAF, MOD(PE) and Industry were demonstrated to be sound. It was confirmed that CSDE should assist from the early stages of any project in choosing appropriate techniques and setting alarm levels with the MOD project office, and that these should be promulgated through the Local Technical Committees and technical publications.

g&h) Preferred combinations of EHM techniques were not recommended. It was shown that in general the available techniques are complementary, albeit with an overlap in some areas. This overlap is not a disadvantage as it may provide diagnostic confirmation or alternatively, information where one technique has failed. Techniques to be considered are:

Indirect thrust estimation,
Performance trending and diagnosis,
Vibration analysis and diagnosis,
Incident analysis (Pilot initiated),
Automatic exceedance recording,
Low cycle fatigue monitoring (real-time on-board),
Creep and Thermal fatigue monitoring,
Oil debris monitoring.

During engine demonstration, design, development, and qualification, consideration should be given to all of the above techniques in conjunction with the factors listed below:

Engine failure modes,

Operating circumstances of the engine and aircraft,

Lifing policy and maintenance philosophy, in particular the minimum issue service life (MISL) required for any engine on return to the fleet after repair, and prior to its next removal due to life expiry of a life limited component,

Realistic estimation of savings accruing from failure prevention and avoidance of secondary damage,

Cost of fitting the necessary equipment,

Fleet size,

Availability of test facilities,

Contracting Policy for maintenance, repair and overhaul.

Imminent and rapid changes in data recording and transmission technologies were anticipated during the trial. Because of this it was felt to be imprudent to make any firm recommendations on "the way to go". However, the 2 extremes are: either to record in the air and analyse on the ground or to record and analyse in the air. The former leads to large ground based overheads, whilst the latter does not. However, the latter may lead into the trap of not retaining enough data for the occasions when further analysis is required to explain some unanticipated event. For this reason RAF policy is for new systems to have a bulk data recorder as an optional fit, and for it to be used on 10% of the fleet. This provides 2 facilities - monitoring of the continuing correctness of the algorithms and system operation, and a readily fitted device to assist in trouble shooting.

7. Current EHM Applications - Feed Forward. Seven fixed wing engine health monitoring projects have followed on from AST603. They vary enormously from each other as the pressures of each aircraft project are brought to bear. Additionally, my colleagues concerned with rotary wing aircraft are planning and conducting Helicopter Operational Data Recording (HODR) exercises on Lynx, Chinook and Seaking using EUMS based equipment. The Anglo-Italian EH101 helicopter is also offering a comprehensive Helicopter Usage Monitoring system (HUM). A brief outline of each fixed wing EHM activity is given below:

7.1 Harrier GR Mk 5 and AV 8B. The Harrier GR Mk 5 aircraft is the first in the UK to have a purpose designed EHM system installed from initial build. The functional elements are directly derived from accumulated previous experience.

Vibration Monitoring (15 narrow band channels cross related to engine speeds)

LCF monitoring - 6 components using real-time "Rainflow analysis" and a further 24 using read across factors.

Creep Monitoring.

Thermal fatigue monitoring.
Limit exceedances.

Pilot initiated events

Hover Performance)
) follow on modifications
Performance Trending and diagnosis)

Data on up to 5 flights can be downloaded via a data retrieval unit for transfer to the ground based computer known as the Harrier Information System (HIMS).

7.2 Tucano. Much simpler than the Harrier system, and procured in haste, many desirable features were omitted from the EMS. Examples are lack of torque monitoring and adoption of a simplistic LCF usage monitor which does not use rainflow techniques.

7.3 EFA. Based on all British, German, Italian and Spanish experience to date this aircraft will have an Integrated Monitoring and Recording System which encompasses all airborne systems. For the first time in Europe the engine specification includes the building up of a data base relating vibration, oil debris and performance to the physical condition of each engine on strip. This will be used to produce a powerful diagnostic capability. At the time of writing many system details have yet to be finalised.

7.4 Tornado (RB199) Mid Life Update (MLU). EUMS1 recorders are fitted to a small number of Tornado aircraft, both IDS and ADV. The variation in usage data seen to date has caused some concern and a burgeoning belief that parts life tracking should be considered for a small group of lifed components. Consideration is now being given to fitting a low cycle fatigue counter to all engines during the MLU.

7.5 RB199 Uninstalled Engine Test Facilities (UETFs). Experience has shown that RAF personnel on the RB199 UEFTs can diagnose 80% of all problems encountered. The remaining 20% sometimes necessitate a degree of nugatory strip and rebuild work that would be better avoided. Based on a cost effectiveness case, Rolls Royce and GEC are producing a performance analysis and diagnosis package to overcome these difficulties. Rolls Royce have been asked to base it upon their COMPASS performance trending and diagnosis system. If successful this will be the first military application of COMPASS.

7.6 Tristar. The RAF has a small fleet of Tristar aircraft used for tanking and troop carrying. These have an airborne monitoring system fitted. In service for only a short time a significant payback has already been seen. The primary example is that of an engine with a rising vibration problem. By careful monitoring of the incipient fault trend (within acceptance limits) it was possible to retain the engine in service for nine months longer than would otherwise have been the case.

7.7 E3A - AWACS. Entering RAF service in the near future a suitable health monitoring system is being sought. For logistics reasons a system already in RAF service is favoured.

8 Observations. In addition to meeting each of the trial objectives with a greater or lesser degree of adequacy, AST603 allowed a significant number of lessons to be learnt along the way. Many were obvious only with hindsight and others merely reinforced the conventional wisdom of project management that every project must (or at least does) reinvent the wheel. No apology is offered for the disjointed list of observations made below.

The objectives of AST603 were to assess the technical and economic viability of engine health monitoring. Although the lack of knowledge in many areas was recognised, it was assumed that the existing technical knowledge and the organisations involved provided an adequate resource to overcome the majority of problems to be encountered. This assumption was not unreasonable. However, the organisational problems encountered were such that in some instances potentially adequate assistance was not made available. This was partly due to conflicting viewpoints and priorities but also to the apparent perception that the project was an impractical "scientific" experiment with a high nuisance value to the mainstream of maintenance. Significantly perhaps, AST603 project management was not by the Adour Mk 151 project team, but by the EUCAMS project team. In future any similar trial should be managed by the main aircraft/engine project team, if necessary with specialist advice. This is increasingly important as moves toward whole aircraft monitoring systems progress.

The choice of aircraft/engine fleet chosen for a trial must be realistic, even if inconvenient. In the case of AST603 a training squadron was chosen. Because high performance engines were not involved serious performance degradation did not exist and was therefore difficult to detect.

Personnel changes should be minimised. During the course of the trial: four different Squadron Leaders held the MOD(PE) project manager post; three different Flight Lieutenants held the CSDE team leader post; and three different engineers held the Rolls Royce programme manager post. All of this occurred over a four year period, and allowed all concerned to make their own inferences as to the importance of the work in hand.

Training of personnel for each post must be considered seriously. The abilities to produce software, to be familiar with maintenance procedures, and to have an in-depth theoretical knowledge of thermodynamics and structures do not often occur in people assigned to such work without careful selection.

Software specialists need help to produce sensible code, which must be validated by an engineer to ensure correct functionality. This could be interpreted as meaning that the engineers are unlikely to write a sufficiently comprehensive specification at the first attempt.

Failures and the associated symptoms are peculiar to each engine type and its application. Monitoring techniques must therefore be selected (and weeded) during development. Equally, provision must be made to allow additional techniques to be added as found to be necessary during development and in-service.

For maximum effectiveness the data relating cause and effect for development failures should form the basis for the ground based maintenance information management system data base. This is also probably the most effective way of delivering a usable ground environment, at the same time as the aircraft is introduced into service, in terms of function and capacity.

Calculations should be performed on-board wherever possible, because this minimises the ground station workload, and costs. Only if there is not enough confidence in the lifing algorithms should bulk data be transferred to the ground environment for routine analysis.

Notwithstanding the above, provision should be made to allow an optional fit of a bulk data recorder for continuing system validation and trouble shooting.

If performance monitoring and fault diagnosis to any level is intended then suitable instrumentation must be fitted. The diagnosis requirement determines the instrumentation fit in terms of quantity of sensors and the quality of measurement, which must be determined during engine design.

Contract arrangements for repair and overhaul must take into account the advent of lifing by cycles rather than hours, and the need to maintain the maintenance information management database.

Aircraft systems are classified in three categories ranging from "safety critical' to "non-essential" MOD consider EHM systems to fall in the middle "essential" category. This is due to the potential for dormant faults to jeopardise safety if accurate life control of engine components and monitoring of the engine conditions is not maintained.

9. Conclusions. The discoveries and lessons learnt from AST 603 and related studies and projects paved the way for widespread gas turbine engine health monitoring in UK service aircraft.

Now that EHM is widely accepted, and the concept of whole aircraft health monitoring is following closely behind, attention should be given to the practicalities of monitoring other mechanical systems, and pneumatic and hydraulic systems. Electrical and electronic systems appear to have relatively advanced BIT capabilities, and consideration should be given to nurturing advances in the other systems. It should not be overlooked that the cost of a modern military aircraft falls approximately equally between structure, avionics and engines.

Main project office reaction to health monitoring often lies at one of the two extremes of either "it's all too diffficult" or "it's too basic to worry me". Both produce the same neglect which cannot easily be rectified at a later date. Hopefully, this and the other papers presented at this conference will provide a suitable reference source that will help future projects avoid some of the pitfalls.

This paper is based upon project reports written by the participants, and the author gratefully acknowledges their contributions.

The views expressed are those of the author and do not necessarily represent the policy of the Ministry of Defence.

DISCUSSION

H.I.H.SARAVANAMUTTOO

You referred both to the difficulty of communication between engineers and software specialists and also to the use of a consultant company to develop an expert system. We should seek out experts from our own community rather than those who would develop expert systems without a detailed knowledge of gas turbine operation.

Author's Reply:

Between 1981 and 1984, a great deal of publicity was given to expert systems and we wanted to evaluate them. The major advantage I see for expert systems is that the languages used, such as LISP and PROLOGUE, provide a very powerful programmers development tool, such that programs are easily modified. This is not permissible in a first and second line service environment.

Much of the difficulty between engineers and software specialists is due to the engineers failure to recognise the depth of their own knowledge. Engineers must write good specifications.

The best performance diagnosis presentation package I have seen to date is the R-R COMPASS System, which, three years later, surpasses the AST 603 displays. We have always considered information presentation to be almost as important as the information itself, and this was an important aspect of the AST 603 work.

The engine performance diagnosis rules were supplied by R-R and encapsulated into a custom expert system by STEWART HUGHES Ltd.

F110 ENGINE MONITORING AND MAINTENANCE MANAGEMENT SYSTEMS FOR F-16 C/D

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SUMMARY

This paper describes the engine monitoring and management systems employed by the Turkish Air Force for F110-GE-100 engines of F-16 C/D aircraft. These systems include the Engine Monitoring System (EMS) and the Minimum Essential Engine Tracking System (MEETS). The EMS performs the acquisition, transfer and processing of engine data for maintenance use. The system monitors engine operation, and determines engine exceedances and faults; isolates faults to appropriate level and processes data to interface with other data systems. The MEETS provides an automated means of managing on-condition maintenance of fighter engines. This system tracks engines and components in terms of operation time, temperature, and cycle limits, and also forecasts remaining flying and engine operation hours for an individual engine, aircraft, or the whole fleet. The operation of the systems and future plans to develop and implement a unique data automation system are discussed. This automated data system will be capable of supporting all the base-level functions of aircraft, engines, trainers, support equipment, test equipment, missiles, munitions and communications/electronics.

ABBREVIATIONS

AFTC	-	Augmenter Fan Temperature Control
AMU	-	Aircraft Maintenance Unit
CAMS	-	Core Automated Maintenance System
DDTU	-	Data Display and Transfer Unit
EMB	-	Engine Management Branch
EMS	-	Engine Monitoring System
EMSC	-	Engine Monitoring System Computer
EMSP	-	Engine Monitoring System Processor
FDS	-	F-16 Data System
GSS	-	Ground Station Software
LRU	-	Line Replaceable Unit
MEETS	-	Minimum Essential Engine Tracking System
OCM	-	On Condition Maintenance
PLT	-	Parts Life Tracking
TEST	-	Installed or uninstalled engine operation at base test facility
TUAF	-	Turkish Air Force
USAF	-	United States Air Force

INTRODUCTION

One of the most effective ways to strengthen the readiness of an Air Force is to improve the flow and availability of logistics information which in turn enhances management and utilization of resources. The capabilities of deployable information system should also be provided for supporting maintenance units in the full range of operating environments. A large, dynamic, on-line automated data system that supports the authorities directly for maintenance activities would be a valuable tool to manage the weapon systems successfully. Such an automated data system in support of base-level maintenance activities (except the supply system) did not previously exist in the Turkish Air Force (TUAF). With the introduction of F-16 weapon systems, data automation became one of the most important issues. To meet this requirement, a detailed research effort was initiated. The most cost-effective approach was to gradually introduce data automation in two stages:

(a) Implementation of already existing basic engine condition monitoring and tracking systems for management of F110-GE-100 engines.

(b) Development and implementation of data automation systems not only for engines, but also for all the maintenance functions.

The basic systems to manage F110-GE-100 engines of F-16 C and D models in TUAF inventory are: (a) Engine Monitoring System (EMS), which was developed by General Electric Aircraft Engines Company/Cincinnati; (b) Minimum Essential Engine Tracking System (MEETS), developed by the USAF Logistics Management Center/Gunter Air Force Station.

The EMS was designed to acquire relevant engine and aircraft data during flight or on the ground, and to process these data and provide a concise output at the flightline to define recommended maintenance actions. For the transfer of stored data from the aircraft to the ground computer system, additional processing and output to the appropriate user was also required. Hence, the scope of the EMS was to provide data acquisition and storage, and to transfer, process and present these data for maintenance usage. More specifically the system is capable of incorporating such features as:

(a) Determination of engine limit exceedances to the appropriate level;

(b) Acquisition of data to support long term engine performance trendings and tracking of life-limited engine components;

(c) Indication of flight line go/no-go conditions to reflect engine status;

(d) The Ground Support Software (GSS) to process the EMS data and interface with other data systems such as the MEETS.

The MEETS receives Parts Life Tracking Data from the EMS and provides an automated means of managing on-condition-maintenance (OCM). The system allows the tracking of engines and engine components by time, temperature and cycle limits based on inputs from the EMS. The MEETS forecasts flying hours and engine operating hours remaining for an individual engine or aircraft, or for a fleet of aircraft. It also provides the capability for shipping or receiving engines to or from other units. An automated data download from the system is also available.

In parallel with implementing the EMS and the MEETS to the TUAF engine management systems, a study of a TUAF unique automated data system, called F-16 Data System (FBS), was initiated. TUAF data automation requirements were defined and the FBS was to be implemented. The network is to comprise the following information systems:

(a) Logistics Management
(b) Flight and Flying Personnel Training
(c) Personnel and Training Requirements
(d) Headquarters Level Management

Logistics Management Information System, resident on an IBM Main Frame, is the major component of FBS and will be similar to USAF developed Core Automated Maintenance System (CAMS), but will have some additional TUAF unique features. The FBS is currently under development and shall be capable of supporting all base-level aircraft, engines, trainers, supp[illegible] equipment, test equipment, missiles, munitions and communications/electronics functions.

SYSTEMS DESCRIPTION AND OPERATION

The F110-GE-100 engine has a full authority, the Augmenter Fan Temperature Control (AFTC), designed with electrical connectors to allow real time access to the engine parameters in analog form. The EMS configuration which interfaces with the AFTC consists of three hardware components: an engine mounted EMS Processor (EMSP), an airframe mounted EMS Computer (EMSC) and a flightline equipment Data Display and Transfer Unit (DDTU). The relative locations of EMS hardware is illustrated in Figure 1. The control/non-control engine and aircraft related parameters utilized by the EMS, listed in Table 1, are available in analog form at the AFTC and are routed to the EMSP where they are multiplexed and digitized for subsequent transmission to the EMSC. The DDTU provides the link between the airborne equipment and the ground computer system. The EMSC and EMSP are accessed by the DDTU and all the data stored are transferred to the ground computers. In addition to temporary storage of the flight data, the DDTU provides a display which allows the maintenance personnel to view, at the flightline, the detected fault/isolation messages determined by the EMSC. The single entry point of all data into the ground computer system takes place at the Aircraft Maintenance Unit (AMU), adjacent to the flightline.

In general, four types of data are available from the EMS: Diagnostic, Parts Life Tracking, Trending and Pilot Initiated Data. These are briefly outlined and some examples for the outputs of the operation are given below.

(a) Diagnostic Data: Parametric data, composed of control and non-control (basic and discrete) engine and aircraft parameters, are saved as a result of a detected engine abnormality. This may be a major limit exceedance, or an out of limit control schedule of a secondary system. In addition to detection of exceedances, the system incorporates isolation logic, present within the EMSC, aimed at identifying the Line Replaceable Unit (LRU) of the engine causing the exceedance. An overview of the EMSC engine diagnostic logic and the EMS messages for fault isolation/LRU identification are shown in Figure 2 and Table 2, respectively. The parameters given in Table 2 are continuously monitored by the system during engine operation. If a signal fails to pass range check and/or loss of a discrete signal, a fault will be recorded and identified in the EMSC and will be displayed when the system is downloaded. Twelve pre-event data records (6 seconds) and up to 18 post-event data records (9 seconds) can be saved by the EMSC. The amount of diagnostic data saved is dependent upon the type of exceedance or fault, as shown in Table 3.

In case of an exceedance or fault, the utilization of the EMS elements and Fault Isolation/Trouble Shooting Data is described in Table 4 and below:

1. On the Flight Line:

   a) Once the EMSC detects the fault, Remote Status Panel indicates NOGO and the data are immediately downloaded to the DDTU.

   b) The DDTU displays the EMS message giving the fault code and Line Replaceable Unit identification for isolation. From this message, the ground crew should have an idea about the probable cause.

   c) With the information available, the fault could be isolated without any delay. If further information or action is required, the data have to be transferred and corrective action has to be determined using the ground computer system.

2. On the Ground Station Computer:

   a) The fault message is printed out again as a warning when the data are processed.

   b) The data records saved by the EMSC for that fault are displayed/printed for troubleshooting.

   c) Referring to the maintenance manuals, detailed analysis could be made and the necessary action could be determined.

(b) Parts Life Tracking (PLT) Data: The EMSP computes and stores the PLT data on a cumulative basis. These data are then used by the ground computer systems to track life limited engine components. Besides the EMSP, a copy of the data is stored in the EMSC to allow single download interface for all the data when the engine is installed. The MEETS utilizes the PLT data to allow predictions for maintenance planning and spares provisioning. PLT is a method of accounting for engine usage and parts' life. The data consist of engine operating times and cycles, such as duration time above T4B limit (5 levels), Engine Operating Time, Augmenter Operating Time, Augmenter On/Off Cycles, Low Cycle Fatigue Counts, Full Thermal Cycles, and Cruise-Intermediate-Cruise Cycles. An example of PLT data output from the EMS is given in Table 5.

(c) Trend Data: The EMSC automatically acquires and stores four data records (2 seconds) per flight during the take-off sequence at approximately 0.3 Mach. The information is presented in four separate scans of basic, control, discrete engine (see Table 4) and aircraft parameters. The data are used for trending and performance checks. Eighteen engine parameters, 6 aircraft parameters and 5 system discretes are available but for the time being, plots of only 7 engine parameters are generated. These 7 parameters are HP Turbine Blade Temperature, Fuel Flow, Exhaust Nozzle Area, Core Speed, Compressor Discharge Pressure, Fan Speed, and Lube Tank Quantity. An example of trending plots for an engine is given in Figure 3.

(d) Pilot Initiated Data: In addition to the EMS automatically saving data as a result of an abnormality, the capability exists for the pilot to request a data save. The same function can be used if test procedures on the ground require the use of engine parametric data. When a switch in the cockpit is activated, 12 pre-event data (6 seconds) and 4 post event data (2 seconds) scans are saved.

The F-16 is equipped with a data transfer system which allows the aircraft on-board computer systems to centralize systems' faults in a common data transfer cartridge (memory module). The data transfer cartridge can be taken to a loader-reader unit and the information can be downloaded for maintenance use as necessary. The Engine Monitoring System has the ability to communicate with this system through the multiplex bus. Selected critical engine faults are made available for the pilot viewing on multifunction display scopes. The Enhance Fire Control Computer (EFCC) commands the EMSC to transmit detected faults through the mux bus to the EFCC. When the faults are received, the EFCC assigns a code to the multifunction display system (MFDS) and stores the faults in their respective memory. Faults stored in the MFDS can be viewed at any time by calling up the test page. If the fault is identified as a pilot fault list item by the EFCC, then a command is issued to the up front controls (UFC) to illuminate the avionics light on the caution panel, which in turn illuminates the master caution light. When the pilot depresses the F-ACK (fault acknowledge) button on the integrated central panel, the fault is displayed on the data entry display.

Zenith Z-248 microcomputers are used at the TUAF for the ground station function of the EMS. The single entry point of all data into ground computer system takes place at the Aircraft Maintenance Unit (AMU). The TEST function, which is defined as installed or uninstalled engine operation, which must be performed at the base engine test facility, is similar to the AMU. At the AMU, which is adjacent to the flightline, the data are formatted and processed. The exceedance, fault and pilot initiated data are presented. The trend and parts life tracking data are subsequently transferred to the base-level Engine Management Branch (EMB) of the maintenance organization. The EMB is the focal point for data from both AMU's and base testing facility (TEST). At the EMB, the trend data are processed and displayed graphically, and the PLT data are formatted for transfer to the MEETS. An overview of all the EMS functions is illustrated in Figure 4. The functions of each unit involved, the AMU, TEST and EMB are summarized in Table 6.

The software package for Z-248 to process and format the EMS data and present it to the appropriate users was developed by General Electric, and is called the Ground Station Software (GSS). The GSS is a menu-driven computer system. There are three menus containing all of the available GSS procedures, and each procedure is executed by a single key stroke.

MEETS receives the data from the EMS via an output file of the GSS and provides an automated means of managing on-condition-maintenance (OCM) functions of F110-GE-100 engines. At the EMB, the parts life tracking data are transferred from the GSS to the MEETS which is loaded on the same micro computer Z-248 at the EMB. The MEETS is also a menu driven computer system, the Master Menu being composed of 12 basic menu options. The main functions of the MEETS are described below:

a) "Engine Tracking" provides the capability of updating engine and component records by inputting the EMS data, printing various management products, and forecasting engine components closest to their life limits. The parts life tracking information from the EMS is input via an electronic data transfer, but a manual update is also available. Printed copies of stored data can be obtained in various formats. The status of all tracked components on any engine in the database or items closest to their limits, by each tracking method can also be listed. An example is given in Table 7. A listing of all engines, spare parts, and all installed parts or the complete database can also be generated. The forecasting option provides a clear picture of the items on any engine or aircraft that are closest to scheduled removal or inspection, along with the projected flying hours remaining for each engine. An example is given in Table 8. A listing of warranted parts can also be provided.

b) "Database Updating" functionally enables adding new engines and components to the database, correcting errors or changing the database, removing and installing components or engines, and deleting aircraft or engines from the database.

c) "Work Unit Code File Maintenance" provides for the addition, deletion, change and deployment or listing of Work Unit Code files - i.e. the tracked items.

d) "Engine Shipment/Receipt" function provides the capability for documenting the configuration/status of the engines to be shipped, and initializing MEETS data base for engines to be received.

FUTURE PLANS - DATA AUTOMATION SYSTEM

The essential systems, the EMS and the MEETS, for managing on-condition maintenance of F-110-GE-100 engines, have been implemented at TUAF. The next step is to proceed with developing and implementing the data automation system, the FBS. Several alternatives were evaluated under the following criteria: TUAF requirements, current technology, the existing NATO countries' Air Force systems, systems proposed by the vendors, TUAF interoperability-systems integration requirements and supportability in Turkey. The decision was to proceed with a unique data system - FBS, comprising of not only Logistics Management Information System similar to USAF developed CAMS, but also Flight and Flying Personnel Information System, Personnel and Training Requirements and High Level Headquarters Management Information Systems.

The FBS scope is defined to have the capability to support:

(a) The Bases
(b) The Tactical Air Commands
(c) The Air Training Command
(d) The Headquarters.

The functions and the features of the FBS are given in Table 9. Comprehensive Engine Management System is one of the subsystems of the FBS and will be integrated into the existing engine monitoring and tracking systems.

TUAF, USAF and IBM will participate in developing the FBS. Application software development/conversion is to be contracted to IBM. The responsibilities of each party are as follows:

(a) TUAF: to establish the requirements, provide functional expertise, participate in system development, and acquire necessary skills to maintain the FBS.

(b) USAF: to manage the FBS as a TUAF agent, provide CAMS functional expertise and advisory assistance.

(c) IBM: to provide the system, programming and database expertise, training for the TUAF and the USAF, development of the system, production of the system and to assist in its implementation.

The FBS configuration is summarized at Table 10. FBS is based on the IBM 3090-200 Computer and Database Management System DB2, versus Sperry U1100 Series computers and Data Management System DMS-1100, used by the USAF developed CAMS.

The FBS will be integrated with the Requirements and Distribution System-Supply System (IBM 4381, MVS/XA, IMS) and Factory Management Improvement Systems (IBM 4381, VM, AS).

CONCLUDING REMARKS

The EMS and MEETS are simple, effective systems, the output products of which are very supportive of all levels of the engine maintenance effort. The systems have become a fully integrated part of the F110-GE-100 engine management system at the TUAF.

It has been observed that the diagnostic parametric data, trending data and parts life tracking data are valuable tools for the mechanics, technicians and managers in increasing the readiness, and flight safety of F-16 C/D aircraft.

The essential F110-GE-100 engine control and cockpit instrumentation was already in existence and the basic configuration of the engine electronic control AFTC was also defined at the commencement of the EMS design phase. The AFTC was normally utilized during engine development testing at the factory to provide a test monitoring capability and to assist in trouble-shooting faults. This feature provided a "ready made" primary interface for the EMS, and no additional sensors were therefore added for EMS purposes. To commence the design of such monitoring systems at the early stages of engine design might increase the cost effectiveness and trouble-free features of the on-condition maintenance systems, and ultimately the readiness of the weapon systems.

Operational experience has shown that the usefulness of diagnostic parametric data highly depends on the experience accumulated worldwide. The engine manufacturer's extensive study and implementation of all the feedback information from users would contribute to a great extent to the success and realization of the engine monitoring system's full objectives. Furthermore, if the operational experiences of the users are not utilized, only a limited portion of the monitoring system's capability could be rendered useful.

Operational experience has also shown that to date, the maximum use of trend data has been limited due to the lack of suitable analysis techniques at the base-level. Only when the engine technicians become fully conversant with demonstrated, reliable trending techniques, could full use be made of the wealth of data being compiled by the engine fleet.

It is believed that weapon systems and operational resources readiness, which is a function of both operational availability and sustainability, is the key to effectiveness. Hence the FBS is designed to document, measure and improve a fielded weapon system's readiness. The system is expected to enhance management functions at all levels.

ACKNOWLEDGEMENTS

The author would like to acknowledge the support provided by the Turkish Air Force Command in sponsoring this activity and the permission to present it. The cooperation of and diligent interest by the Unites States Air Force and General Electric Aircraft Engines Company, are also appreciated.

TABLE 1: PARAMETERS UTILIZED BY EMS

(A) Engine Related Parameters

Parameter	Symbol
HP Turbine Blade Temperature	T4B
Engine Power Lever Angle	EPLA
Fan Inlet Temperature	T2
Fan Inlet Guide Vane Position	IGV
Compressor Discharge Pressure	PS3
Main Fuel Valve Position	MVPOS
Main Torque Motor Current	MTM
Fan IGV Torque Motor Current	IGVTM
Lube Tank Quantity	QL
Fan Speed	NF
Core Speed	NG
Aircraft Power Lever Angle	APLA
Exhaust Nozzle Area	A8
Fan Duct Pressure Ratio	DPP
Fan Duct Pressure Differential Delta	DP
Augmentor Fuel Valve Position	AUGPOS
Augmentor Fuel Valve Torque Motor Current	WFRTM
Exhaust Nozzle Torque Motor Current	A8TM
Anti-Icing Valve Position	A/I
Lube Temperature	TL
Augmentor Flame Detector Signal	FDS
Augmentor Initiation Signal	AIS

(B) Aircraft Related Parameters

Parameter	Symbol
Aircraft Mach Number	MN
Angle of Attack	AOA
Normal Acceleration	NA
Total Engine Fuel Flow	TFF
Altitude	ALT
Gear Up	GUL

TABLE 2: ENGINE MONITORING SYSTEM MESSAGES

E-CODE	MESSAGE	E-CODE	MESSAGE	E-CODE	MESSAGE
-01	NF O/SP • AFTC	-28	NO AUG • AFP	-55	SENSR • FDS
-02	NF O/SP • MEC/BE	-29	NO AUG • IGN SYS	-56	AB SIG • AFTC
-03	NG O/SP • AFTC	-30	BLOWOUT • AFP/BE	-57	REG PWR • AFTC
-04	NG O/SP • MEC/BE	-31	BLOWOUT • SEC FLT	-58	DATA FLT • EMSP
-05	T4B O/T • AFTC	-32	(SPARE)	-59	BIT FAIL • EMSP
-06	T4B O/T • MEC/BE	-33	AUG SCH • AFTC	-60	BIT FAIL • EMSC
-07	C/STALL • BE	-34	AUG SCH • AFC	-61	MEMORY FULL • CLR
-08	C/STALL • SEC FLT	-35	A8 SCH • AFTC	-62	LO BATTERY • EMSC
-09	POWER LOSS • BE	-36	A8 SCH • HYD	-63	AUG INHIB • AFC
-10	FLAMEOUT • BE	-37	A8 SCH • BE	-64	SIG • AFTC
-11	(SPARE)	-38	A8 SCH • HYD/BE	-65	SIG • PYROM/AFTC
-12	NO A/I • A/I VALVE	-39	IGV SCH • AFTC	-66	SIG • EPLA/AFTC
-13	LO OIL LEV • BE	-40	IGV SCH • IGV ACT	-67	SIG • T2 SENS/AFTC
-14	HI OIL TEMP • BE	-41	IGV SCH • BE	-68	SIG • IGV/AFTC
-15	AUG INHIB • AFTC	-42	NF SCH • AFTC	-69	SIG • PS3/AFTC
-16	PILOT DATA SAVE	-43	NF SCH • MEC	-70	SIG • MVPOS/AFTC
-17	LO NF • AFTC	-44	NF SCH • BE	-71	SIG • PWR/AFTC
-18	LO NF • MEC/BE	-45	NF/NG • T2.5/MEC	-72	SIG • OIL LEV/AFTC
-19	LO NF • BE	-46	NF/NG • BE	-73	SIG • NF SENS/AFTC
-20	SPARE	-47	(SPARE)	-74	SIG • C-ALT/AFTC
-21	SPARE	-48	(SPARE)	-75	SIG • APLA/AFTC
-22	SPARE	-49	A/C SIG • PLA	-76	SIG • A8/AFTC
-23	SPARE	-50	A/C SIG • MN	-77	SIG • DPP/AFTC
-24	SPARE	-51	PLA DISAGREE*	-78	SIG • DP/AFTC
-25	PS3LIM • AFTC	-52	AI ON • AI VALVE	-79	SIG • AUGPOS/AFTC
-26	PS3LIM • MEC/BE	-53	(SPARE)	-80	DOUBLE FAULT
-27	NO AUG•AFTC	-54	SENSR • OIL LEV		

EXCEEDANCE PEAK/TIME DURATION

E- MESSAGE

-NF#####P/C • ###SECS
-NG#####P/C • ###SECS
-T4B####D/C • ###SECS

EXAMPLE OF DISPLAY

1-NF107·1P/C • 014SECS

ENTRIES MARKED # SHALL CONTAIN ACTUAL VALUES OF NF, NG, T4B, AND TIMES.

TERMS AND ABBREVIATIONS

ACT	ACTUATOR	EMSC	ENGINE MONITORING SYSTEM COMPUTER	NG	CORE ENGINE SPEED
AFP	AUGMENTER FUEL PUMP	EMSP	ENGINE MONITORING SYSTEM PROCESSOR	O/SP	OVERSPEED
AFTC	AUGMENTER FAN TEMP CONTROL	EPLA	ENGINE POWER LEVER-ANLGE	O/T	OVERTEMPERATURE
AI	ANTI-ICING	FDS	FLAME DETECTOR SIGNAL	P/C	PERCENT
AIS	AUGMENTER INITIATION SIGNAL	FLT	FAULT	PLA	POWER LEVER ANGLE
A/C	AIRCRAFT	HYD	HYDRAULIC	PS3	COMPRESSOR DISCHARGE STATIC PRES.
AUG INHIB	AUGMENTATION INHIBITED	IGN	IGNITION	PWR	POWER
AUG POS	AUGMENTER POSITION	IGV	INLET GUIDE VANES	PYROM	PYROMETER
AUG SCH	AUGMENTER SCHEDULE	LEV	LEVEL	REG	REGULATED
A8	NOZZLE AREA	LIM	LIMIT	SEC FLT	SECONDARY FAULT
BE	BASIC ENGINE	MEC	MAIN ENGINE CONTROL	SIG	SIGNAL
C-ALT	CONTROL ALTERNATOR	MN	MACH NUMBER	SYS	SYSTEM
CLR	CLEAR	MV POS	METERING VALVE POSITION (MEC)	TEMP	TEMPERATURE
C/STALL	COMPRESSOR STALL	NF	FAN SPEED	T2.5	COMPRESSOR INLET TEMPERATURE
D/C	DEGREES CENTIGRADE	NF SENS	FAN SPEED SENSOR	T4B	TURBINE BLADE METAL TEMP
DP	FAN DUCT PRESSURE			UNSTAB	UNSTABLE
DPP	FAN DUCT RATIO				

TABLE 3: AMOUNT OF DATA SAVED BY AIRBORNE COMPUTER

TYPE OF DATA	DATA RECORDS			
	12 Pre	4 Post	18 Post	Total
DIAGNOSTICS				
* Overtemp, Overspeed	X		X	30 Scans
* Flame-Out, Power Loss, Stall	X	X		16 Scans
* All Other Faults		X		4 Scans
* Pilot Requests	X	X		16 Scans
TRENDS		X		4 Scans

TABLE 4: AN EXAMPLE OF FAULT ISOLATION AND TROUBLESHOOTING DATA UTILIZATION

(1) On the Flight Line:

a) Remote Status Panel - NO GO INDICATION

b) DDTU Fault/LRU Message - 66 SIG*EPLA/AFTC

EMS MESSAGE DESCRIPTION - The engine power lever angle signal is detected out of range at the AFTC/EMSP interface. Probable cause is engine power lever angle sensor with AFTC as alternate.

(2) On the Ground Station Computer:

a) Print Fault/LRU Message:

EMSC SN GDB00424   DOWN LOADED 05/09/1988   19:30:14

AIRCRAFT TAIL NUMBER .. 86-0071
AIRCRAFT TYPE F-16
ENGINE S/N 509264

THIS DOWN LOAD CONTAINS THE FOLLOWING FAULT MESSAGES

1-66 SIG*EPLA/AFTC

b) Display Print Data Records for Troubleshooting
(4 scans for this message. 1st scan is given below as an example.)

```
05/10/1988                                                     10:30:11
ENG S/N               AC TAIL #               DATE 05/09/1988   TIME 18:00:26
FAULT   1-66 SIG*EPLA/AFTC                                      SCAN   1
|-----------------------------------------------------------------------------|
|                     ENGINE PARAMETERS                      |    AIRCRAFT    |
|------------------------------------------------------------|                |
|       BASIC          |      CONTROL          |  DISCRETES  |   PARAMETERS   |
|-----------------------------------------------------------------------------|
| APLA..  133.5 DEG   | MVPOS.    7648 PPH   | TL....   OK  | ACMN.. ****** UNIT |
| EPLA..  132.4 DEG   | AUGPOS    16.8 R/U   |              | MNAFTC    .09 UNIT |
| NF....   95.6 %     | MTM...    17.0 mA    | A/I...   OFF |                    |
| NG....   99.1 %     | IGVTM.   -20.7 mA    | AID...   NO  | AOA...   13.6 DEG  |
| T2....  516.9 DEGR  | A8TM..    15.9 mA    |              | ALT...   2720 FEET |
| T4B...   1316 DEGF  | WFRTM.    25.5 mA    | AIS...   ON  | NA....     .9 G    |
| IGV...   14.7 DEG   | DPF...    .209 R/U   | FDS...   ON  |                    |
| A8....    510 SQIN  | DP....     5.9 PSID  | E28V..   OK  | GUL...  GRND       |
| PS3C..  280.6 PSIA  | AFTPWR   -14.9 V DC | NFXFER   NO  |                    |
| QL....   2.13 GAL   | SECNF.    95.4 %     |              | TFF...  13422 PPH  |
| CDPCBP   12.8 PSID  | SECTM.      .0 mA    | TREND.   NO  |                    |
|                     | SNFLIM   100.2 %     | WARDAT   NO  |                    |
|-----------------------------------------------------------------------------|
```

TABLE 5: AN EXAMPLE OF PARTS LIFE TRACKING DATA STORED

ENGINE S/N   AC TAIL #   DATE 05/09/1988   TIME 18:58:15
EMSP S/N 361

EMSP CYCLE COUNTER DATA

	HOURS	COUNTS
T4B > 1600 DEG F	.533	16
T4B > 1630 DEG F	.100	6
T4B > 1660 DEG F	.000	0
T4B > 1685 DEG F	.000	0
T4B > 1705 DEG F	.000	0
ENGINE RUN TIME	142.000	1420
AUG RUN TIME	1.850	111
	CYCLES	**COUNTS**
LCF COUNTER	85	85
FTC COUNTER	530	530
CIC COUNTER	612	612
AUG COUNTER	181	181

TABLE 6: SUMMARY OF FUNCTIONS OF EACH UNIT INVOLVED IN EMS

(1) AMU (Flight Line) Functions

- Accept DDTU data
- Convert fault associated data to engineering units
- Display/print fault code/message and associated engine data
- Transmit trend data, maintenance events and actions, and parts life tracking information to the EMB
- Accept maintenance action input
- Maintain a maintenance event history file
- Transmit and accept maintenance event history records

(2) TEST Functions

(Installed or uninstalled engine operation at base engine test facility)

- All AMU functions
  - plus using the operator (pilot) initiated data to perform preliminary data analysis
  - but TEST does not maintain/transmit and accept event history file/records.

(3) EMB Functions

- Accept and store AMU and TEST data
- Provide access to engine level life usage data
- Provide trend plots
- Accept maintenance information from intermediate shop
- Maintain an engine history file
- Provide maintenance history as required
- Transmit and accept engine history records
- Transmit parts life tracking data to MEETS

TABLE 7: AN EXAMPLE FOR STATUS OF TRACKED COMPONENTS AND ITEM CLOSEST TO ITS LIMITS

```
PREPARED: 10 MAY 88                 MINIMUM ESSENTIAL ENGINE TRACKING SYSTEM

ENGINE #:         AIRCRAFT #:          DATE: 88071            CURRENT READINGS
```

WUC	SERIAL #	PART #	EOT	AB CYCLES	AB HOURS	ELC	ETT	FLY TIME	TAC	SCY	INSP EOT
27EDC D	00NWLAF2E1	1270M80P01	110.5	213	4.3	107.0		69.0	261.5	107.0	110

```
**** FOLLOWING ITEMS CLOSEST TO LIMITS ****
METHOD: EOT      WUC: 27GPL      NOMEN: AFT CONTROL
METHOD: INSP     WUC: 27GAH      NOMEN: MAIN FUEL PUMP (MFP)
METHOD: ELCF     WUC: 27CLC      NOMEN: HPT BLADE FWD RETAINER
METHOD: SLCF     WUC: 27BDE      NOMEN: FAN DISK STG 1
METHOD: TAC      WUC: 27FBM      NOMEN: BEARING #2
METHOD: ETT      WUC: 27CLG      NOMEN: HPT BLADE SET
```

TABLE 8: AN EXAMPLE OF COMPONENT LIFE PREDICTION

```
GE0110             MINIMUM ESSENTIAL ENGINE TRACKING SYSTEM

   ITEMS CLOSEST TO LIMITS ON ENGINE #                 AIRCRAFT #

                                                           NEXT     TIME
SERIAL #   PART #                                   EOT     DUE     REMAIN
00ECDK2207 7117M10G05                              110.5   2000.0   1889.5
           WUC: 27GPL   NOMEN: AFT CONTROL

                                                           NEXT     TIME
SERIAL #   PART #                  LCP   FTC   CIC   TAC    DUE     REMAIN
00FAFE8301 9732M22P07              107   579   389  261.5  2000.0   1738.5
           WUC: 27FBM   NOMEN: BEARING #2

SERIAL #   PART #        T1600    T1630    T1660    T1685    T1705     ETT
00MPOU3284 9530M95P13     0.4                                          0.1

                                 K - F A C T O R S          NEXT     TIME
                          3     4     5     6     7          DUE     REMAIN
                        2.000 1.230 0.736 0.376 0.179       342.0    341.9
           WUC: 27CLG   NOMEN: HPT BLADE SET

                                    K FACTORS               NEXT     TIME
SERIAL #   PART #                    1     2        ELC      DUE     REMAIN
00CAV22114 9528M68P04              0.005           109.9    1581     1471.1
           WUC: 27CLC   NOMEN: HPT BLADE FWD RETAINER

                                    K FACTORS               NEXT     TIME
SERIAL #   PART #                    8     9        SCY      DUE     REMAIN
00FBNA0018 1359M11P01              0.250 0.025     261.5    2000     1738.5
           WUC: 27BDE   NOMEN: FAN DISK STG 1
```

TABLE 9: FUNCTIONS AND FEATURES OF THE FBS

THE FBS IS A SYSTEM TO ACCOMPLISH:

A. MAINTENANCE DATA COLLECTION

B. MAINTENANCE MANAGEMENT INFORMATION AND CONTROL

1. Planning/Scheduling and Controlling Maintenance
2. Configuration Status Accounting
3. Comprehensive Engine Management
4. Serialized Parts (LRU/SRU/Engines) Tracking
5. Tracking Weapon System Utilization and Readiness (MICAP) Status
6. Time Compliance Technical Order (TCTO) Management
7. History and Resource Consumption Recording
8. Trend Analysis/Forecasting

C. FLIGHT AND FLYING PERSONNEL TRAINING MANAGEMENT

1. Requirements Computation
2. Automated Flight Scheduling
3. Flying Personnel Records
4. Data Analysis and Management Reports
5. Activities Tracking

D. CENTRALIZED MANAGEMENT INFORMATION SYSTEM OPERATIONS/DECISIONS/ADMINISTRATION

E. CENTRALIZED DATA BASE

F. SECURE NETWORK COMMUNICATIONS

G. CENTRALIZED PROJECT CONTROL AND MANAGEMENT

TABLE 10: FBS CONFIGURATION

HARDWARE CONFIGURATION:

1. IBM 3090-200
2. IBM PS/2's
3. IBM Peripherals
4. 3270 Terminals and Printers
5. 3745 Communication Controllers
6. 3174 Cluster Controllers/Modems

SOFTWARE CONFIGURATION:

1. MVS/ESA
2. VTAM
3. DB2
4. CICS/MVS
5. COBOL
6. Application System (AS)

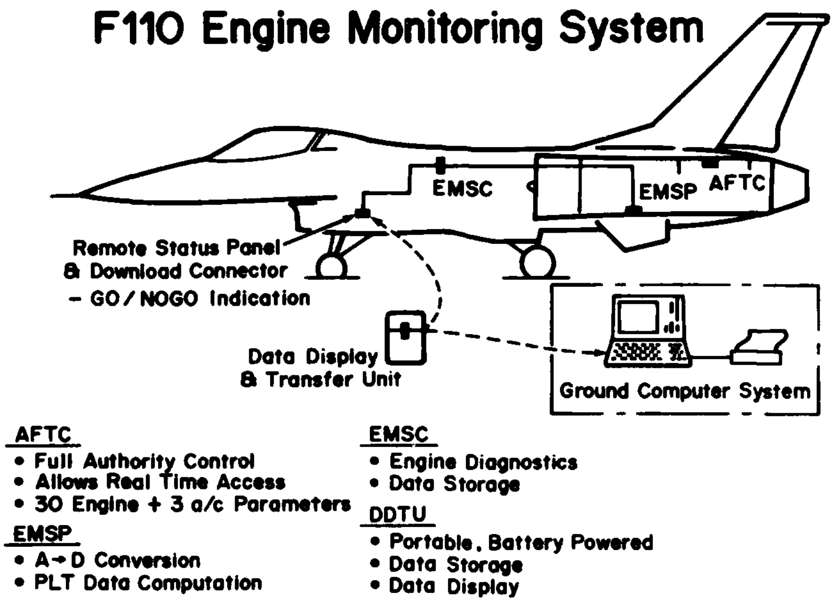

FIGURE 1: RELATIVE LOCATIONS OF ENGINE MONITORING SYSTEM HARDWARE

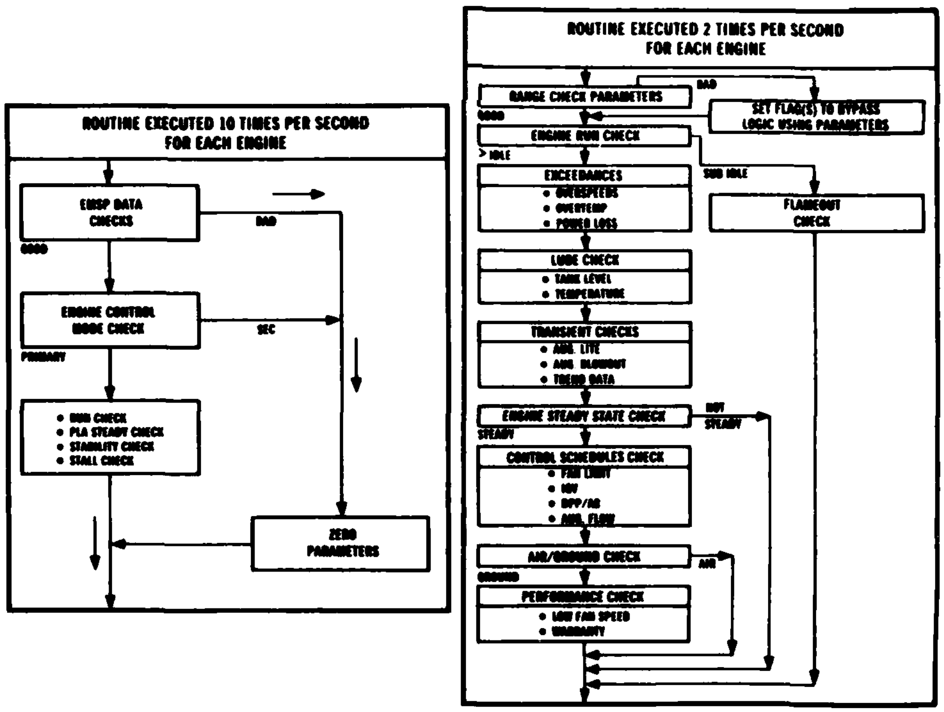

FIGURE 2: AIRBORNE COMPUTER ENGINE DIAGNOSTIC LOGIC

F110-GE-100 TREND PLOT REPORT

```
ENGINE S/N:                 AIRCRAFT ID:                    05/10/1988
INSTALL DATE:  08/20/1987

           100 :
            50 :         t t t t
DEL T45/F   00^:---t-t-t---------t-t-t-t-t-t-t-t-t-t-t-t-t-t-t-t-t------
           -50 :
          -100 :
          -150 :

            16 :
            12 :
% DEL WF    08 :
            04^:   w w w w w w w w w w w w w w w w w w w   w w w w
            00 :-----------------------------------------w-------------
           -04 :
            04 :                 f
            02 :           f f     f f f f f f f f f f f f   f
DEL % NF    00^:-----f---f-----f---------------------------f---f-f------
           -02 :   f   f
           -04 :
           -06 :
                   X                     X                 X X
                   0 0 0 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
                   8 8 9 0 0 0 0 1 1 1 1 1 1 1 1 1 1 1 1 4 4 4 5 5
                   2 2 0 0 3 3 3 1 1 1 1 2 2 2 2 2 2 2 2 2 2 2 0 0
                   6 8 1 6 0 1 1 8 8 9 9 0 1 1 2 6 7 8 8 0 1 4 5 9
```

Figure 3: An Example of Trend Plots for an Engine

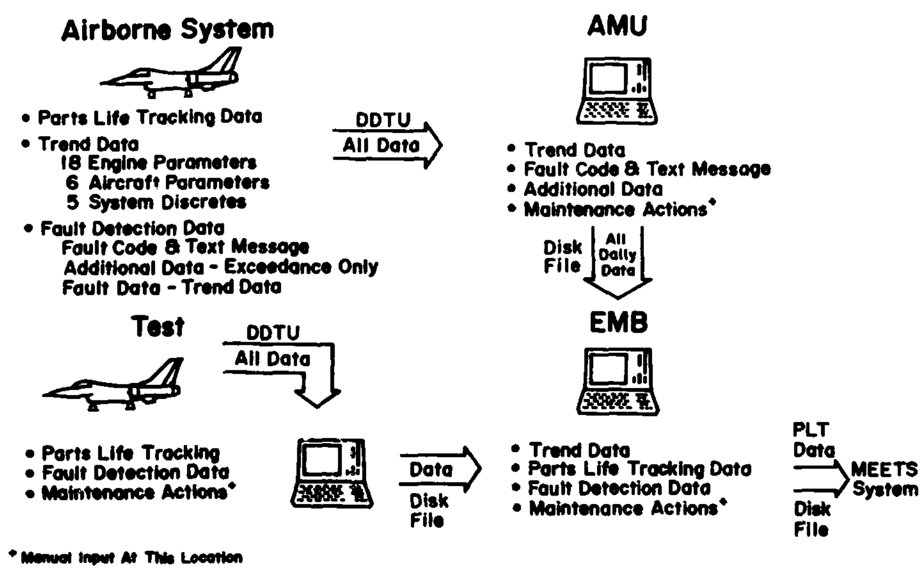

FIGURE 4: AN OVERVIEW OF ALL ENGINE MONITORING SYSTEM FUNCTIONS

ENGINE CONDITION MONITORING - STATE-OF-THE-ART CIVIL APPLICATION

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Summary

With the introduction of the AIRBUS A310 in 1983, an enhanced ECM concept was established at Lufthansa. Highlights of the theme include application areas and the economic aspects of everyday airline operation.

The ECM information system supports maintenance personnel in detecting incipient engine failures, in carrying-out optimum adjustment of engine controls, and in cutting down the number of engine run-ups. It also assists overhaul personnel in removal planning and overhaul planning. All data are acquired by an aircraft integrated data system through expanded engine instrumentation and are periodically reported through an on-board printer. Data printouts are entered into the Lufthansa computer network from each flight destination station. For a high degree of actuality data are processed on-line in the central computer at the Frankfurt maintenance base. In addition to engine modular performance and mechanical parameter analysis, data processing also performs automatic trend recognition and alert report generation.

1. Glossary

ACM	Aircraft Condition Monitoring
ACMS	Aircraft Condition Monitoring System
APU	Auxiliary Power Unit
ECM	Engine Condition Monitoring
EGT	Exhaust Gas Temperature
EROPS	Extended Range Operations
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Engine Control
GE	General Electric Company
GEM	GE Ground based Engine Monitoring Software
LH	Lufthansa
MEC	Main Engine Control
OCR	Optical Character Recognition
PMUX	Propulsion Data Multiplexer
SLOATL	Outside Air Temperature Limit at Sea Level
SOAP	Spectrometric Oil Analysis Program
VBV	Variable Bleed Valve
VSV	Variable Stator Vane

2. Introduction

As an early failure detection tool Engine Condition Monitoring has been an integral part of Lufthansa's "On Condition" maintenance concept since the early 1970's and has been paying an essential contribution towards enhancing dispatch reliability and safety.

At the beginning of the 1980's, the development of improved engine diagnosis procedures and the increasing availability of digital electronics in the aircraft lead to Lufthansa's decision to introduce a new and more comprehensive engine condition monitoring concept along with the advent of the AIRBUS A310.

The advanced system is aimed at achieving, in addition to the reduction of operational irregularities, a minimization of the engine's total operating cost (fuel, material, maintenance). Also, reduction of ground operation for lower emission has ever increasingly gained in significance in the past years.

This paper reviews the application and economical aspects of this concept based on 5 years of operational experience with the combined A310/A300-600 fleet.

3. Conceptual Background

A modern ECM system is intended to allow comprehensive assessment of each aircraft engine's condition through

- diagnosis of its gas path performance down to the level of each individual module;
- diagnosis of its mechanical condition in regard to vibration and lubrication system parameters.

The objectives in detail are:

- verification of engine health;
- detection of incipient engine problems;
- optimum adjustment of engine controls (fuel, speed margin, stability);
- avoidance of engine run-ups;
- assistance in engine removal planning;
- optimization of the engine's overhaul workscope.

Aimed at efficient and cost effective application of ECM major emphasis was put on the establishment of an information system, which is characterized by the following conceptual highlights:

- expanded engine instrumentation and propulsion data multiplexer (PMUX);
- automatic on-board data acquisition system;
- integration of all engine condition relevant information from operations, maintenance, work shop, and test cell;
- central organisation/analysis;
- high degree of actuality;
- high degree of user friendliness, versatility and expandibility.

4. System Description (Fig. 1)

The Lufthansa A310's and A300-600's are equipped with an expanded aircraft integrated data system which generates reports for later on ground analysis. Included in this system is an airborne printer which serves as the prime data output device. The layout of the print reports meets OCR standards (Optical Character Recognition) and by this permits automated reading.

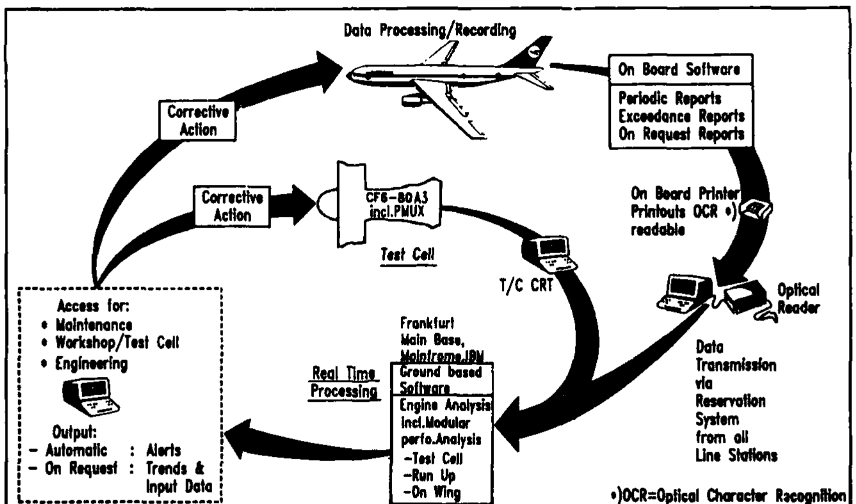

Fig. 1 LH A310/A300-600 ENGINE CONDITION MONITORING SYSTEM

Since data link is currently not available at Lufthansa this inevitably leads to a time lag between data recording and central analysis. For a high degree of actuality, however, a fast data transmittal medium is required. An extended on-board diagnosis capability is not considered a rewarding goal.

The contents of the reports generated during flight are entered into Lufthansa' ground-based computer network from all flight destination stations. After line station personnel have submitted the data by means of hand held video scanners those are transmitted to the central computer at the Frankfurt maintenance base where extended analysis is performed on-line by the General Electric ECM software "GEM" (Ground based Engine Monitoring) which was specified in a combined GE/airlines effort.

All input data and results are stored in a data base for trending purposes thus making complete ECM histories available. Upon analysis all results are automatically checked for findings and, if significant, are output to the maintenance engineers in the form of an alert message. This concept releases the maintenance personnel from the previous need to inspect all engine data and thus assists in concentrating on problem cases. For in-depth data analysis engine history output is provided on request via computer terminals.

In case an engine removal is due the overhaul engineers make use of engine history information for definition of the optimum shop work scope.

Upon test cell acceptance which the engine has to pass after overhaul PMUX as well as test cell instrumentation data are transmitted to the central computer for modular performance analysis. While the engine is still running the analysis results are made available automatically by return to the test cell personnel indicating the quality of measurement and performance of the engine and its individual modules.

The ECM user family connected to the ground based information system is depicted by Fig. 2. Maintenance engineering in charge of the daily monitoring and trouble shooting work is located at the maintenance base in Frankfurt. Engine overhaul, production planning and control, engine test cell, as well as central engineering is located in Hamburg. The engine manufacturer, i.e. General Electric in Cincinnati, are also connected to the ECM system.

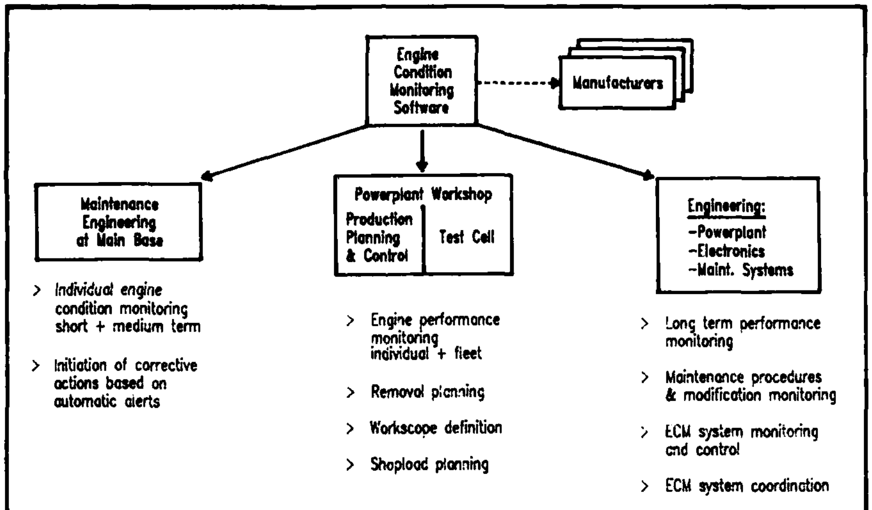

Fig. 2 ECM USERS COMMUNITY

5. Review of Application

In the following the main application areas are discussed focussing on cost and savings.

The financial balance as depicted in Fig. 3 is based on the experience gained between 1983 and 1987 and is projected until 1992 to cover the planned aircraft operating time of ten years.

For the given LH A310/A300-600 fleet and the considered time period the resulting net savings through ECM amount to 3.9 mio US $.

This is 23.000 US $ per aircraft and year.

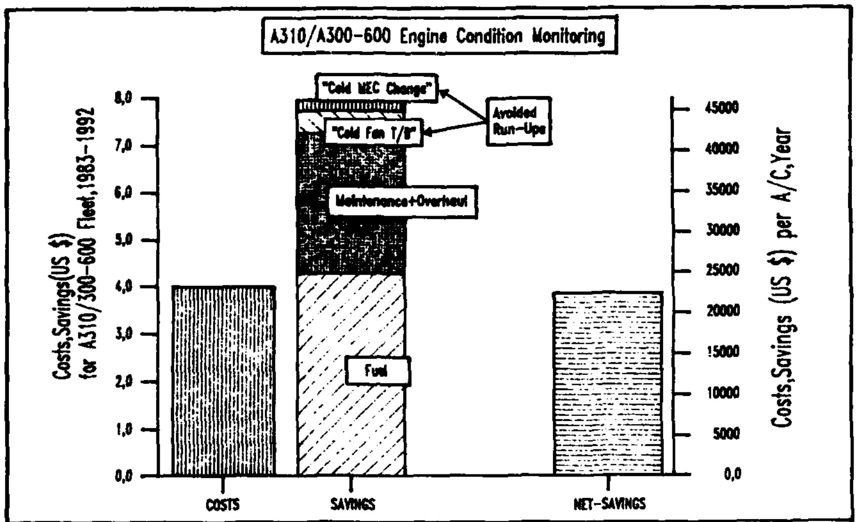

Fig. 3 COSTS/SAVINGS

5.1. Cost

There are four main factors:

"Onboard Hardware"

This factor includes the cost for expanded instrumentation and PMUX as well as a 50 % share for the Airplane Integrated Data System attributed to ECM.

"Project Cost"

Establishing the basic computer structure required expenditures for:

- creation of the software for data input at line stations;
- peripheral hardware investment;
- creation of a new real time/online data/software structure;
- incorporation of manufacturers' programs into LH's computer environment.

It has to be emphasized that most of the project cost are onetime-investments charging the A310 fleet for the pioneering effort without recurring for the further fleets to come.

"Computer Processing Cost"

Currently this amounts to approx. 1,000 US $ per engine and year which is 0.3 % of the engine maintenance cost. This is deemed to be favorable. Intended program optimization will further reduce this figure.

"Software Maintenance"

To a certain extent, the ECM software is subjected to continual modifications of its analytical functionality. This also extends beyond the project period and requires some manpower on a permanent basis.

5.2. Savings

"Fuel" (Optimum Control Adjustment)

Currently the largest portion of the savings is achieved by ensuring optimum adjustment of the variable stator vanes (VSV) and variable bleed valves (VBV).

Since the hydromechanical Main Engine Control (MEC) is per design not able to compensate internal deterioration this task has been integrated into ECM:

Maintenance engineering is automatically informed about off-optimum-schedule shifts derived from inflight VSV/VBV data. The corrective action, so triggered, is reduced to a verification of the transducer calibration and the adjustment itself by turning the MEC adjustment screw a defined number of turns.

No ground run is required !

The consequent application of this feature does reduce the fleet fuel consumption by 0.5 % !

The associated savings depend on the actual price of fuel. For the time beyond 1987 the price has been assumed to keep the '87 level - for the cost/benefit balance a conservative approach.

"Avoidance of Engine Run-ups"

Acquisition of operational data by ground runs is no longer required in particular for troubleshooting and verification of maintenance actions due to expanded instrumentation and availability of appropriate inflight data.

Two features are reducing especially the number of high power runs:
After replacing the MEC an optimum rig run/tracking check is normally required. Through ECM, pre-adjusted MEC's get this optimum adjustment using inflight data. Only an engine leak check is performed.

For fan trimbalancing the specific engine characteristic is derived from inflight data subsequent to installing a 'trial' balance weight. From this the optimum balance bolt configuration in the fan spinner is determined.
The convenience of this method allows a frequent application to keep fan vibration to a minimum for the entire fleet.

The savings are based on the experience that for both adjustment procedures 2 run-ups per engine and year are avoided with total cost of 1,000 US $ per run-up.

"Maintenance Cost"

For engine overhaul it is of essential importance to optimize the workscope with respect to both performance recovery and cost. By the availability of performance data down to the individual engine module, this task can be performed.

The information provided includes the modular performance parameter deltas (efficiencies, flow capacities) relative nominal and appearant measurement errors. The contribution of each individual module to the engine's exhaust gas temperature as the most indicative performance quality parameter is derived from this.

The overview of the actual engine health status is completed by:

- initial modular performance information;
- overall performance status (T/O EGT margin);
- non gas path related information (Oil Consumption, SOAP, Vibration).

The above mentioned information derived prior to engine disassembly provides assistance in defining the workscope. Modules requiring performance recovery in any case are indicated as well as modules with slight degradation to be returned to the engine assembly line without overhaul.

The reduction of maintenance cost currently amounts to 5 %.

The realization of these savings is highly dependent on experience, which was gained on deteriorated engines since 2 years. For the financial balance this figure is kept constant beyond 1988 although higher savings can be expected with further practice.

"Early Failure Detection"

This function is primarily aimed at reducing operational irregularities (delays, cancellations) and unscheduled engine removals particularly at line stations.

Within the advanced ECM system this is supported by:

- online processing and automatic trend recognition reducing the time gap between occurrence of an incipient engine failure and detectability through maintenance personnel;
- trending of an extended parameter set including modular performance.

Failure - ECM detectable and inhering the risk for a line station removal - did not occur yet for A310/A300-600. This is due to the engines' high reliability standard, application of other ECM functions and the fleet size. With no occurrence the cost and benefit balance currently cannot take this factor into account.

Experience from other fleets proves that such failures are reduced but not avoided. They are still a significant saving potential due to the steady increasing cost for unscheduled removals at line stations.

"Unquantified savings"

Beyond the savings described so far, ECM also offers a series of advantages whose quantification, however, is somewhat difficult.

This category includes monitoring hot day EGT margin and the limiting outside air temperature (SLOATL) respectively. Engine overall performance status and engine deterioration characteristics provided by this function enable maintenance to determine the remaining on wing time. Using this information for engine removal planning provides the key to an even shop load rate.
In addition the application of SLOATL does contribute positively to flight safety: It does prevent unexpected EGT exceedances during Take Off.

Due to the availability of modular performance information it is possible to combine modules with regard to optimum engine efficiency and lowest fuel burn. Since the savings for the attainable fuel burn reduction are currently lower than the cost for additional spare parts, module management is not applied. This scenario will change with an increasing fuel price.

Further benefits are:

- reduced emission due to avoided ground runs (pollution and noise) and lowest inflight fuel consumption;
- less unscheduled lay-overs due to "cold" adjustment methods ("cold fan trimbalance", "cold MEC change");
- reduction of secondary damage/high cycle fatigue (e.g. duct ruptures) thanks to engine vibration minimization.

It must also not be forgotten that, in many cases, ECM provides information to the effect that no problem is pending. This facilitates or additionally consolidates decision-making processes.

6. Conclusion

The aim of the original Engine Condition Monitoring approaches was to increase the dispatch reliability by means of early failure detection.

For the advanced ECM introduced with the A310, additional objectives are pursued in order to save fuel and maintenance cost.

The now available A310/A300-600 experience does prove the validity of this approach. Also, the high acceptance by the users has to be emphasized.

The ECM investment had to cover the implementation of the basic computer infrastructure as a major one time effort which therefore cannot be assigned exclusively to the A310. Fleet enlargement and incorporation of new fleets improve economics.

Considering today's high technological standards, it is questionable whether optimum treatment of an engine can be ensured without an extended ECM.

The on-line availability of a large amount of engine operational data will assist the engine manufacturer to better understand and quantify the mechanisms by which engines deteriorate in service. This will contribute to product improvements to the benefit of the airline industry.

7. Outlook

The above described concept will be used as the standard for future aircraft/engine types with some further enhancements.

For AIRBUS A320 and BOEING B747-400, ECM will be extended to a comprehensive "Airplane Condition Monitoring" (ACM) covering engine, APU and airplane performance.

The engines of these aircraft are generally equipped with a Full Authority Digital Engine Control (FADEC). The FADEC per design (Closed Loop Concept) automatically ensures optimum VSV and VBV adjustment. The cost for ECM related on-board hardware is reduced because the FADEC amongst other things replaces the PMUX.

As a further "Data Transport Channel" it is planned to establish a direct transfer of digital data from the aircraft via ground stations to the central computer.

The expansion to ACM necessitates software standardization for minimizing the airline's implementation effort. Standardization endeavors are currently being forced ahead by SAE under strong support by manufacturers and airlines.

ECM is of particular importance for all airlines operating twin engine aircraft under extended range conditions (EROPS). This is supported by the FAA in drafting of an appropriate recommendation for operation under EROPS conditions.

The changing attitude of the manufacturers must also be mentioned. While ECM was still largely left to the initiative of the airlines a few years ago, particularly also the aircraft manufacturers have realized that they have a relevant contribution to make.

A step in the right direction is the approach for integration of an Aircraft Condition Monitoring System (ACMS) in the BOEING 7J7 aircraft. The ACMS requirements are already being taken into account in an early phase of the development. Both the on-board hardware and also the ground-based software will be provided and supported by the aircraft manufacturer. As a matter of course, also in this scenario the challenge of implementation and successful application still remains with the user airlines.

DISCUSSION

M. BRUSSELEERS

1. Can the transition of a classic ECM system to a system as you presented be done without any increase in man power. Did you account for this increase in man power if necessary?
2. The ECM system requires additional hardware such as instrumentation, PMUX, AIDS ...What is your experience with the reliability of this hardware? Did it yield additional maintenance costs and did you account for it in your cost figures?

Author's Reply:

1. There is no man power increase with respect to the maintenance engineering being in charge of the daily trend monitoring. The automatic trend recognition and alerting feature even compensate for the fleet increase. Within the engineering division there is a certain man power required to evaluate advanced maintenance procedures and to coordinate the ECM system itself. Our cost figure do not account for this.
2. We had problems with the pressure sensor lines in the beginning These problems are solved since the PMUX is redesigned. Additional costs are minor, our cost figure do not account for it.

P.J.JENKINS

What advantages are provided by using ACARS downlink instead of a ground based data transfer.

Author's Reply:

The ACARS is used for flight operations and also for the transmission of troubleshooting messages from the Central Maintenance Computer(uplink and downlink).

The main advantages of ECM are:

-reduction of time interval between recording and analysis down to a few seconds.

-Reduction of workload for line personnel

-slightly higher data quality becaus input errors from the human interface are eliminated.

H. AHRENDT

Could you outline the cold fan balance procedure?

Author's Reply:

From the vibration level, amplitude and phase angle, the speed and the bolts configuration we calculate on a P.C. the corrections to apply on the spinner by changing the bolts configuration.

F. AZEVEDO

Is the relation between imbalance and vibration units different from engine to engine?

Author's Reply:

The reaction is similar, but not identical. For that reason the specific engine characteristic is derived by installing a "trial" balance weight prior to installing the final balance bolt configuration.

LE CFM 56-5 SUR A320 A AIR FRANCE

par
P.Chétail
AIR FRANCE
DM-UW
Direction du Matériel
Air France Orly
94396 Orly Aerogare, France

1. HISTORIQUE

Air France a été, dès 1967, une des premières Compagnies en Europe à mettre en oeuvre le suivi permanent au sol des paramètres réacteur en croisière.

Ceux-ci, enregistrés à bord par les mécaniciens navigants sur des cahiers préformatés (fig 1) sont ensuite transmis par télégramme, à la première escale touchée, à un ordinateur central situé près de Paris, au centre Air France de Vilgénis, où elles sont traitées "en batch", la nuit, selon un programme fourni par les constructeurs moteur Pratt et Whitney, Rolls Royce ou General Electric. Les listings correspondants (fig 2, 3, 4) sont transmis le lendemain matin par navette automobile, aux centres de maintenance situés sur les aéroports de Charles de Gaulle et d'Orly.

Au cours des 20 dernières années, ce traitement journalier a fait la preuve de son efficacité et figure d'ailleurs nommément aux programmes de fiabilité déposés par la Compagnie Air France, auprès des Autorités de Tutelle Françaises. Des cahiers de signature de panne existent qui regroupent la méthode de suivi des paramètres et d'autres, telles que le SOAP, qui, toutes ensembles, participent à la surveillance permanente des moteurs entretenus selon état (fig 5).

2. LIMITATIONS RENCONTREES EN SERVICE

Le recours aux mécaniciens navigants présente certains avantages. Ceux-ci exercent leur jugement quant à la représentativité des valeurs enregistrées, et d'ailleurs, depuis quelques années, ils suppléent, dans une certaine mesure, aux limitations inhérentes à ce système de surveillance à moyen et long terme. Ils procèdent à bord, en temps réel, à certains calculs destinés à déceler les pannes brusques et notent un nombre réduit de valeurs au décollage, qui complètent utilement ce traitement des données de croisière, en permettant de surveiller au sol l'évolution de la marge résiduelle EGT à pleine puissance en ambiance "chaude".

En 1983, l'arrivée à Air France d'un avion piloté à deux, le B.737, a entraîné la remise en question des conditions d'acquisition et de transmission des données réacteurs. La solution de relevés manuels faits par l'officier pilote fut rejetée par principe, cette tâche ne participant pas directement à la conduite du vol. L'acquisition des B.737 à Air France, en 1983, était alors supposée temporaire. Il fut alors décidé de ne procéder qu'à des modifications mineures de l'avion de base (installations supplémentaires d'un capteur EGT par réacteur), et de profiter de l'installation du QAR pour extraire en différé, au sol, les données réacteurs à partir des enregistrements magnétiques continus réalisés à bord sur cassette (fig 6).

Très rapidement, deux limitations apparurent :

- le nombre de points extraits dut être limité à un seul par jour et par avion (bien que le logiciel développé au sol ait été capable d'en reconnaître beaucoup plus),
- le retard à l'exploitation des résultats, fonction du délai de dépose et transmission des cassettes, était de l'ordre de 8 à 9 jours, surtout dans le cas où ces cassettes devaient être déposées dans des escales autres que celles de la région parisienne.

Cependant, cette méthode permettait d'assurer un "traitement monitoring minimal" acceptable des réacteurs.

3. DEFINITION ET MISE EN OEUVRE D'UNE NOUVELLE ETAPE

Spécification ETMT n° 2 et expérience ATLAS A310.

Dès 1975, en étroite coopération avec les autres membres du groupe ATLAS (1), et notamment avec la participation de Lufthansa, une spécification ATLAS était mise au point et adressée à Airbus Industrie, pour la mise en oeuvre de l'acquisition automatique des données sur avion A310, à l'aide d'un calculateur de bord et d'une imprimante.

Tandis qu'à LH, ce système était généralisé sur tous leurs A310 et donnait lieu aux développements très intéressants qui ont été présentés par ailleurs, la présence d'un troisième membre d'équipage dans les avions A310 d'Air France permettait de continuer la méthode antérieure de relevés manuels. Toutefois, le système AIDS/imprimante était expérimenté à Air France de façon extensive sur le premier avion livré (F-GEMA).

Grâce à la participation active des équipages Air France d'une part, et de SFIM (constructeur de l'AIDS) d'autre part, au bout d'un an d'exploitation, deux conclusions essentielles purent être dégagées :

- la logique de reconnaissance de l'état "moteur stabilisé", basée sur la constance de la TAT une fois le mode "cruise" engagé, devait être changée au profit de la reconnaissance d'un N1 stabilisé,
- l'acquisition pratique des données (à l'aide d'une imprimante de bord), leur lecture ultérieure au sol, leur transmission par telex au calculateur central de Vilgénis, même limité à un seul avion se révéla trop lourde à mettre en oeuvre efficacement et rapidement par les services au sol, dont les moyens n'avaient pas été augmentés.

En conséquence, il apparut à l'évidence qu'il était nécessaire d'automatiser cette transmission en prenant avantage de l'expérience des compagnies américaines, DAL, AAL et PAA en particulier, qui transmettaient directement ces données au sol, par VHF selon un système dit ACARS.

La Direction Générale d'Air France décidait alors d'équiper les A320 (pilotés à deux dès leur mise en service) (fig 7), d'un système AIDS/ACARS destiné dans un premier temps, à acquérir et transmettre automatiquement les données réacteurs au décollage et en croisière, l'extension de ce mode de traitement à d'autres types de données (informations opérationnelles, météo, etc.) étant prévue dans une étape ultérieure (fig 8 et 9).

4. DEFINITION DU SYSTEME A320

4.1. Acquisition.

De façon simplifiée, on peut considérer le système A320 comme la superposition au système réglementaire traditionnel d'acquisition et de stockage de données sur un DFDR, d'un système d'acquisition en parallèle de ces mêmes données et de transmission au sol par un système du type ACARS (AIRCOM). Ce système repose sur l'existence d'un réseau sol de transmission par telex, le SITA. Ce réseau recouvre déjà suffisamment bien, en 1988, l'ensemble des lignes exploitées par les A320 d'Air France pour devenir complet en 1990 (fig 10).

4.2. Transmission.

Les données transmises par AIRCOM sont reçues automatiquement par la station sol SITA la plus proche, la reconnaissance et mise en transmission du message étant complètement automatique et pouvant être effectuée dès l'émission du message qui, s'il n'est pas transmis immédiatement, est stocké en mémoire à bord.

La station sol retransmet le message à l'ordinateur central AF de Vilgénis via Hong-Kong.

<u>NOTA</u> : Au moment de l'établissement de ce rapport (février 1988) quelques difficultés de réalisation étaient apparues chez les équipementiers choisis

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(1) ATLAS est un consortium formé par les cinq Compagnies :
Air France / Lufthansa / Iberia / Alitalia / Sabena

par Airbus Industrie, BENDIX pour les ACARS et NORD MICRO pour les AIDS. Air France a prévu de pallier à ces difficultés temporaires en recourant à une méthode du type B.737 décrite ci-dessus.

4.3. Traitement GEM (Ground based Engine Monitoring).

A Vilgénis, les données sont traitées en temps réel suivant le programme GEM (version 10.0), et une surveillance automatique est programmée qui vise à reconnaître, dès qu'elles apparaissent, les anomalies de tendance.

Afin de limiter le nombre de fausses alertes, le système de surveillance automatique a été limité volontairement à Air France aux seuls paramètres EGT et VIB, au moins dans un premier temps.

Le listing habituel ADEPT émis journellement pour les autres types de réacteurs est remplacé par un listing GEM, établi d'une façon systématique seulement une fois par semaine, mais celui-ci peut être "appelé" automatiquement à partir des terminaux du service utilisateur, par une transaction particulière, pour un matricule, un avion ou un réacteur donné (fig 11).

4.4. Alerte automatique.

L'algorithme de reconnaissance est le suivant :

$$IXn = IXn-1 + \alpha 1 * (Xn - IXn-1)$$

Si Xn est l'écart d'un paramètre avec sa valeur de référence pour le relevé de rang n

IXn la valeur lissée de cet écart pour le rang n

$\alpha 1$ un coefficient de lissage dit exponentiel compris entre 0 et 1

Lorsque la différence $|Xn - IXn|$ est supérieure ou égale à un seuil pré-déterminé, un message est émis automatiquement par le calculateur central de Vilgénis et apparait sur les écrans du service contrôle de la base principale de maintenance DM.QN de l'aéroport Charles de Gaulle (fig 12).

Le service peut alors demander des informations supplémentaires à l'ordinateur et le listing GEM, en particulier.

Les réacteurs CFM 56-5 n'avaient pas encore, à la date d'émission de ce rapport, donné d'alerte réelle, c'est pourquoi le programme a été appliqué rétrospectivement aux données brutes réelles CF6-50C et E correspondant à des incidents réels, enregistrés à Air France au cours de l'année 1987 (fig 13 et 14).

Il convient de noter que ce système de reconnaissance de tendance, basé sur les déviations brusques du réacteur par rapport à lui-même, recoupe en général celui qui est installé sur le calculateur de bord et qui, pour l'EGT seulement, décèle ses variations brusques d'un réacteur par rapport à son (ou ses) homologues, fonctionnant sur le même avion et dans le même environnement. Mais, tandis que la surveillance installée ne s'adresse qu'au paramètre principal d'état qu'est l'EGT, la surveillance au sol peut plus facilement être programmée pour surveiller également d'autres paramètres, avec des algorithmes analogues ou même différents. Ces méthodes sont complémentaires et ne se superposent que pour l'EGT.

4.5. Surveillance de l'état des modules.

Depuis plus de 10 ans, Air France évalue les performances modulaires de ses réacteurs CF6-50 et -80, au banc d'essai, où une instrumentation spéciale est installée à cet effet. Sur CFM 56-5, cette installation existe (fig 15) en permanence, et ses informations sont recueillies sur AIDS et transmises par AIRCOM en même temps que les informations relatives aux paramètres usuels.

Ainsi que l'ont démontré sur le CF6-80A3, LH et KL, Air France a l'intention d'utiliser cette information pour optimiser la définition des travaux à effectuer sur un réacteur descendu, soit pour une cause mécanique, soit pour limite thermique potentiellement atteinte (méthode OATL). Après entrée en atelier, l'état physique des composants du réacteur est rapproché des éléments de rendement et/ou de capacité de débit déterminés par le traitement GEM/TEMPER, et le worskcope est affiné en conséquence.

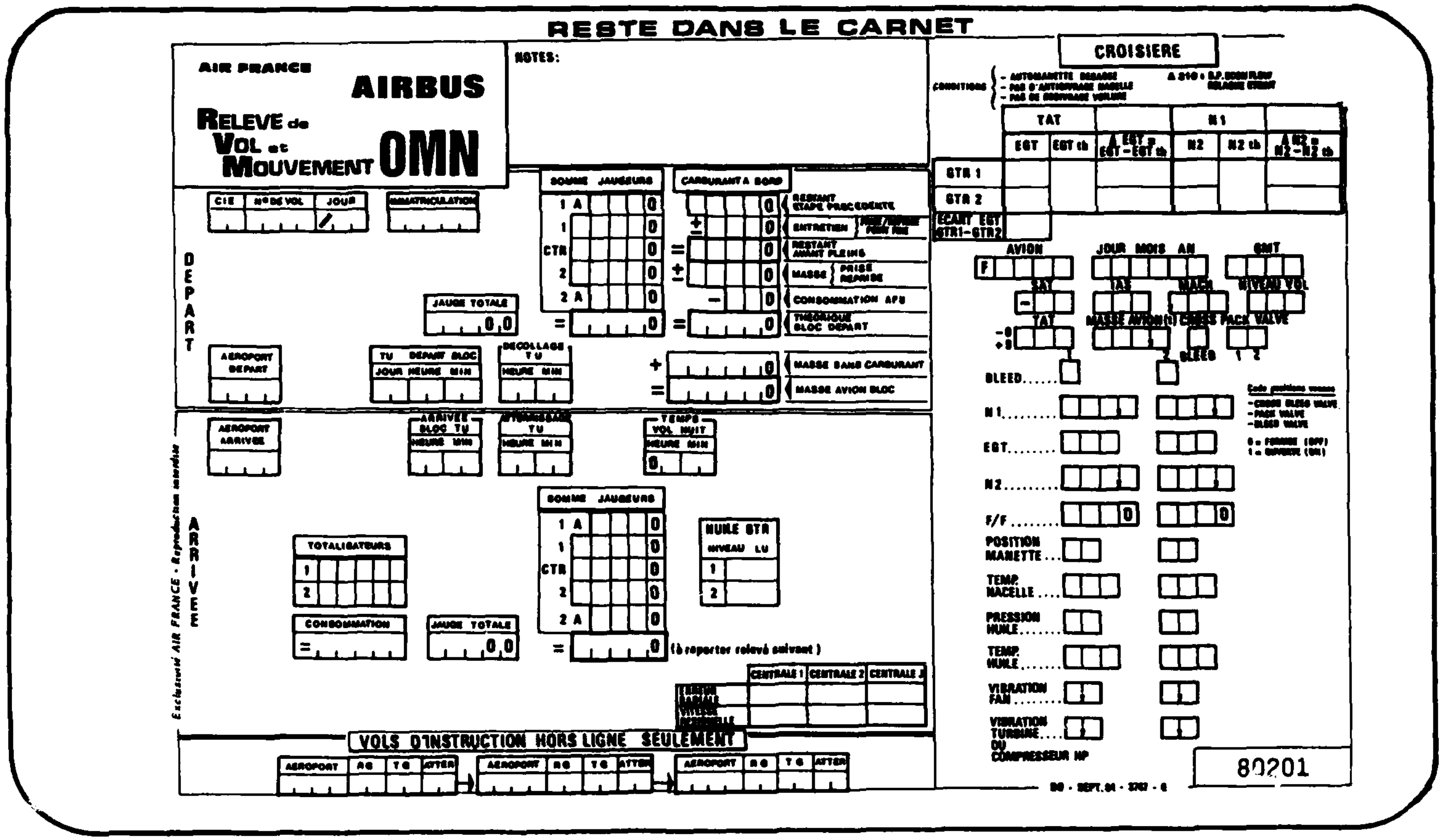
Ainsi est bouclé le traitement des données réacteurs.

En conclusion, il convient de souligner que le traitement des paramètres réacteurs sur A320, n'est qu'une des méthodes de surveillance de l'état des CFM 56-5. Elle est complétée par deux types de surveillance permanente, l'un de l'état des pièces mécaniques par observation visuelle, borescopique ou gammagraphique, et l'autre de l'état d'usure/fatigue des pièces lubrifiées par l'huile par bouchon magnétique et spectrographie d'échantillon d'huile. C'est de l'harmonisation de ces méthodes et de la mise en oeuvre de leur complémentarité que dépend l'amélioration de la fiabilité du propulseur.

Sur A320, à Air France, la philosophie d'entretien des réacteurs n'est pas différente de celle de tous les autres propulseurs, du DART à l'Olympus en incluant tous les réacteurs PWA et GE, mais l'installation AIDS + AIRCOM contribue à rendre beaucoup plus efficace que par le passé, la surveillance de l'intégrité du passage des gaz.

Le but recherché par l'emploi de ces techniques d'entretien peut d'ailleurs se résumer d'une façon lapidaire :

"MONITORER POUR MIEUX ANTICIPER"


RESTE DANS LE CARNET
AIR FRANCE
AIRBUS
RELEVE de VOL et MOUVEMENT
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TU DEPART BLOC
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JAUGE TOTALE
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CARBURANT A BORD
RESTANT ETAPE PRECEDENTE
ENTRETIEN
RESTANT AVANT PLEINS
MASSE
PRISE
REPRISE
CONSOMMATION APU
THEORIQUE BLOC DEPART
MASSE SANS CARBURANT
MASSE AVION BLOC
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AEROPORT ARRIVEE
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GTR 2
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JOUR MOIS AN
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EGT
N2
F/F
POSITION MANETTE
TEMP. NACELLE
PRESSION HUILE
TEMP. HUILE
VIBRATION FAN
VIBRATION TURBINE OU COMPRESSEUR HP
80201
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Fig. 1

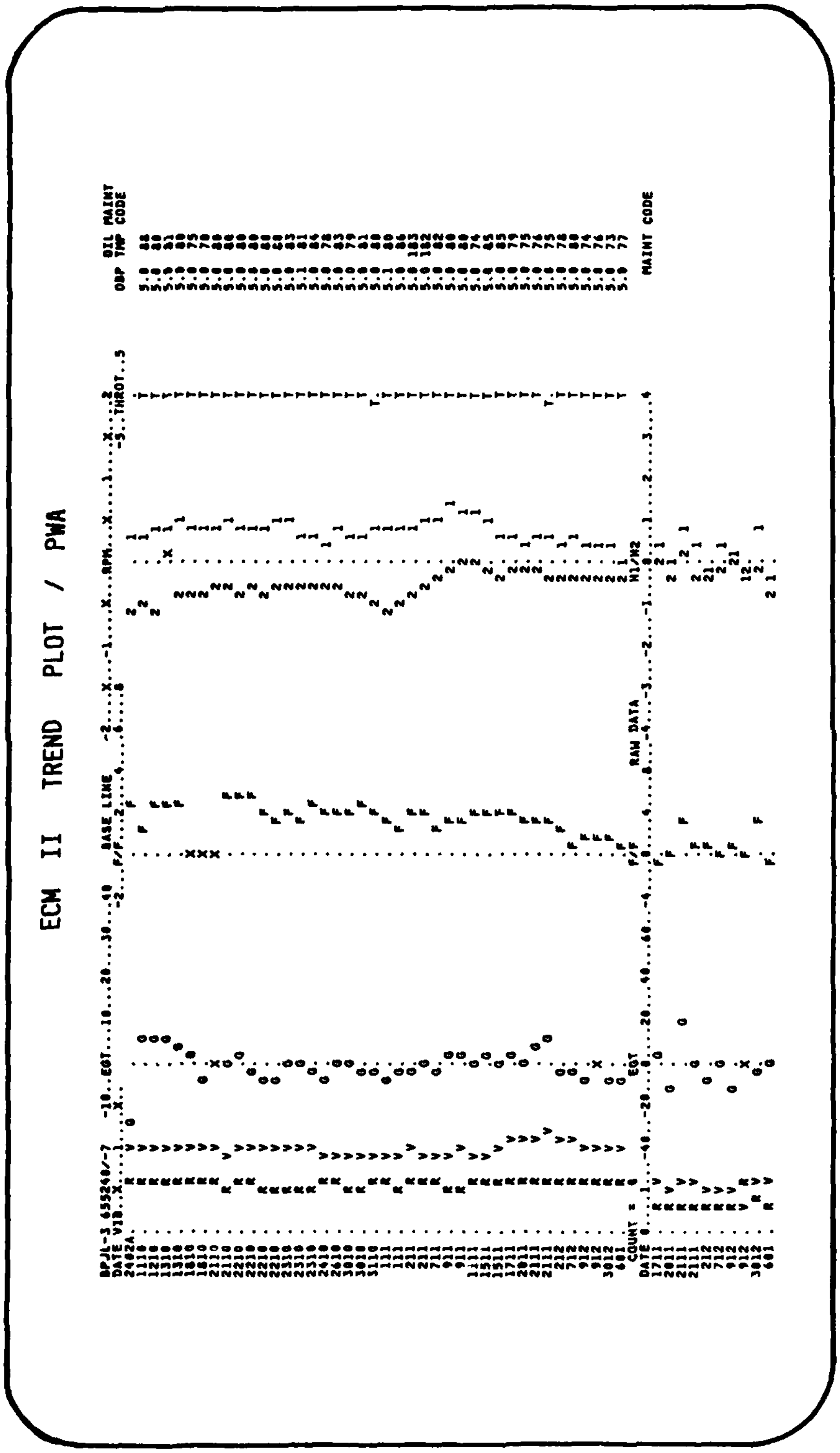

ECM II TREND PLOT / PWA
BASE LINE
RAW DATA
MAINT CODE
OIL MAINT
OBP TMP CODE

Fig. 2

CONCORDE TREND PLOT / RR

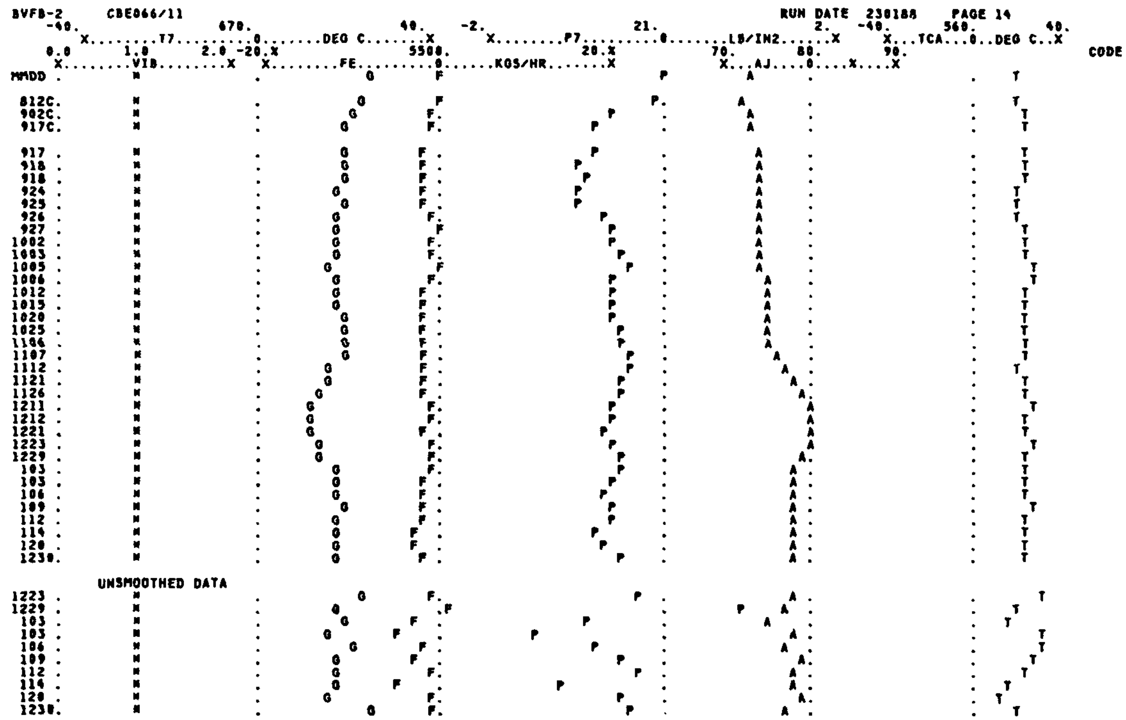
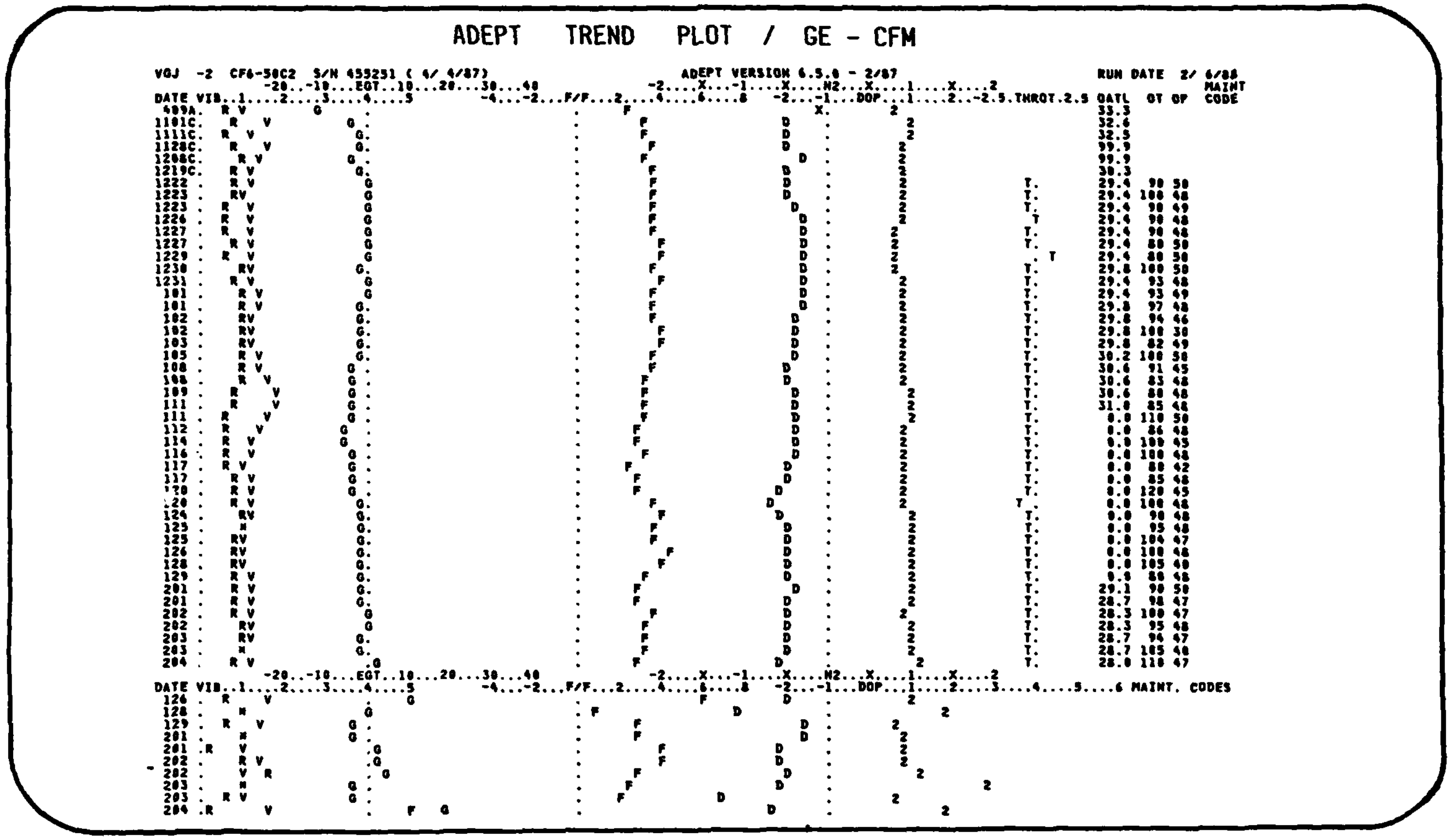


Fig. 3


ADEPT TREND PLOT / GE - CFM
VOJ -2 CF6-50C2 S/N 455251 (4/ 4/87)
ADEPT VERSION 6.5.6 - 2/87
RUN DATE 2/ 6/88
MAINT CODE
DATE VIB
EGT
F/F
N2
DOP
THROT
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MAINT. CODES

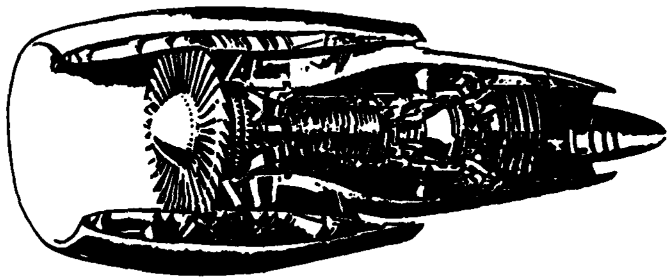
Fig. 4

METHODES DE SURVEILLANCE

EN CONTINU

DES REACTEURS AVIONNES

CF6



MANUEL D'UTILISATION

Fig. 5

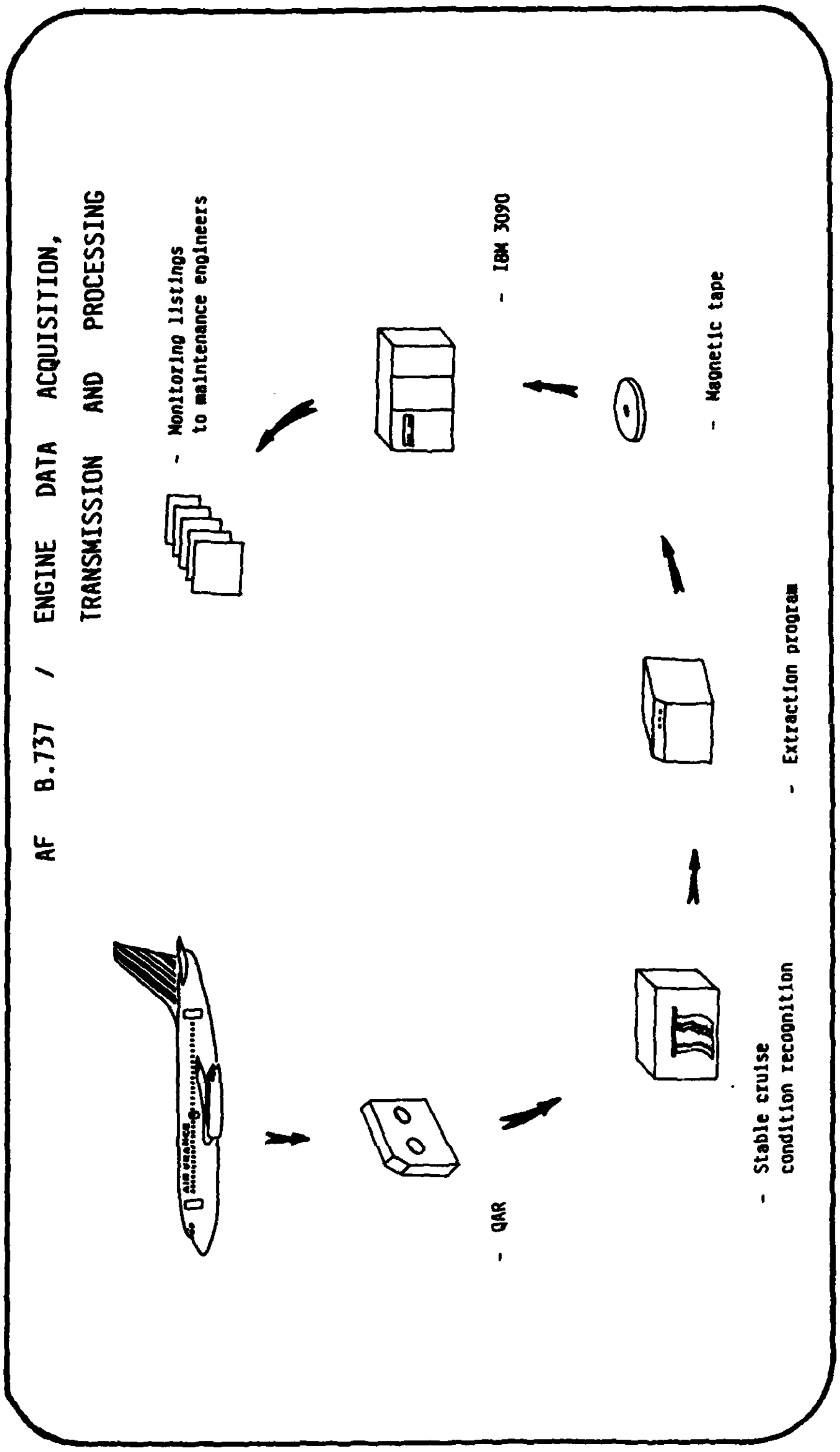

AF B.737 / ENGINE DATA ACQUISITION,
TRANSMISSION AND PROCESSING
- QAR
- Stable cruise
condition recognition
- Extraction program
- Magnetic tape
- IBM 3090
- Monitoring listings
to maintenance engineers

Fig. 6

A320 Flight deck

EIS, General arrangement

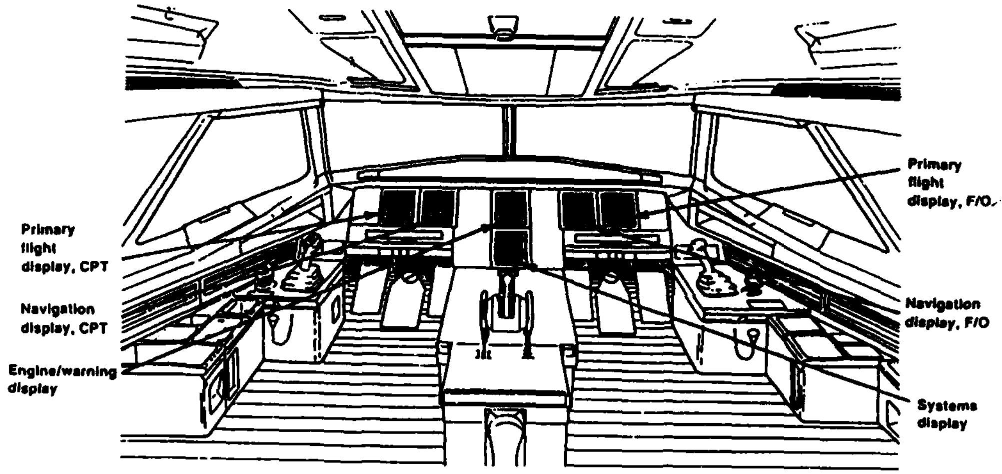
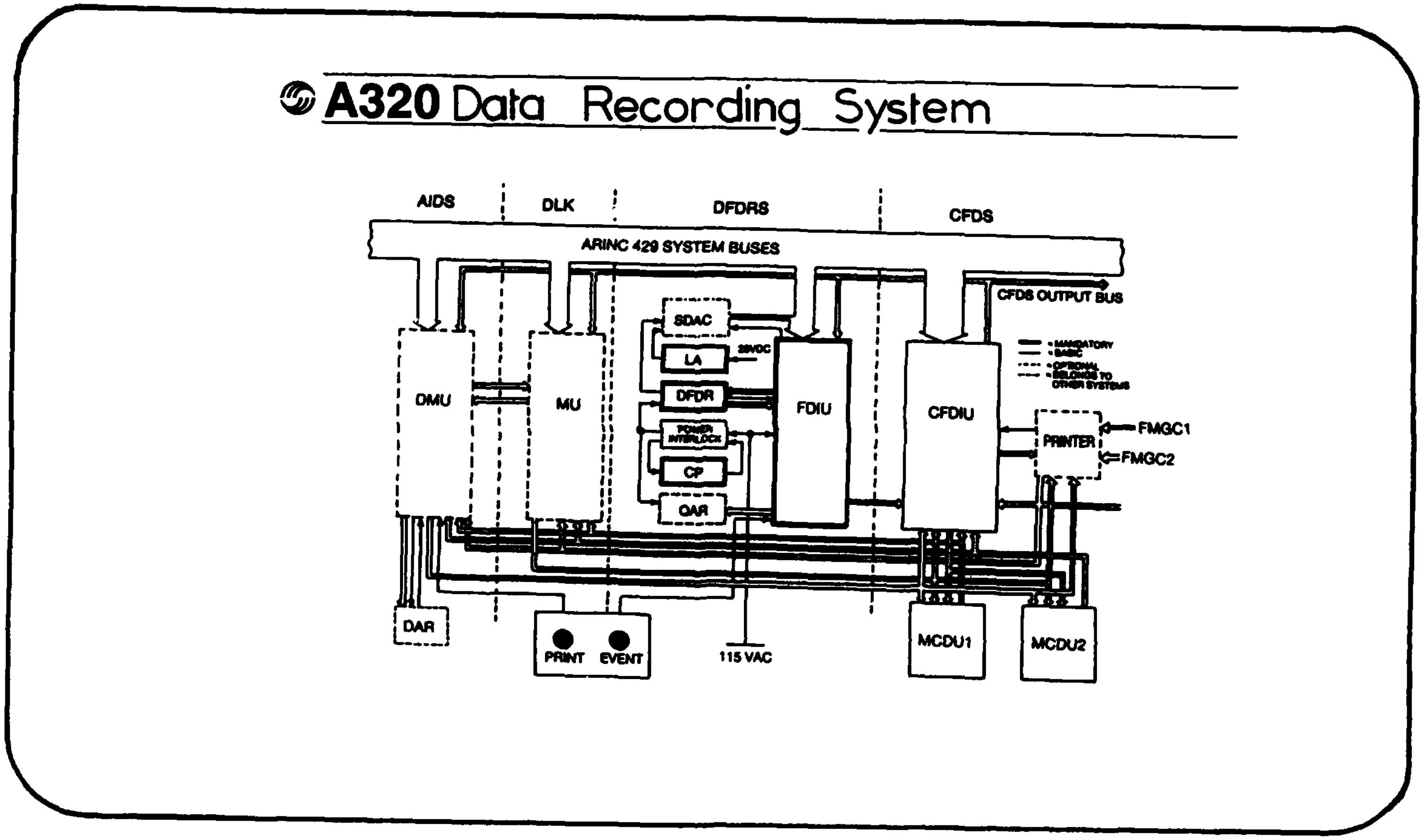


Fig. 7



A320 Data Recording System
AIDS
DLK
DFDRS
CFDS
ARINC 429 SYSTEM BUSES
CFDS OUTPUT BUS
DMU
MU
SDAC
LA
28VDC
DFDR
POWER INTERLOCK
CP
QAR
FDIU
CFDIU
PRINTER
FMGC1
FMGC2
DAR
PRINT
EVENT
115 VAC
MCDU1
MCDU2

Fig. 8

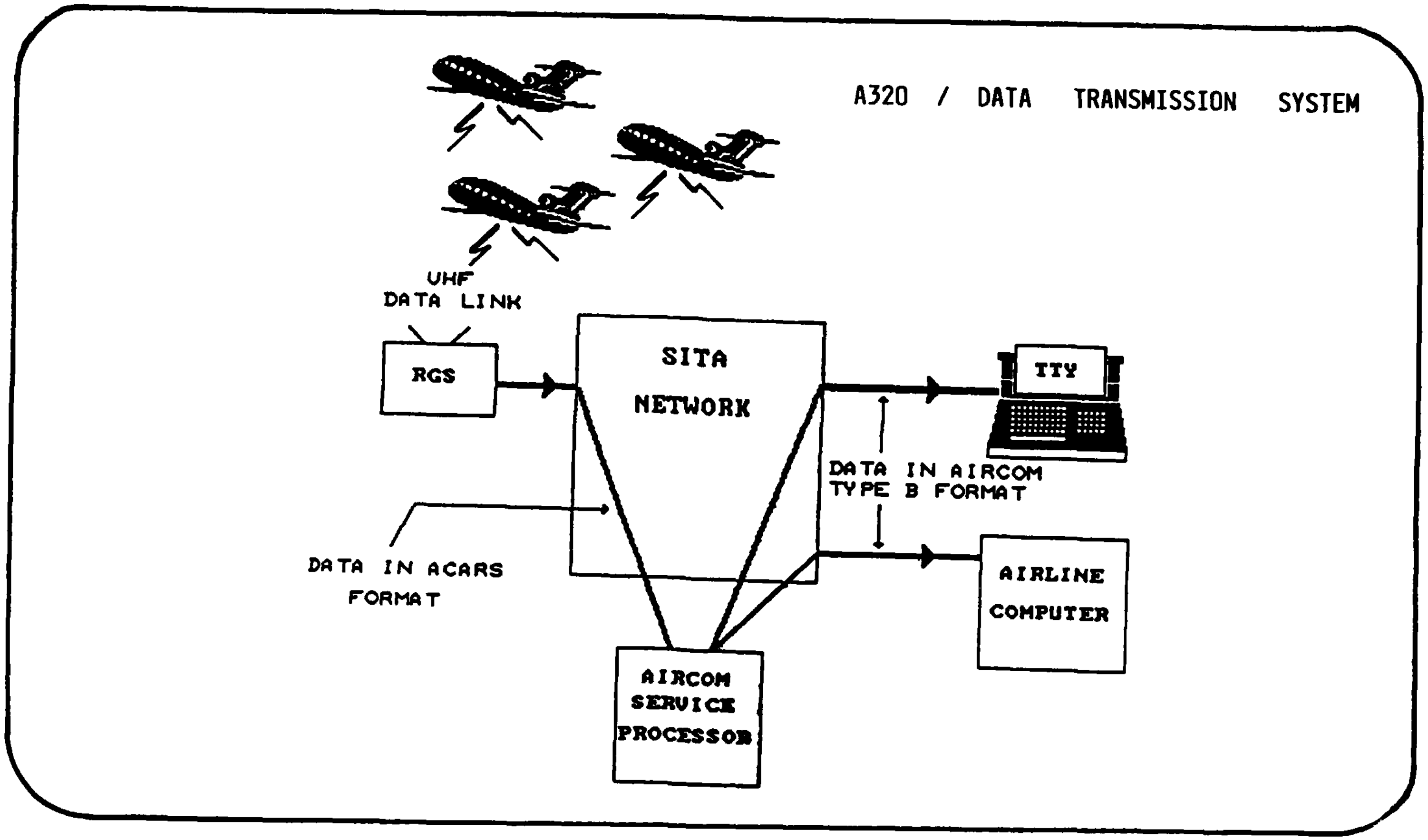

A320 / DATA TRANSMISSION SYSTEM
UHF
DATA LINK
RGS
SITA
NETWORK
TTY
DATA IN AIRCOM
TYPE B FORMAT
AIRLINE
COMPUTER
DATA IN ACARS
FORMAT
AIRCOM
SERVICE
PROCESSOR

Fig. 9

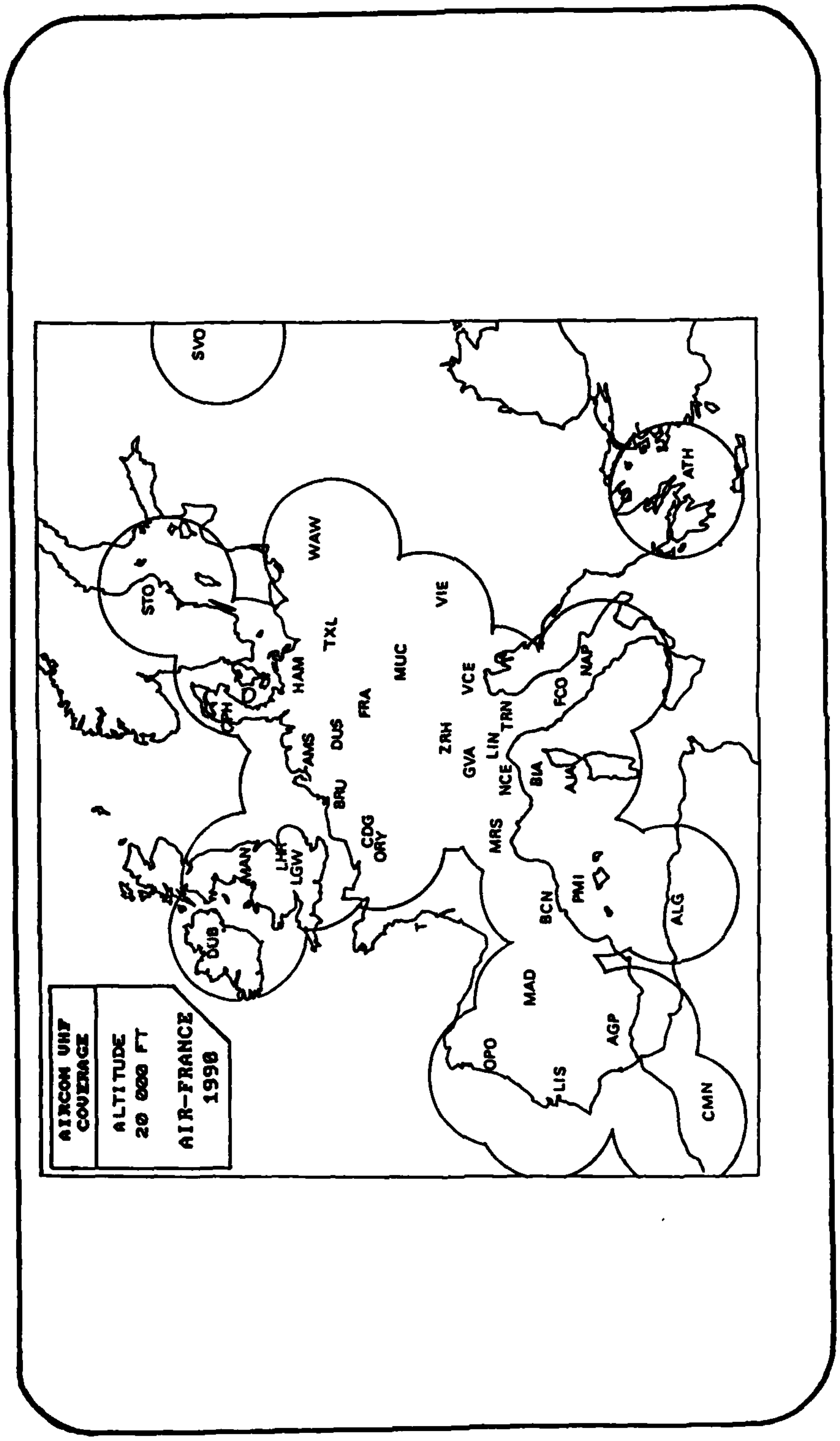
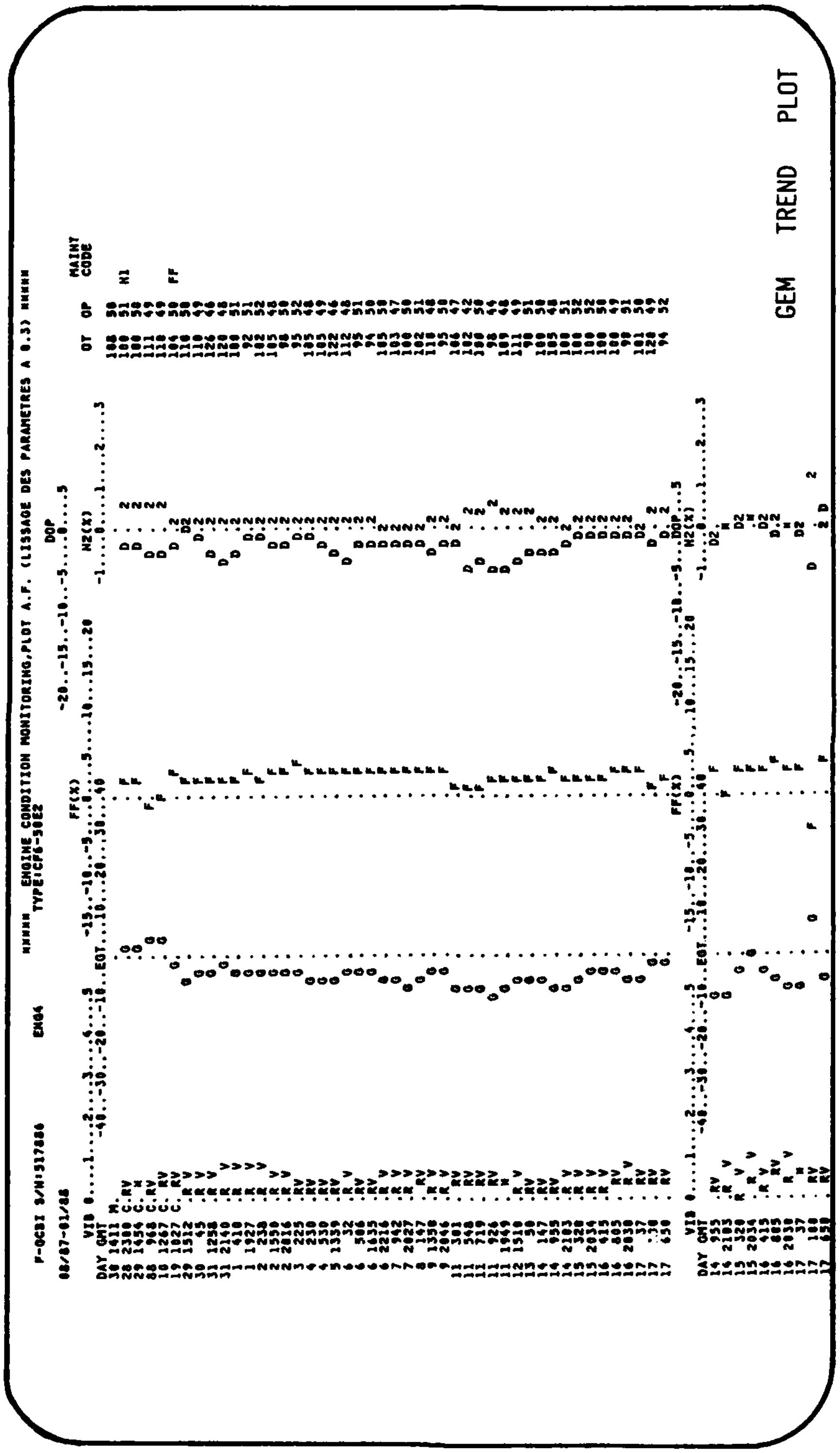

AIRCOM UHF COVERAGE
ALTITUDE 20 000 FT
AIR-FRANCE 1990
SVO
STO
WAW
CPH
HAM
TXL
VIE
MUC
AMS
DUS
FRA
VCE
ZRH
LIN
TRN
NAP
FCO
GVA
NCE
BIA
AJA
BRU
CDG
ORY
MRS
MAN
LHR
LGW
DUB
BCN
PMI
ALG
MAD
OPO
AGP
LIS
CMN
ATH

Fig. 10



GEM TREND PLOT

Fig. 11

```
 TYPE          A/C      POS     S/N        DATE    GMT

CF6-50C2      F-BUAJ   ENG1   455386     880119   1820
SEUIL DECLENCHEMENT =       6.50    ECART REEL   =      10.51
 *** EGT *** ALERTE DU TYPE COURT TERME


CF6-50E2      4-544F   ENG4   517601     880120   1747
SEUIL DECLENCHEMENT =      12.00    ECART REEL   =      17.38
 *** EGT *** ALERTE DU TYPE MOYEN TERME




                 GEM   ALERT   MESSAGE
```

Fig. 12

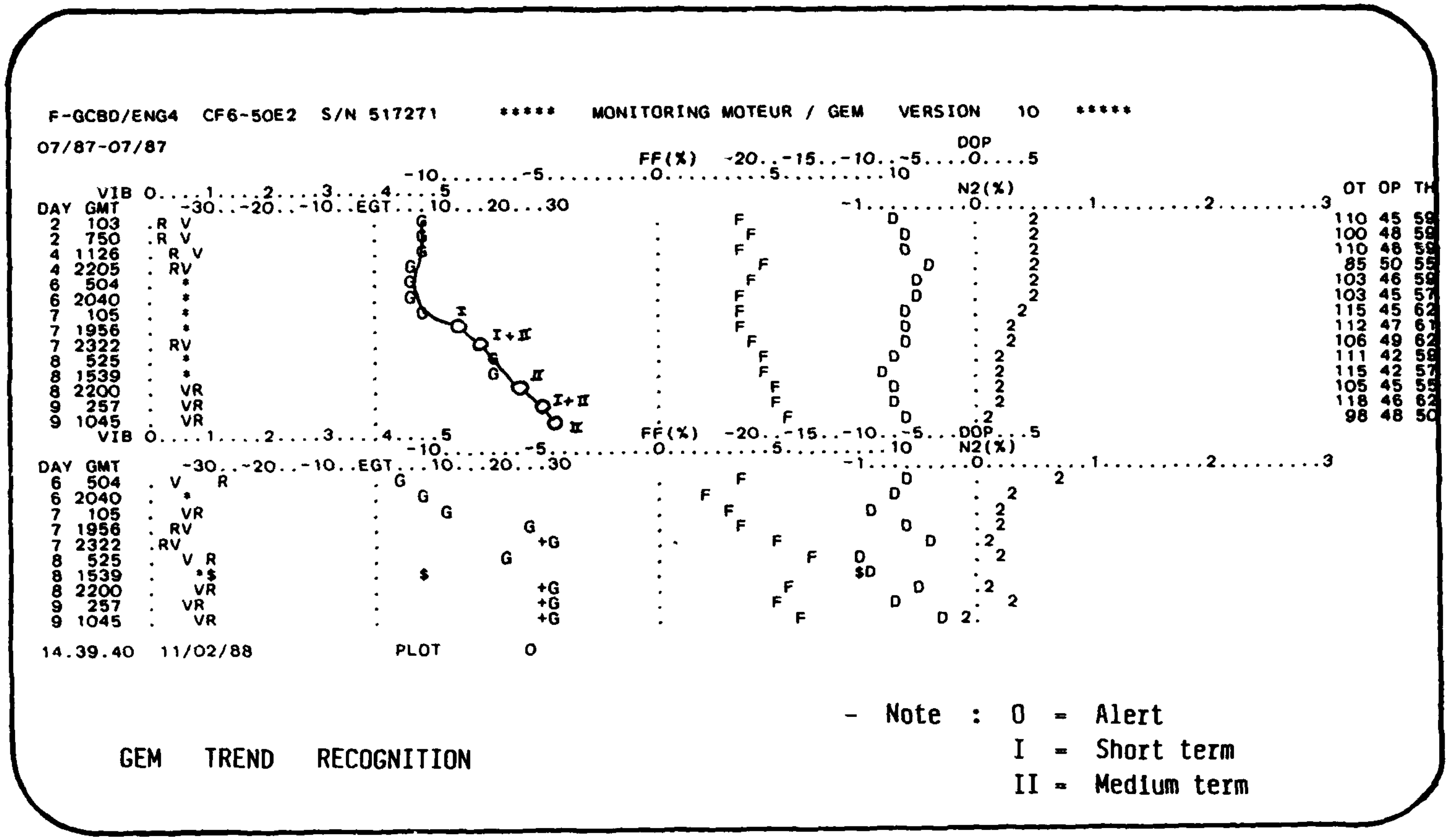

F-GCBD/ENG4 CF6-50E2 S/N 517271 ***** MONITORING MOTEUR / GEM VERSION 10 *****
07/87-07/87
VIB
DAY GMT
EGT
FF(%)
DOP
N2(%)
OT OP
14.39.40 11/02/88
PLOT
- Note : O = Alert
I = Short term
II = Medium term
GEM TREND RECOGNITION

Fig. 13

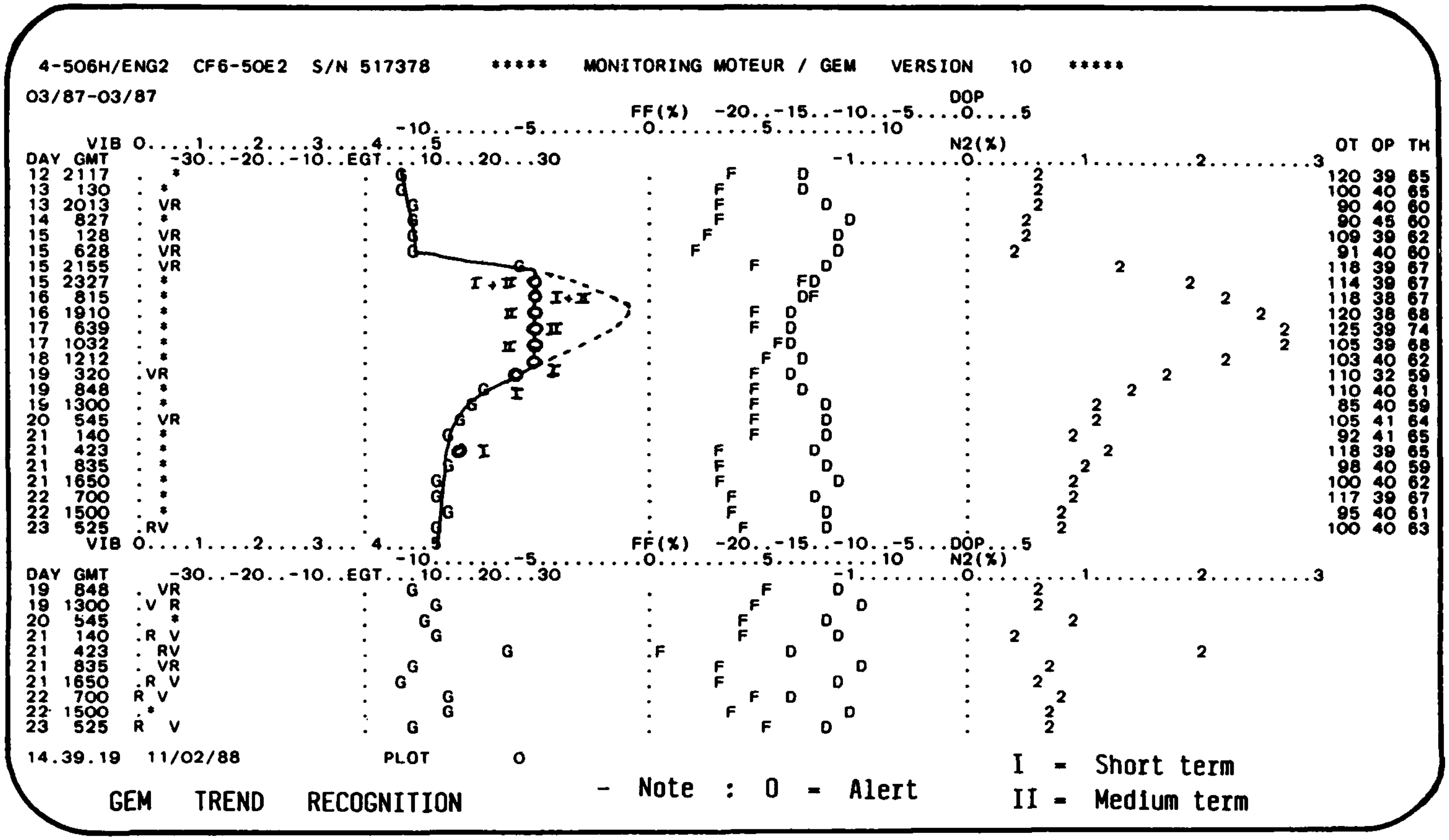

4-506H/ENG2 CF6-50E2 S/N 517378 ***** MONITORING MOTEUR / GEM VERSION 10 *****
03/87-03/87
14.39.19 11/02/88 PLOT O
GEM TREND RECOGNITION
- Note : O = Alert
I = Short term
II = Medium term

Fig. 14

A320 Engine control

Full Authority Digital Electronic Control

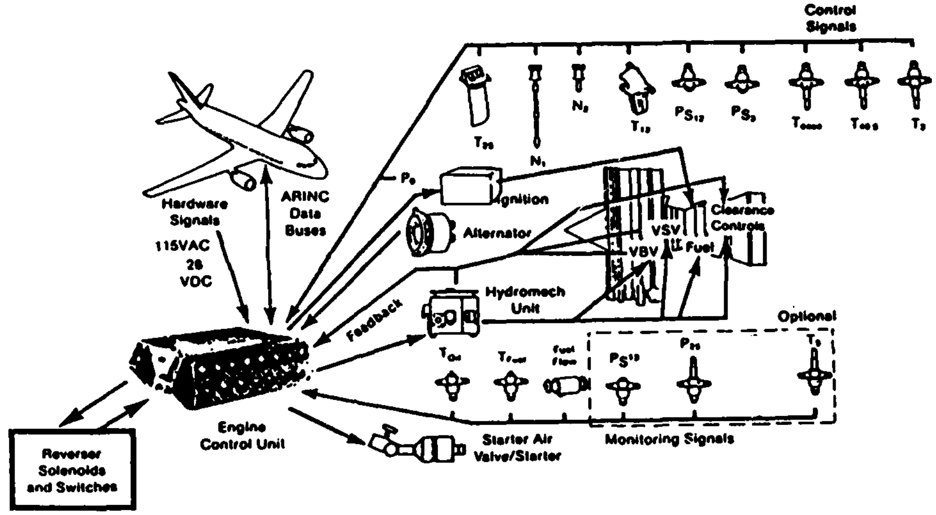


Fig. 15

AUTOMATISED GAS TURBINES IN COMBINED CYCLE-UNITS FOR ELECTRICITY AND HEAT PRODUCTION

by
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SUMMARY

In 1983 two RR 25 MW Olympus SK 30 gas turbines came in service together with a 25 MW steam turbine in a combined cycle concept in the powerworks of The Hague (NL) in order to supply electricity and heat to the city.

The reasons why this concept - being the first one in the NL - was chosen are given, followed by description of the unit, its automation and monitoring and control equipment. Experience obtained is given.

1. INTRODUCTION

In 1983 in the powerworks of the city of The Hague (NL) a combined cycle-unit consisting of two Rolls-Royce gasturbines, two flue gas boilers and a DeLaval-Stork steam turbine was commissioned.

Except for the electricity supply for the center of the city and cooperation in the national electricity-grid this unit is the main production-unit of the district heating system of the city.
As third city in succesion in the country The Hague started a district heating system in 1975. This system was in so far unique that apart from steam-bleeding of an excisting steam-turbine of the powerworks the heat is also obtained from the refuse incineration plant next to the powerplant.
As the heat demand (connected load) was (and is still) increasing already in 1978 it became clear that the replacement of two old turbo-generators of 30MW electrical of the condensation type that was to be realised in 1983 had to be done by installing a combined cycle of about 75 MW electrical and 80 MW thermal output.

In this paper the reasons why this concept was chosen are given, followed by a description of this unit for electricity and heat production based on the lightweight type gas turbine.
Furthermore the automation and monitoring and control equipment are described and experience obtained in some 5 years of service is discussed.

2. CHOICE OF THE COMBINED CYCLE-UNIT

The power station in The Hague has a middle load function in the case of electricity supply. This is an intermediate stage between base load and peak load.
The middle load operation (4 to 5000 hrs/a) is characterised by relatively frequent starts en stops (about 250 times per annum) and a demand for short load increasing times from no load to full load.

It is well known gas turbines can be put on load very quickly, so they are extremely suited for accomodating peak loads. It is true that their heat consumption is relatively high but the low costs of installation per kW compensate this fact at peak load. Moreover, gas turbines require no cooling water facilities and can easily be automated and remotely controlled. Large numbers of gasturbines have been installed all over the world for peak load service. In our country since 1968 some 140 gasturbines have been installed, lately to "repower" existing powerworks. Developments of gas turbines and, therefore of important components of combined cycle-units have led to the existence of two main types.
On the one hand land based machines have been developed and on the other hand the types known from aviation have been rendered suitable for generating electricity. The former is the heavy duty type characterised by sturdy constructions with all advantages of this robustness. The second, the aero-derived light-weight type, is characterised by lighter constructions and very short load increase time.

Combined cycle-units consisting of a combination of gas turbines and steam turbines can generate electricity at a high efficiency, in addition to which they can relatively quickly be put into service. Therefore combined-cycle units are very suitable for middle-load electricity supply, as was needed in The Hague. Furthermore heat for a district heating system can be obtained by bringing an extra pipe-section in the flue-gas-flow down stream of the boiler and extracting steam from the steam turbine.

3. DESCRIPTION OF THE UNIT

With a view to the availability for the generation of heat and power the installation of two units was being considered. Because of the standardization of existing gas turbine units, two 25 Mwe gas turbines were chosen, each with a heat recovery boiler.

The steam from the two unfired heat recovery boilers is led to one 25 MWe steam turbine, thus resulting in a total power of 75 MWe (FIG 1).

In order to increase the availability of the installation both for the heat and power production, various features were included in the system, i.e.:

- two separate steam circuits enabling the gas turbines with their own boiler to be started and stopped independently;
- a bypass of the steam turbine in order to be able to continue generating electricity by means of the gas turbines and covering the need of heat when the steam turbine is shut down, combined with an emergency condenser;
- further, with regard to the availibility of heat and power, mention may be made of the possibility of quickly starting up the unit; within 20 minutes which is a very short time for electricity works, the system can be brought to full electric load and then 2/3 of the maximum capacity is available.
- the starting system consists of a hydraulic starter motor that is driving the HP compressor of the gas turbine. The motor itself is driven by pressure oil obtained from an electrical driven pump.

Thanks to the measures taken, the availability of the installation as a whole is as good as that of a conventional power station.

Power control
The operation control of this three shaft gasturbines is done by means of an electronic Woodward governor. The power controlling is based on the speed of HP en LP compressor parts, the speed of the electric generator via the power turbine (primary control), the pressure control of the compressor and temperature control of the outlet of the gasgenerator.

For the automation the Siemens Teleperm M system was chosen enabling all controls to be visualised on a screen. With the aid of a luminous pin the control data can be adjusted and control actions can be carried out. By means of a process computer in this advanced installation various computing programs and data acquisition can be carried out, including optimalisation calculations for the operation.

3.1 DESCRIPTION OF THE GASTURBINES

The package gasturbine consists of the gas generator and power turbine (FIG. 2) and is placed in the existing building in a structure fabricated from metal plates secured to a metal frame. The structure is double skinned, the inner skin being perforated. Sound absorbent material is packed into the space between the two skins to reduce noise to an acceptable level.

Located in the gas turbine enclosure is a fabricated base frame which supports both the gas generator and the power turbine. The gas generator is trunnion mounted to support columns bolted to the base frame. The power turbine support pedestal is bolted directly to the base frame (FIG. 3).

After the gas generator exhaust gases have passed through the power turbine, the gases are used to fire the boiler and then are vented to atmosphere through a stainless steel exhaust stack, mounted on the roof of the building.

3.1.1 GAS GENERATOR

The gas generator is a Rolls-Royce Industrial Olympus straight-flow unit having a medium compression-ratio of 10 and consisting of a five-stage LP compressor and a seven-stage HP compressor, arranged in tandem.
Each compressor is separately driven by its own one-stage turbine through co-axial shafts. Being mechanically independent each compressor is rotating at optimal speed, having flexibility in service, fast acceleration and a high degree of stability at all loads without the need of variation of engine geometric or blow off-facilities. Another advantage is that when starting it is sufficient to drive the HP compressor and turbine only.

Burners
The eight burners are secured to the HP compressor delivery casing and project into the combustion chambers. Each burner has a main and primary liquid fuel feed and a gas fuel feed. The main liquid fuel enters each burner from an individual hose directly connected to the pressurizing valve whilst the primary liquid fuel pipes are connected to the burner via a manifold pipe.

A separate LUBRICATING OIL SYSTEM for the gas generator having pipings, filters, magnetic inspectionplugs and accessoires, consists of four main components.
The main oilpump unit is consisting of a main pressure pump and a scavenge oil pump unit.
The auxiliary scavenge oil pump unit incorporates four gear-wheel type scavenge pumps and four associated filters and is mounted at the rear of the tank. These pumps are

scavenging the front bearing of the LP compressor and oil separator, the HP turbine bearing, the intermediate casing with its intershaft bearing and the LP turbine bearing.

FUEL CONTROL OF THE GAS GENERATORS
Each gas generator has its own fuel controlsystem controlling the power by means of the quantity of fuel streaming from the burners. The main components are a gasfilter, a pressure control valve, a gas control valve and operating device, fast-closing valve and a power speed regulator. The latter is mounted off the engine.

ELECTRIC SYSTEM OF GAS GENERATOR
The electric equipment of the gas generator includes an ignition system, instrumentation for the LP and HP speed and a DC-solenoid to control the anti-icing hot-air value.

The STARTER MOTOR is a hydraulic motor that is to be connected to the HP-compressor shaft by means of an automatic coupling. The hydraulic energy for the motor is supplied by a separate AC-driven pump that is mounted among the accessories.

BOROSCOPE INSPECTION can be done through four openings in the combustion chamber casting to the nozzle guide vanes of the HP-turbine and the combustion chambers (crater-openings) and after removing the burners cans an opening in the exhaust annulus allows inspection of the nozzle guide vanes of the LP-turbine.

3.1.2 POWER TURBINE

The power turbine is a Rolls-Royce three-stage axial-flow turbine. The rotor is overhung mounted on the main shaft, that is supported in two big white metal bearings, which are mounted in a pedestal that is mounted on the base plate. The exhaust gases from the gas generator discharge into the interturbineduct, expand in the three stages of the power turbine and finally discharge into an uptake by means of an exhaust volute.

BOROSCOPE INSPECTION of the first stage nozzle guide vanes of the power turbine can be done via eight openings equally spaced over the circumference of the interturbine duct.

4. AIR SYSTEMS

Air, taken from selected stages of the compressors is used for:
- cooling, to insulate areas against heat inflow from combustion to prevent leakage of hot gases from the main stream and to dissipate heat from the turbine assemblies;
- seal pressurizing to make effective the clearance labyrinth type seals for oil containment that are employed due to the high rotational shaft speeds for low friction;
- anti-icing.

5. FUEL SYSTEM/POWER CONTROL

Automatic starting, loading and synchronizing of the generating sets is catered for in the design of the fuel control systems.
The power control done by the electric Woodward governor is actuating the fuel flow.

6. OIL SYSTEM DEBRIS MONITORING

There are certain components in GT engines c.q. bearings, gears, splines etc. which release wear debris into the scavenge oil flow.
These components do not usually fail suddenly. There is a normal period in which wear and failure particles are released at a greater rate than normal before actual failure. Monitoring and trending this release of wear debris combined with debris identification techniques allows diagnosis of impending failures.

Three methods of monitoring wear debris can be used:

1. Systems which capture the debris and allow later evaluation and analysis;
2. Systems which count debris particles as the scavenge oil passes through them;
3. Analysis of scavenge oil samples in a laboratory by means of a microscope or spectromatic analyses.

The first method, used in the installation in The Hague, includes the ferrograph and magnetic plugs with their associated back up systems. Metallic debris are seperated from the oil for separate evaluation each month.
Quantitative assessment is in an instrument plotted against running hours to monitor changes in trends.

7. ADVANCED CONTROL SYSTEMS BASED ON DECENTRALIZED SYSTEMS CONTROLLED BY A MICROPROCESSOR

Before the 70's control apparatus in power generation consisted of separate components, each with its own specific function. They were connected with copperleads. These installations had a low automation degree.
Increasing the efficiency of the power generation needed modern control and monitoring, thus leading to more complex and voluminous installations.
For information and datalogging computersystems were introduced.

The next logic step was that also executive functions were to be fulfilled by the central computer system. It turned out that centralization in Digital Direct Control (DDC) instead of the original decentralized concept led to vulnerability of the central computer. Due to this vulnerability a large conventional back-up was neccessary, through which the installation remained expensive.
The development of the micro-electronics made it possible to combine in one system the advantages of digital control, decentralized and hierarchical structure and concentrated datalogging.
The info-transmission between the partial systems can furthermore be done by a greatly reduced number of cable connections.
The communication between man and system for information as wel as for control is done concentrated via displays and functional keyboards.

7.1 HIERARCHICAL DECENTRALIZED CONTROL SYSTEMS

Instead of an "automation-island" where all functions of an installation are assembled in one autarktic automation system it is possible to realise the same availability and network security as in conventional systems by means of a decentralised system with different algorithms located in microprocessor based digital regulatory unit controllers per function. High reliability and flexibility are possible and as an extra advantage low-volume field-wiring occures. (FIG. 4)
Parallel communication paths for gathering the process-data and control-actions as well as serial communication paths for mutual communication of the automationsystems and with productive control and observation systems are possible. (FIG. 5)

The components of the used Teleperm M system are in general:
. Automation subsystem AS 220 for monitoring, regulating, computation and control;
. Operating subsystems OS 250 and OS 251 for process monitoring and handling;
. Coupling (bus) system CS 275 for datatransmission between the subsystems.

The Automation Subsystem AS 220 consists of the basic unit and the extension unit. The basic unit comprises a power supply, the central micro-programmed processor (16 bit telegram, 60 k-byte memory CMOS-RAM) and connection to control unit (monitor display and keyboard), bussystem CS 275, mini-floppy disc and recorder printer.

The Operating Subsystem OS 250 (and OS 251) has communication by alphanumeric signal and thermometer indication on the display while control can be done by a process control keyboard connected with an alphanumeric keyboard. Signals visible on the display can also be printed via a hard copy unit.
The station is connected to the bussystem CS 275 in order to activate several automation subsystems A220 simultaneously.

Subsystem OS 251 has the possibility to an extensive process control and monitoring and can be connected to several automation subsystems over the bussystem.
The basic unit comprises a powerful central part and connections to bussystem, keyboard, display, mini-floppy disc, printer and analog recorder.
Perception is possible in a hierarchical 4 type standard survey system:
. Plant survey;
. Overall survey, monitoring the process;
. Group survey, for operation;
. Circuit survey, for tracing.
The screen is divided in different parts, each picture having the overall heading repeated while the working part below that head due to the call is changed and showing other information.
In FIG. 6 this hierarchical system is shown.

The group survey f.i. can show simultaneously 8 circuits at the most (regulating, measuring, binarysignal etc.) which is done for all groups in standard signals.
Thus 3.072 circuits, 384 groups and 12 overall surveys can be shown.
The circuit survey is repeating a certain circuit from the group survey, adding parameter and trend developments in graphics or numerically.
The control of the OS 251 is preferably done with the luminous pin or the control keyboard. Calling of pictures or info is done by tipping names and signals. Process control, changing setpoints or on/off switching can only be done in group pictures and circuit pictures.

The coupling Bussystem CS 275 has communication tasks: data transmission between the automation systems and coordinating and managing the dataflow. Normally in powerworks there is a large distance, also functionally, between the automation systems, this is not the case in our works.

The bussystem of 2 coaxial cables itself has no central systems. Its transmissionspeed 25 k-bit/s (long distance). Each "connection" can get a masterfunction, which can be done with time-out on call, or ordered with priority.

The basic components of the bussystem are the interfaces and secondary bussystem, that is connecting the automationsystem and the processcomputer Siemens R 30 type.
A maximum of 16 connections for the secundary system is possible, the total of stations can be 256.
The inductive interfaces consist of a transmitter, a receiver, digital electronics and powersupply.
Faults that occur in the circuit of a connected system can not be transmitted to the bus.
The interfaces have a transmission rate of 2,4 k-bit/sec to the bus. A transfer element is 4-9 bit brought together in a unit telegram. Master transfer needs 300 micro sec., maximum length of a telegram 128 k-byte.

The system configuration is given in FIG. 7 consisting of a number of subsystems having capacities attuned to each other.

7.2 DATA ACQUISITIONSYSTEM

The operator can get a great lot of information and elucidation through:
. alarmsignals
. life-process diagrams
. efficiency figures
. startsequence
. trendgraphics
. events sequence printing faults

The simultaneous information of a great number of components enables mutual during tests and fault-analysis.

To set up further maintenance philosophy recording of running hours versus events is an important help.
The storage of different criteria and data for longer periods by discs enables a quicker check of long term developments. In the past it was nearly impossible to have the same number of data (in a reasonable time).
The most important condition is that the software is of a good quality.

8. EXPERIENCES

Teleperm control system
The first year of operation was needed for the personnel to get totally used to the new philosophy of this way of control. Once used to it the operators became enthusiastic about the system. With the supplier of the system a limited fault abolition contract for the hardware is agreed. Few faults occurred and they were nearly always adequately solved.
Data Acquisation System
A great deal of information is available and it can be of great importance. Now and then even to much info can be supplied.

In practice it turned out that the great number of data is confusing and therefore categories have to be introduced indicating the degree of urgency of faults e.g.:

Category 1: Urgent, reported without delay
These signals occur when the process proceeding is obstructed or a trip of the engine can be expected.

Category 2: Important, reported automatically when category 1 is receipted
These signals accur to inform the neccessity for action to avoid further difficulties and the possibility to become category 1.
A category 3 can be used to draw attention to certain imperfections, after having solved the other two categories.

9. CONCLUSION
. The primary process system of the combined cycle is an efficient and reliable way of electricity and heat production.
. The automation by means of the described control and monitoring system turned out to be reliable.
. The data acquisition system can give a great number of data, which is very important during fault solving.

10. ACKNOWLEDGEMENT
Except for the experiences of the staff of the Production Department also some suppliers' publications were of great help in composing this paper.

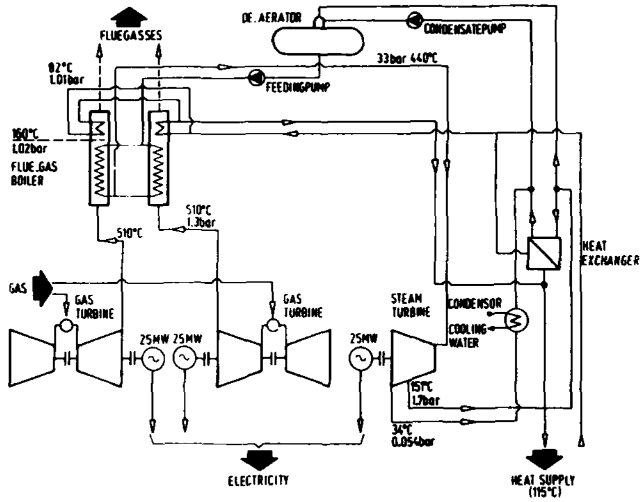

Fig. 1: Processcheme combined cycle-unit for CHP production.

Fig. 2: Package gasturbine in existing building (far end).

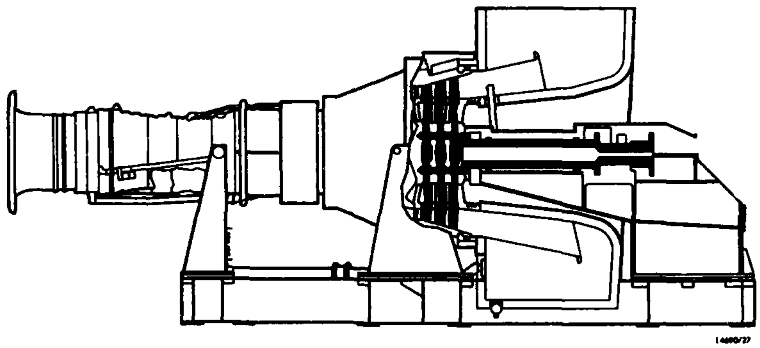

Fig. 3: SK 30 Olympus (typical)

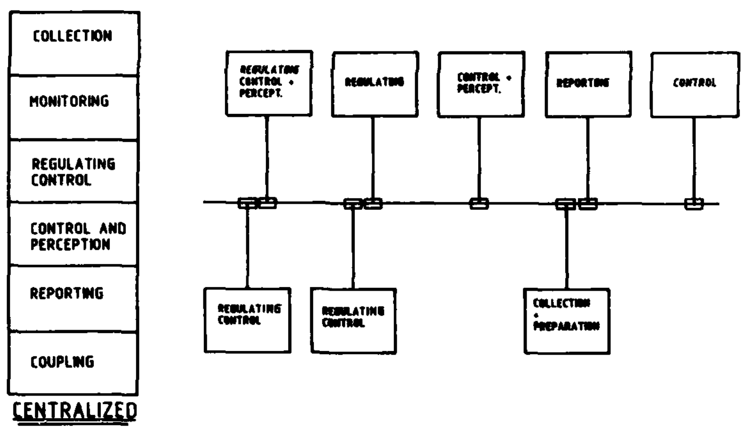

Fig. 4: Control system lay-out.

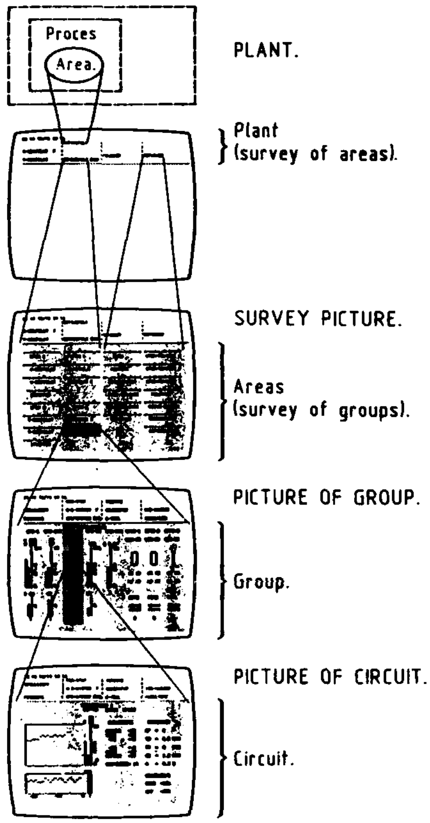

Fig. 5: Hierarchy operating station OS 251.

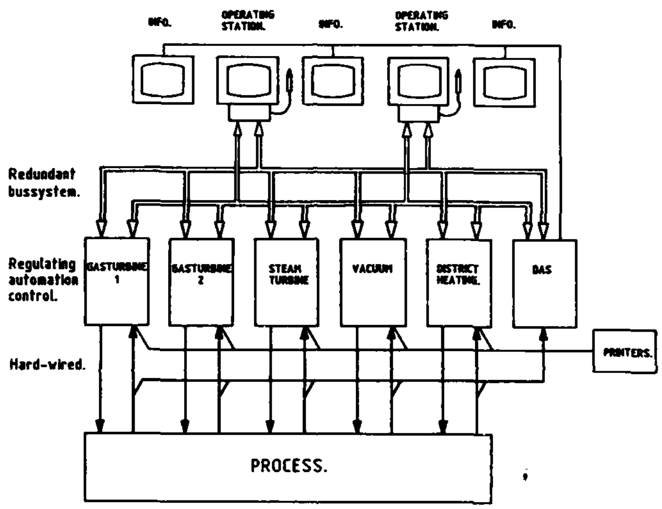

Fig.6: Total hierarchical control and monitoring system.

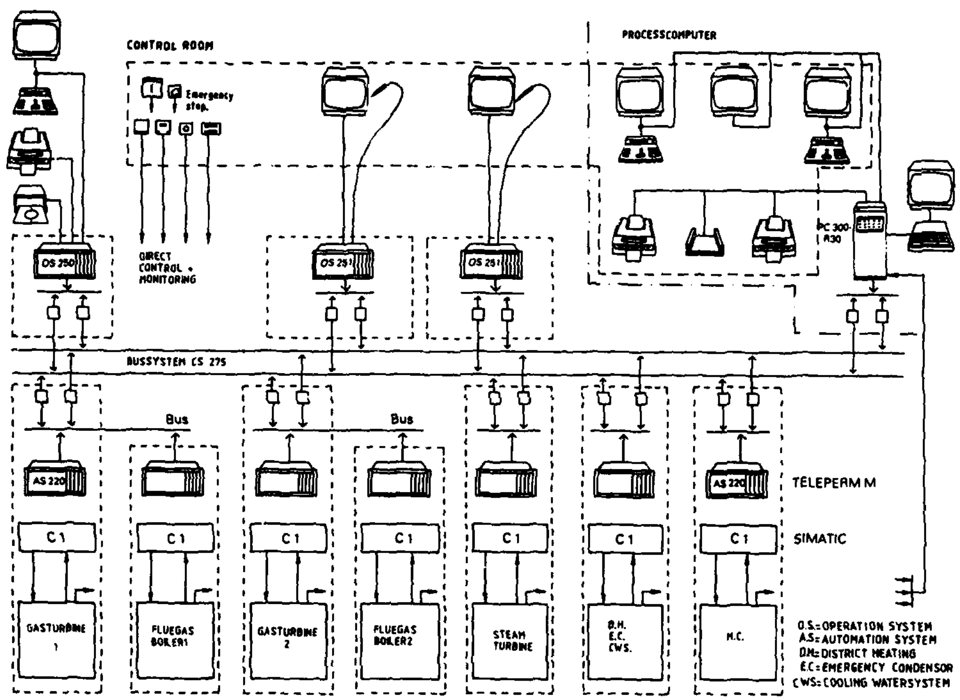

Fig. 7: Control and monitoring system.

DISCUSSION

H. SAVARANAMUTTOO

1. Is it possible to run the system with one gasgenerator shut down for planned maintenance?

2. How many man are required to operate the system and is it possible to operate unmanned?

Author's Reply:

1. The unit with only one gasturbine and the steamturbine in service can produce half the power of about 40 MW electrical and 40 MW thermical This was deliberated designed to have the possibility to keep upright energy supply at least partially during maintenance or failure.

2. Fully automatical service is possible. Due to the fact that for other reasons(for instance:load-management and other apparatus control) personnel is present the full-automation is only used for processes of parts of the unit. Normally three men are present.

H. SCHLUETER

1. Is in depth performance analysis performed to detect incipient engine problems?

2. Is long term performance monitoring performed in order to assist optimum engine operation, planning of maintenance actions and long term system control?

Author's Reply:

1. Indeed, analysis of deviations is made to check engine performance in service.

2. The data obtained are used to optimise operation and for planning actions on long term control. This is only used in our works with its own performance as unit for combined electricity and heat production.

IMPLICATION DE L'AVIONNEUR DANS LE SUIVI DES PERFORMANCES DU MOTEUR

par

A.Vieillard
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Toulouse
France

The experience acquired by Aerospatiale in the Airbus and ATR programs has highlighted the necessity for the aircraft manufacturer to be associated with E.C.M. system implementation.

The aircraft manufacturer will thus be more involved as regards:

- the acquisition of information on the design of airborne systems (AIDS) and validation of measurement systems on the basis of flight tests;
- the use of information to ensure the consistency of and engine models used by the aircraft the engine monitoring systems and familiarity with the E.C.M. system.

The predictable growth of this performance monitoring activity will necessitate closer coordination with the engine manufacturers and airlines, the objective still being to quantify the deterioration of each aircraft "sub-assembly", i.e.: the engines, the airframe and their respective components.

L'expérience acquise par l'Aerospatiale dans les programmes Airbus et ATR a mis en évidence la nécessité pour l'avionneur d'être associé à la mise en oeuvre des systèmes d'"ECM".

Ainsi, ce dernier sera de plus en plus impliqué pour ce qui concerne:

- L'acquisition de l'information dans la définition des systèmes embarqués (AIDS) et dans la validation des chaînes de mesure à partir des essais en vol.
- L'utilisation de l'information pour s'assurer de la cohérence des modèles moteur utilisés par les systèmes de suivi du moteur et de l'avion et pour se familiariser avec le système ECM.

L'accroissement présible de cette activité de suivi des performances nécessitera une coordination de plus en plus étroite avec les motoristes et les compagnies aériennes, l'objectif restant de quantifier la degradation de chaque sous-ensemble de l'avion à savoir les moteurs, la cellule et leurs composants respectifs.

PRELIMINAIRE

Cette presentation fournit les principaux centres d'intéret de l'avionneur Aerospatiale dans le suivi selon l'état des moteurs. Il est tout à fait clair que les programmes de suivi moteur sont et restent de la responsabilité du motoriste.

Il faut également rappeler que l'Aerospatiale intervient en tant que partenaire dans les programmes Airbus et ATR.

Les differents chapitres abordés sont:

Au cours de la phase de developement de l'avion avec:

Les études
Les essais en vol

Puis l'activité de suivi en compagnie.

INTRODUCTION

Dans l'aéronautique civile, ce sont les compagnies aériennes qui, pour répondre à leurs besoins, on été motrices pour le développement des systèmes embarqués. Si, dans un premier temps, l'avionneur n'a fait que répondre à une demande pour tous les avions developpés depuis l'Airbus A310, le système de bord fait parti de la définition de l'avion en tant qu'option constructeur, en collaboration avec les compagnies aériennes, les fabricants de moteur et l'avionneur.

Le moteur, par ces contraintes de fonctionnement est plus sensible à la detérioration, ce qui explique qu'ils aient été surveillé prioritairement.

Le moteur est un élément fondamental de l'avion, il l'est aussi de sa modélisation, les performances de l'avion sont liées à celle du moteur.

1. DURANT LA PHASE DE DEVELOPPEMENT

- La qualité de l'analyse, est fonction de la précision et de la répétitivité de l'acquisition des paramètres.
- Les programmes permettant de discriminer la contribution des modules demandent une instrumentation importante.
- Afin de bénéficier au mieux de l'intérêt des programmes existant, il est nécessaire d'avoir une mise en forme et une transmission rapide des informations.

Ce sont autant de taches qui ne peuvent être assurées que par un système automatique.

L'AIDS (Airborne Integrated Data System) est apparu avec l'Airbus A310. Il est devenue une option standard sur l'Airbus A320 (Voir figure 1). Il en sera de même, avec une autre appelation, sur les Airbus A330 et A340. Son role est de permettre le suivi des moteurs, de l'APU (Auxiliary Power Unit) et des performances de l'avion. Il collecte, valide, convertit en unités ingénieur, met en form et émet les informations qui seront utilisées par les programmes au sol.

L'AIDS se compose d'un calculateur central, le DMU — Data Management Unit — qui gère les informations à l'aide des fonctions suivantes:

- Détection des phases de vol
- Filtrage des données
- Détection des dépassements, des phases stables
- Déclenchement de l'enregistreur continu le DAR — Direct Aids Recorder

Le DMU inclut 2 OBRM (On Board Replaceable Module) contenant le logiciel qui peut, ainsi être facilement remis à jour. Ces informations sont mises sous forme de rapports qui sont transmis à l'imprimante ou au sol par data link. Les valeurs qui gèrent le déclenchement des rapports peuvent être modifiées via le MCDU — Multi Purpose Control and Display Unit.

Les principaux rapports pour le moteur sont la phase croisière stabilisée, le décollage, la divergence des paramètres, le démarrage.

De même les commutters comme les ATR 42 et 72 ont un système complet, (voir figure 2) développé avec la SFIM. comprenant à bord de l'avion, un FDAU — Flight Data Acquisition Unit — qui sélectionne et stocke les paramètres moteurs et avions.

Le transfert, entre l'avion et la station sol, est assuré par une valise, terminale portable, qui permet aussi d'aller interroger les mémoires du FDAU.

Un logiciel sol a été fait pour stocker, sur IBM PC, les données et assurer le transfert automatique des informations du rapport croisière au logiciel de "Trend Monitoring" de PW CANADA, l'ECTM (Engine Condition and Trend Monitoring).

Ce système permet l'acquisition de 4 types d'informations

- Le rapport d'évènement généré sur demande.
- Le rapport de croisière stabilisée.
- L'acquisition des dépassements en niveau et en temps
- L'acquisition du temps de fonctionnement du moteur.

A titre d'exemple, sur la figure 2A, on peut comparer la qualité du Trend Monitoring entre l'enregistrement manuel et celui obtenu par le système Mini-Aids sur ATR. L'interprétation des tendances reste l'une des phases délicates et pour laquelle il est envisagé de développer des outils d'aide à l'analyse.

Il faut noter que la quasi totalité des avions vendus par Airbus et ATR sont équipées de l'AIDS.

2. DURANT LES ESSAIS EN VOL

Les essais en vol permettent de:

- Valider l'instrumentation qui sera utilisé en service
- Verifier/adapter les critères utilisés pour la génération des rapports

- s'assurer, point important, de la cohérence des modèles moteurs qui sont utilisées par les programmes motoristes et avionneurs
- Se familiariser avec les programmes de suivi moteur utilisés par les compagnies clientes.

2.1 La validation de l'acquisition des paramètres

Les essais en vol fournissent l'occasion de comparer l'instrumentation utilisé par les programmes d'ECM avec l'instrumentation etalonnée d'essais en vol. Durant ces comparaisons, nous nous sommes aperçus que le positionnement des capteurs, notamment les pressions et temperatures pouvaient affecter à la fois le niveau et la pente des résultats obtenus. Les déformations des profils aérothermodynamiques en sont la cause. Il est important de le savoir puisque les modelisations du groupe propulseur sont faites à partir de l'instrumentation d'essais en vol. Les valeurs relevés restent généralement minimes.

A titre d'illustration la figure 2B montre le N2 relevé sur 2 moteurs CF6-80C2 d'essais en vol.

2.2 La définition des critères de génération des rapports AIDS

Les essais en vol permettent en outre de s'assurer de la cohérence des fenêtres utilisées pour la sélection des rapports de phase croisière.

Les séries de décollage, qui identifient l'évolution des paramètres, fournissent l'occasion de définir le critère le plus judicieux pour l'enregistrement du rapport décollage. Ce critère, ayant pour but de releve le "Peak" d'EGT est, sur les dernières motorisations, un temps à partir de la mise en poussée ou au passage à une vitesse donnée (50 secondes après 80 KTS pour l'A320 équipe de CFM 56-5A). De même il est possible de fournir des valeurs par défaut qui définissent les seuils d'avertissement pour les rapports de divergence, ou de recommander des temps de séquence pour l'acquisition des rapports d'évènements.

Pour les critères de stabilisation en croisière, et compte tenu des essais en vol qui se font dans des conditions très spécifiques, une étude, basée sur des enregistrements continu (DAR) provenant de vols en service a été faite. Elle portait sur 42 heures de croisière representant 33 vols d'une durée allant de 5 minutes à 3 heures. Cette étude avait pour but de définir des critères cohérents, du rapport croisière, de déclenchement.

La figure 3 montre pour 3 critères de stabilité le nombre de rapports croisière que l'on peut obtenir sur des vols en service. Le point dimensionnant est d'obtenir des rapports pour les vols court courrier.

La figure 4 fait apparaître l'effet du temps pour lequel la stabilisation est demandée. Chaque subframe correspondant à 20 secondes.

Au cours de cette étude, nous avons pu également noter la très bonne correlation qui existe entre les paramètres moteurs. Les critères de stabilité ainsi déterminés seront utilisés sur l'A320.

2.3 La cohérence des modèles moteurs

Les modèles moteurs sont utilisés par l'avionneur dans ces programmes de performances et par le motoriste dans ces programmes de suivi. Pour éviter qu'une analyse faite selon le programme de suivi des performances avion ou de suivi moteur soit incohérente, il est nécessaire d'assurer la similarité des modèles moteurs. L'évolution des moteurs, notamment les régulations affinées par les FADEC rendent ces modèles de plus en plus complexes.

3. FAMILIARISATION AVEC LES PROGRAMMES D'ECM

Un autre aspect est de se familiariser avec les programmes de suivi du moteur. C'est pourquoi nous avons installé et évalué le PW TEAM III (Turbine Engine Aids Monitoring) d'analyse modulaire pendant les essais en vol du PW4000. De même le programme GEM (Engine Condition Monitoring) devrait être utilisé avec les essais de l'A320 CFM56-5. Le COMPASS (Condition Monitoring and Performance Analysis Software System) suivra la même voie.

Les programmes COMPASS, GEM et TEAM III sont des programmes permettant l'analyse modulaire des moteurs.

Si les essais en vol permettent d'explorer tout le domaine de vol avec une très bonne précision, c'est avec un échantillon limité (de l'ordre de 150 points de croisière) et pour un temps restreint. Ils ne permettentt pas de couvrir les phénomènes inhérents au vieillissement.

4. L'ACTIVITE DE SUIVI EN COMPAGNIE

Pour les ATR un groupe de travail a été crée. Une des activités de ce groupe est de suivre et d'améliorer le système existant de Trend Monitoring. Ce groupe est composé de representants des compagnies du motoriste et de l'avionneur. Pour Airbus Industrie, c'est essentiellement du suivi des differentes activités. Il peut s'agir aussi répondre à des demandes spécifiques.

Lorsque des détériorations de performance sont relevés, il est nécessaire de pouvoir déterminer la contribution de la cellule et du moteur. C'est un exercice toujours délicat. La poussée du moteur et la trainée de l'avion sont très difficile à dissocier.

CONCLUSION

En conclusion, l'avionneur est et sera de plus en plus impliqué dans les systèmes de suivi selon l'état par:

- La définition de l'avion et l'intégration des moteurs.
- L'intérêt grandissant dans les aspects de performance et le lien direct entre le suivi des performances du moteur et de l'avion.
- *Rapports de suivi qui seront* utilisés *comme* source d'information pour la maintenance.

Le propos de l'avionneur est d'être en mesure de répondre aux demandes des compagnies et d'assurer une communication tri-partite fructueuse entre les compagnies, les motoristes et l'avionneur.

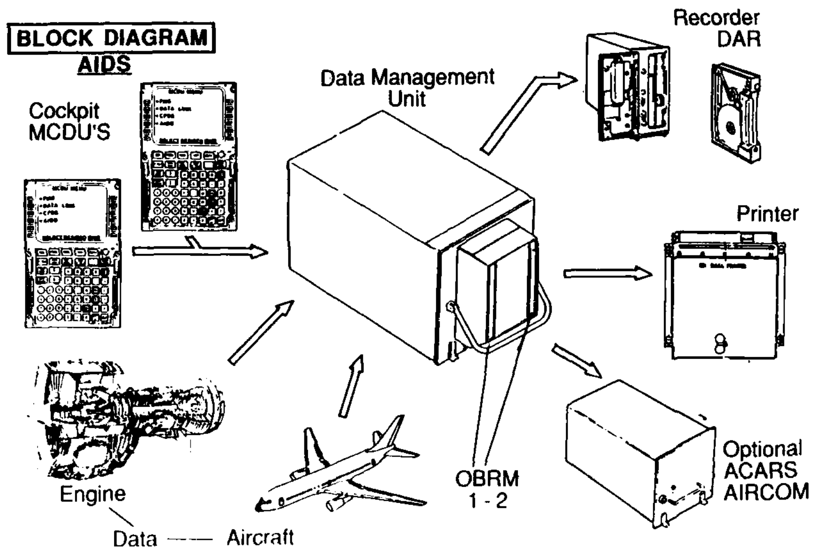
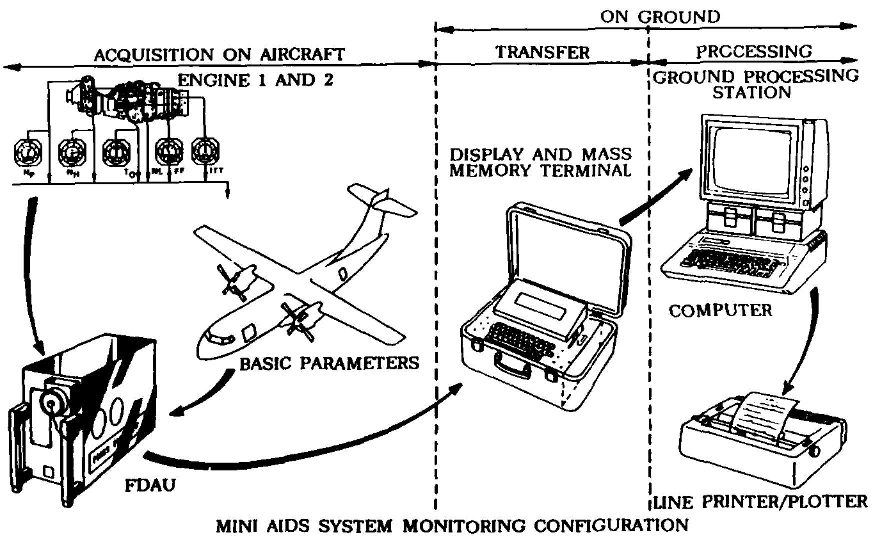


Figure 1



MINI AIDS SYSTEM MONITORING CONFIGURATION

Figure 2

EXAMPLE OF RECORDING

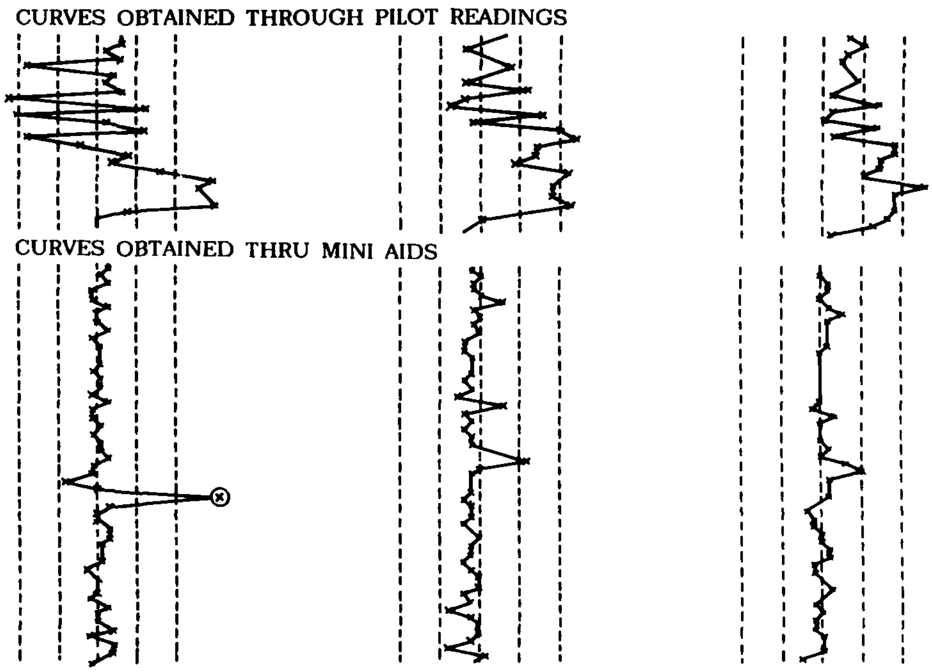


Figure 2A

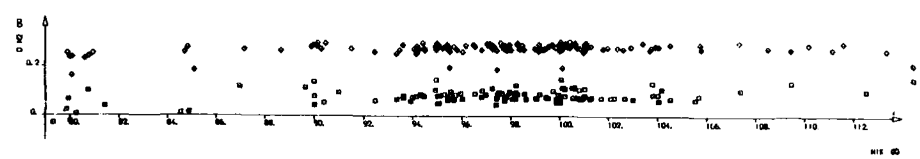


Figure 2B

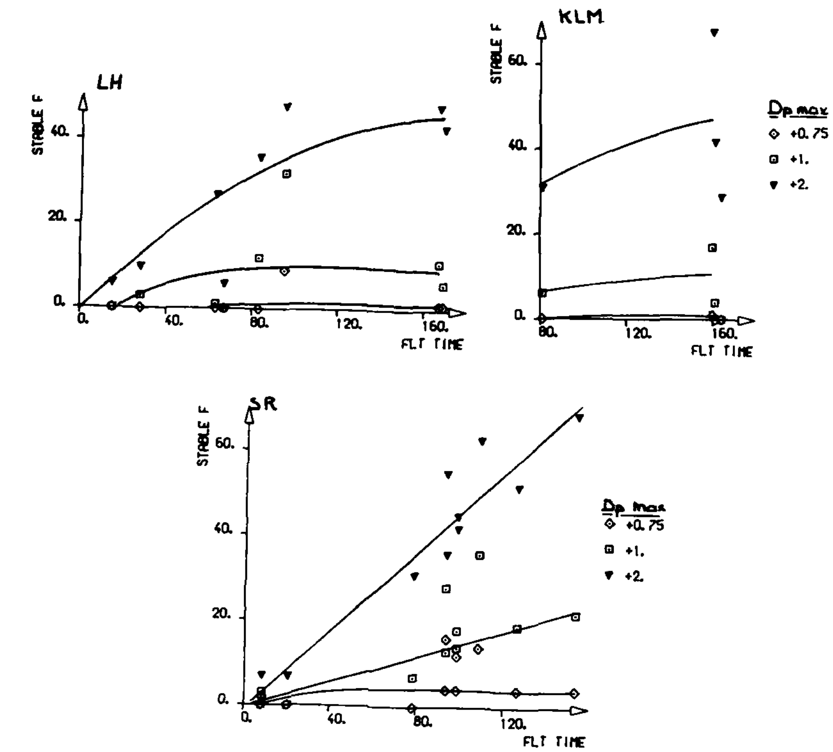


Figure 3

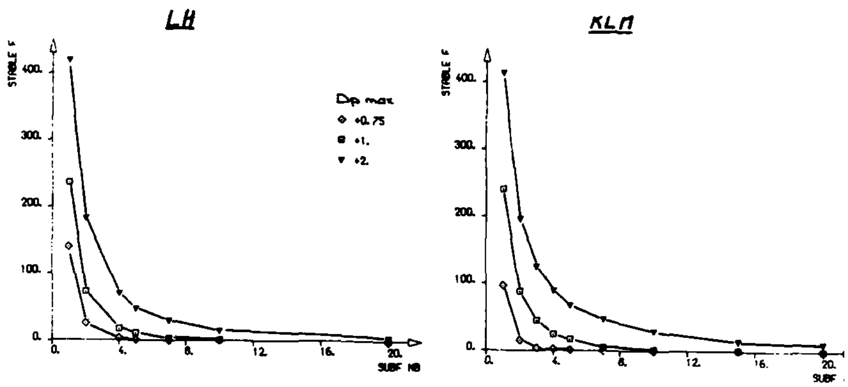


Figure 4

F100-PW-220 ENGINE MONITORING SYSTEM

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FOREWORD

This discussion reviews the development and operational experience of the F100-PW-220 Engine Monitoring System currently in service with the United States Air Force and other national defense air forces utilizing the F100-PW-220 engine and its derivatives.

INTRODUCTION

The F100-PW-220 Engine Monitoring System (EMS) is one of the most advanced logistics support tools in production for the Pratt & Whitney F100 family of gas turbine engines. The highly successful introduction of the PW-220 EMS represents over ten years of diagnostic system and maintenance technology development using the latest in aerospace electronic component design and digital, engine control system implementation. The PW-220 EMS is a comprehensive engine support system that is fully integrated with in-flight aircraft operating systems, as well as, ground-based maintenance and logistics systems.

BACKGROUND

The PW-220 EMS was developed by Pratt & Whitney and Hamilton Standard, both of United Technologies Corporation, in conjunction with the F100 Digital Electronic Engine Control (DEEC), for the Aeronautical Systems Division, Air Force Systems Command, USAF. Many of the PW-220 EMS hardware and monitoring concepts were derived from an earlier development system, known as the F100 Engine Diagnostic System (EDS), which acquired over 2500 flight hours of operational testing with F100-PW-100 engines in USAF F-15 aircraft. Experience from the initial F100 production engine monitor, the Events History Recorder (EHR), also contributed to engine usage algorithms for the PW-220 EMS. The "lessons learned" from these early efforts, along with the improved data acquisition and self-testing capabilities of the DEEC system, provided the basis for development of an effective diagnostic, maintenance and logistic support system.

PW-220 EMS development began in April 1982 and achieved an interim milestone with first production deliveries in November 1985. Engineering work continued through November 1987 to incorporate additional aircraft integration and logistics database compatibility features. System growth and improvements are an on-going effort, as field experience is accumulated.

SYSTEM OBJECTIVES

The primary objective of the PW-220 EMS is to provide information to assist in identifying faulty engine control system components, detecting and documenting engine operation beyond acceptable limits, recording normal engine usage, and tracking engine performance. Encompassed in this single objective a redesign goals which include: 1) Fully automatic in-flight operation, 2)Electronic data transfer to aircraft and ground systems, 3) No off-engine mounted flight components, 4)Modular component design for enhanced system maintenance, 5)Minimum dedicated flight sensors, 6) Field upgradable software and flightline reprogrammability, and 7) Engine and aircraft interchangeability.

For the maintenance/logistics user, achieving the system objectives means fewer maintenance actions, fewer maintenance man-hours expended, fewer on-site spares required, increased maintenance effectiveness and increased engine/aircraft availability. For the operational user (pilot), a reliable EMS provides better real-time analysis of propulsion system integrity, higher probability of successful mission completion, and an overall reduced cockpit workload. For the engineer, the PW-220 EMS provides in-flight operational data automatically or on pilot request, without adding extensive instrumentation and specialized recording equipment; however, unlike earlier, less successful attempts, the PW-220 EMS is designed for maintenance support first, and engineering data acquisition is accomplished as a secondary benefit.

SYSTEM DESCRIPTION

The PW-220 EMS is comprised of five subsystems (Figure 1). There are two engine mounted units: 1) the digital control, DEEC, and 2) a dedicated engine monitor designated the Engine Diagnostic Unit (EDU). Two ground support units are used for flight line and uninstalled engine test stand operations: 1) the Data Collection Unit (DCU), and 2) the Engine Analyzer Unit (EAU). The fifth subsystem is the link to the user's engine logistics database system; in the USAF, this interface is called the Ground Station Unit (GSU).

Digital Electronic Engine Control (Figure 2)

During engine operation, whether installed in an aircraft, or a stand-alone test cell, the DEEC continuously transmits engine parametric and control system fault data to the EDU across a simplex, serial digital communication bus, at the rate of 9600 bits per second. Approximately 300 individual pieces of information are transmitted every 250 milliseconds.

In the process of controlling the engine, the DEEC is measuring and evaluating temperatures, pressures, speeds, positions and interface conditions to maintain stable, safe operation in response to the pilot's power lever or discrete input commands. If a failure is detected in the internal electronics of the DEEC, or in the sensor input circuits, or the DEEC is unable to maintain control, automatic fault accommodation takes place to regain control or operate in a degraded capacity. The resulting fault data is transmitted to the EDU in the form of an eight bit "Fault Code", for each failure.

Engine Diagnostic Unit (Figure 3)

The EDU performs a passive function as an electrical junction box, routing analog electrical signals to the aircraft for display. In its active role, the EDU operates on a basic computational cycle determined by the update rate of the data being received from the DEEC; ie., 250 milliseconds or four times per second. Within the nominal compute cycle, the EDU: 1) receives serial data from the DEEC, 2) conditions and measures the analog cockpit signals , 3) evaluates the integrity of the data acquired, 4) executes a pre-determined diagnostic logic sequence, 5) records in non-volatile memory the fault codes from the DEEC, data exceptions identified from the logic execution and data from the engine usage algorithms, 6) performs a comprehensive internal electronic self-test, 7) responds to high-speed digital communications from aircraft data systems, 8) generates a real-time serial digital data transmission for off-engine acquisition systems, and 9) activates aircraft-mounted engine status indicators, when faults are detected.

Data Collection Unit (Figure 4)

On the flightline, the DCU is used by the aircraft support technican to retrieve and review flight data recorded in the EDU. The portable, battery-operated DCU is connected by means of an integral cable assembly to a readily accessible engine harness. By following the menu-driven instructions displayed on the hand-held unit, the operator automatically downloads the recorded data into non-volatile memory devices housed in a removable cartridge within the DCU. Electrical power for the EDU, during the 30 second download operation, is provided by the removable DCU battery pack.

If the engine status indicators, located in the aircraft, are tripped denoting faults detected during the flight, the technician may choose to review the fault codes and event data recorded. The DCU will also evaluate the combinations of reported faults against an internal set of engine trouble shooting logic, and display a "maintenance code", which is referenced to the detailed maintenance instructions needed to isolate and correct the fault. Normally, a single DCU with a fully charged battery pack and a clean memory cartridge has sufficient capacity to service a complete squadron of aircraft.

Engine Analyzer Unit (Figure 5)

When an engine fault has been detected and the DEEC or EDU may be suspect, the EAU is used to assist in fault isolation. With access to the underside of the engine, special circuit simulators, stored on the EAU, are substituted for the normal electrical interfaces on the DEEC. Duplex serial communication is established between the DEEC and EAU, and, once again, by following the menu-driven instructions, the operator performs a complete check of the DEEC, executed by means of temporary diagnostic programs uploaded automatically from the EAU. The pass/fail results displayed to the technician either confirm the location of the fault within the DEEC, or direct further troubleshooting. A similar capability exists to test the EDU, and the EAU can be used to perform all the data retrieval functions of the DCU, except non-volatile data storage.

Although the EAU requires an external electrical power source, it does supply conditioned power to the DEEC and EDU, when under test, to permit trouble-shooting without engine operation. If the fault isolation procedures do require engine operation, or for post-repair operational verification testing, the EAU may be used as a real-time monitor and display; data from the DEEC, EDU or both serial digital outputs may be viewed simultaneously. Changes to the programmed control law limits in the DEEC or the diagnostic constants in the EDU are also accomplished using the EAU, with the components remaining installed on the engine.

Ground Station Unit (Figure 6)

The GSU hardware may vary from user to user, but it is generally some microcomputer-based device capable of standard serial digital communication. For the USAF, the GSU is a desktop, commercially available computer standardized for use in multiple applications. It is the interface device to the base-level logistics system from, not only the flightline, but the various base maintenance facilities, as well.

PW-220 EMS data products are downloaded to the GSU by electronic transfer from a DCU. The recorded memory cartridge is first installed in a local DCU, or the flightline DCU is carried to the aircraft maintenance support hangar and then connected by means of interface cabling to the serial port on the GSU microcomputer. Selecting the appropriate operating mode from the DCU menu, the GSU operator follows a second GSU menu of instructions to complete the data transfer to GSU memory. GSU software processes the EMS data to formulate engine history records, calculate engine life-limited part parameters and evaluate engine performance margins.

DIAGNOSTIC LOGIC

Analysis of engine data in the PW-220 EMS is accomplished in real time, any time the engine is operating. Decisions concerning control system health and engine operating conditions are made continuously by the EDU during every computational cycle, (Figure 7). For some conditions, where the four hertz data rate from the DEEC is not adequate for the EDU to reliably capture high speed events, the DEEC, which operates on a shorter compute cycle, pe forms the event detection function in the process of accommodating the anomaly, and the EDU records the occurrence later, when notified in the DEEC serial data.

The EDU uses the parametric data obtained from the DEEC for diagnostic logic execution. Data which the EDU acquires from its own measurements or from aircraft systems generally supplement the DEEC data, in case of communication failures or DEEC input faults. Prior to executing the diagnostic logic, data validity checks are performed to avoid erroneous conclusions. If a required parameter is determined to be invalid, a substitute parameter is selected, an alternate logic path is executed, or the logic function may be bypassed entirely.

At the end of each logic sequence, the results are evaluated against any faults previously stored during the current flight cycle, and, in the condition is the first occurrence during the flight, a fault code, similar in format to those transmitted by the DEEC, is recorded along with the relative time of occurrence in the flight. During each subsequent compute cycle in the EDU, the condition is re-evaluated. Depending on the type of anomaly in progress, raw and or computed data may accumulated, which describes the severity of the condition or provides some key information necessary to accurately assess the effect of the occurrence on engine health or assist in directing post-flight investigation and repair. As an example,the duration and maximum temperature reached is recorded, when a turbine over temperature event is detected.

Engine Events

The following table identifies the engine events recorded by the PW220 EMS:

Table 1. F100-PW-220 EMS Engine Events

Turbine Overtemperature	Low Rotor Overspeed
Augmentor Anomaly	High Rotor Overspeed
Stall Detect	Compressor Vane Flutter
Stagnation Detect	Control Auto-Transfer
Dieout Detect	Low Oil Pressure
Hot Ground Start	High Oil Pressure
Hot Air Start	Start Bleed Failure
No Start	Inhibited Augmentor
Anti-Icing System Overtemperature	Low Thrust
Anti-Icing System Failed Open	Anti-Icing System Failed Closed
Slow Turbine Temperature Probe.	

AIRCRAFT INTEGRATION

The availability of high-speed data bus communications with aircraft systems, offers an excellent, relatively inexpensive data source for engine monitoring purposes, as well as, an opportunity to provide the pilot better indications of the propulsion system health, without the need for analyzing cockpit gauges or stuffing indicator panels with confusing lights. Through interaction with the aircraft cockpit display and data management computer, the PW-220 EMS is capable of supplying real-time engine operating data to augment or replace normal analog data systems. It also provides a continuously updated message identifying every fault detected and each engine event recorded. In exchange, the EDU acquires aircraft altitude, speed and attitude information to supplement recorded event data.

OPERATIONAL EXPERIENCE

The F100-PW-220 engine entered production service in November 1985 with USAF F-15 aircraft. During 1986 and 1987, F-16 aircraft were delivered with F100-PW-220 engines to the USAF, as well as, the air forces of South Korea and Egypt. Approximately 400 units have now accumulated over 20,000 flight hours in world-wide operations,including scenarios ranging from routine training missions to full defense alert. The PW-220 EMS has also supported remote site deployments for extended time periods. In all applications, the performance of the EMS has met or exceeded its operational objectives.

System Performance

EMS performance monitoring is primarily accomplished by tracking the detection of engine faults and events by both EMS and the pilot. Each report is evaluated for validity and then the pilot and EMS reports are compared to determine an interim classification of "HIT" or "MISS", where:

HIT = Valid EMS detected occurrence

MISS = Invalid EMS detected occurrence, or
Valid pilot detected occurrence, within the EMS detection criteria,
but not detected by EMS

These categories are further subdivided for detailed analysis as follows:

HIT = ACTUAL, or INDUCED occurrences

where,

ACTUAL = Real fault or event

and,

INDUCED = Real occurrence resulting from pilot or maintenance actions

Also,

MISS = FALSE, or UNDETECTED occurrences
where,

FALSE = Invalid fault or event

and,

UNDETECTED = Real occurrence not detected

For the purpose of determining a figure of merit for EMS performance, two additional values are needed:

OPEN = Occurrence of undetermined validity

and,

GOOD = Sortie (flight) with no occurrences

From these statistics, two performance factors are derived:

The first, system effectiveness, is a measure of the EMS capability to correctly detect occurrences or confirm the absence of them. In equation form:

EFFECTIVENESS = 1 { (OPENS + MISSES) / (GOODS + HITS) }

The second factor, confirmation rate, only considers the validity of detected occurrences, and is expressed as:

CONFIRMATION RATE = (HITS) / (HITS + MISSES)

Both performance factors are generally calculated as percentages.

Field Results (Figure 8)

Based on operations through August 1987, with 19043 total engine flight hours and 9502 sorties flown, the PW-220 EMS performance factors are:

EFFECTIVENESS = 99.3 %

and

CONFIRMATION RATE = 92.7 % 8

Analysis

Although system performance criteria were not strictly defined for the PW-220 EMS prior to initiating the design activity, a general operational goal of less than 10% unconfirmed occurrences at introduction was established. For purposes of operational trending, introduction is baselined around 20,000 engine flight hours (EFH); whereas, system maturity is assumed after 1,000,000 EFH.

Analysis of the system performance factors indicates that, even though the introductory confirmation rate has been achieved, the primary negative contributors are FALSE and INDUCED detections. As a result, changes to the diagnostic logic criteria have been identified and incorporated in the production EMS configuration. These changes, along with some related improvements to other engine components, are expected to reduce the system unconfirmed rate to less than 1% at maturity.

MAINTENANCE IMPACT

The direct effect of the EMS on engine maintenance is somewhat difficult to isolate from other factors such as improved component reliability, better component accessibility, and modular component design, which all influence the number, duration and frequency of maintenance actions performed. The F100-PW-220 engine incorporated many changes, including EMS, which were intended to enhance overall maintainability.

Two of the more common maintenance measurement standards are: 1) the number of maintenance man-hours expended for each hour of flight time accumulated, and 2) the sortie generation rate, or aircraft availability. A comparison of the F100-PW-220 engine with EMS to the remainder of the F100 fleet reveals that the EMS-equipped engines are averaging approximately 33% fewer maintenance man-hours per flight hour, and are in flight ready status five times more often, (Figure 9). Additional investigation with the EMS users indicates that a significant contributor to this reduced workload is the ability, with EMS, to rapidly isolate a control system anomaly to a faulty component. Coupled with the improved testability of the DEEC system, using the EMS ground support equipment, the fault isolation capability of EMS engines is expected to reduce maintenance manpower requirements to less than 50% of the non-EMS engines at maturity.

LOGISTICS SUPPORT

Evaluation of the PW-220 EMS logistics support performance is also difficult to accomplish, due to the absence of valid comparative data. Not only are there few, if any, figures of merit available for the non-EMS engine support system, but some of the users have not fully implemented the electronic transfer features of the GSU subsystem. However, where the GSU is being used, no data discrepancies have been noted, and the users have submitted new requirements to expand the system functions.

ENGINEERING DATA ACQUISITION

Some features of the F100-PW-220 engine and EMS represent development and design substantiation compromises, which, with extended operational experience, have been proven to need refinement or enhancement. The parametric data obtained by the EMS has been a valuable asset in analyzing engine and control system responses to unusual flight and aircraft conditions, and formulating hardware and software changes to tolerate those situations. In several cases, the EMS data revealed operational anomalies totally unknown, and for which no design consideration had been given. Engine system changes have been developed and verified in less than half the normal time, as a result of EMS being available.

NEW APPLICATIONS

Development of the potential benefits of an EMS have been encouraged and supported by the F100 engine family users, (Figure 10). Upgrades to the PW-220 EMS were incorporated to permit aircraft systems to better utilize the data available and provide new methods of improving overall weapons system effectiveness. Additionally, derivative F100 engines are now in development with EMS hardware and diagnostic logic tailored for new engine and mission requirements. The EMS concepts have also been integrated with advanced engine control systems projected for full-scale development in the next five years. With the success of the PW-220 EMS, it is unlikely that any future Pratt & Whitney military engine will enter service without an EMS.

CONCLUSIONS

The PW-220 EMS experience has not only demonstrated the capabilities of engine diagnostic systems to positively influence engine maintainability and logistics support, but it has also highlighted the potential of EMS to improve overall propulsion system and aircraft integration. Having met system objectives and introductory performance goals, the PW-220 EMS is continuing to provide significant enhancements in failure detection, fault isolation, and repair verification. The PW-220 EMS is confirming the significant payback in reduced maintenance costs and improved logistics support offered by real-time engine monitoring.

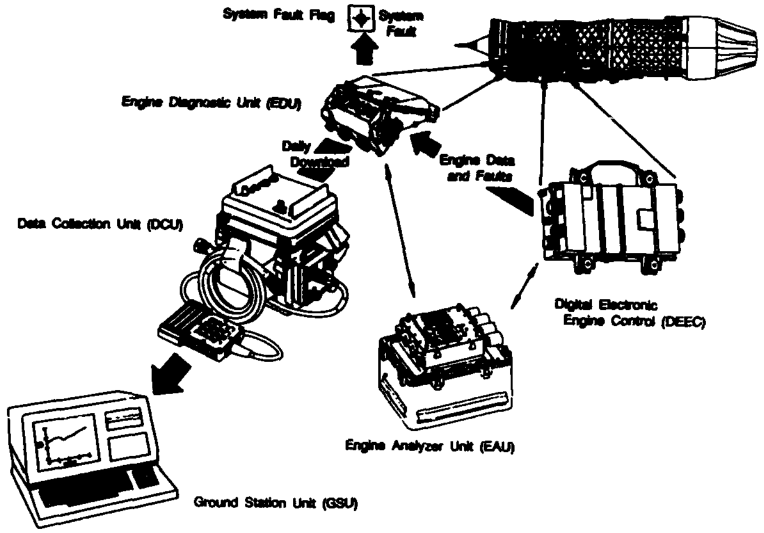


Figure 1. *F100–PW–220 Engine Monitoring System*

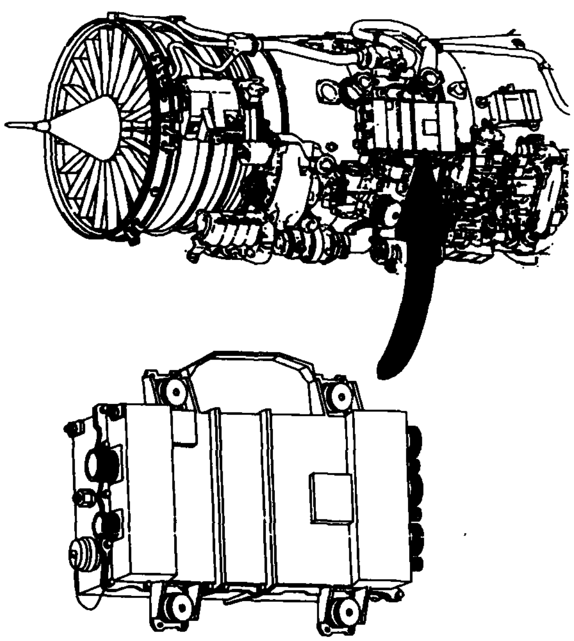


Figure 2. *Digital Electronic Engine Control*

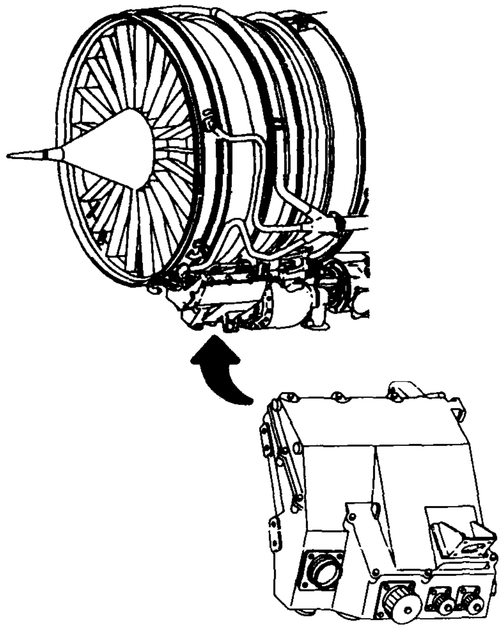


Figure 3. *Engine Diagnostic Unit*

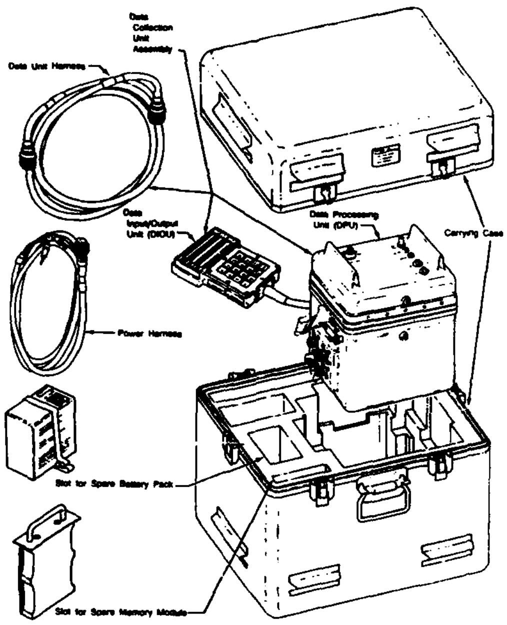


Figure 4. *Data Collection Unit*

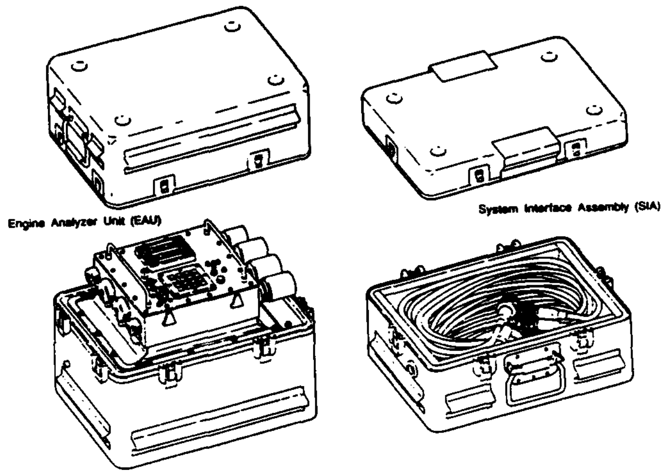


Figure 5. *Engine Analyzer Unit*

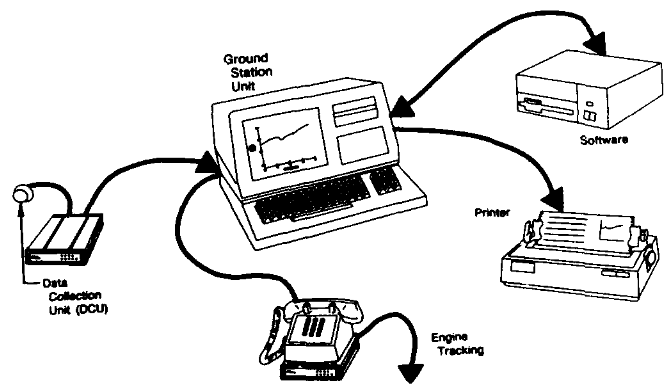


Figure 6. *Ground Station Unit*

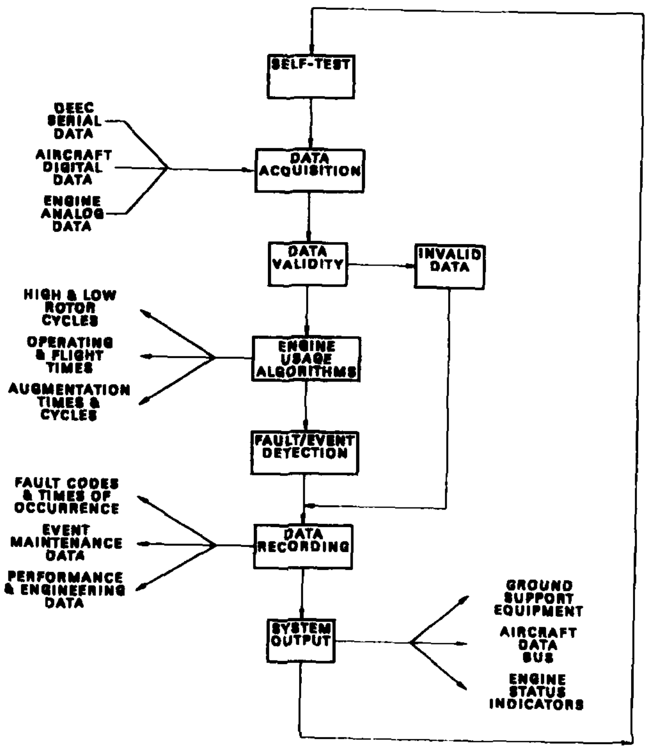


Figure 7. *EMS Diagnostic Logic*

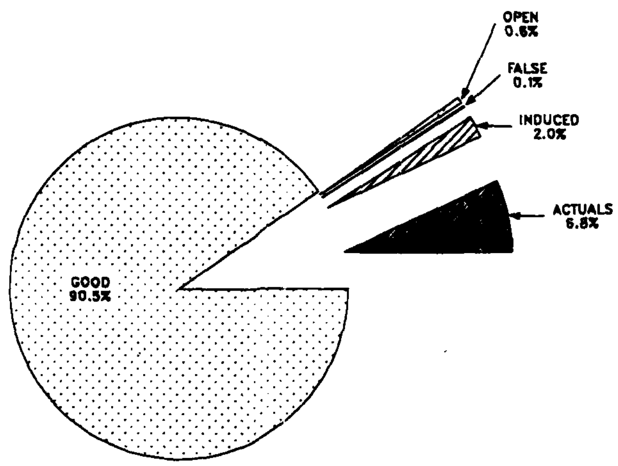


Figure 8. *EMS Field Performance*

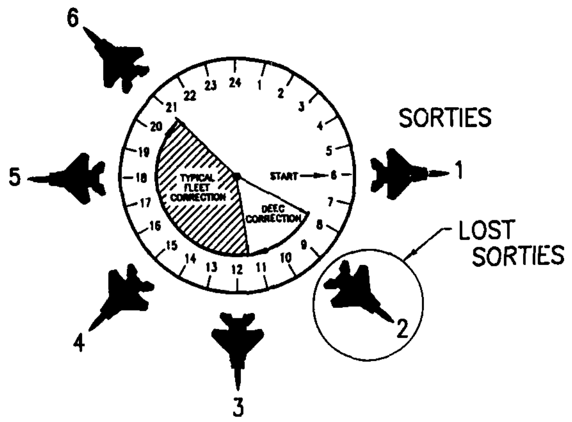


Figure 9. *Aircraft Turn-Around Time Improvement*

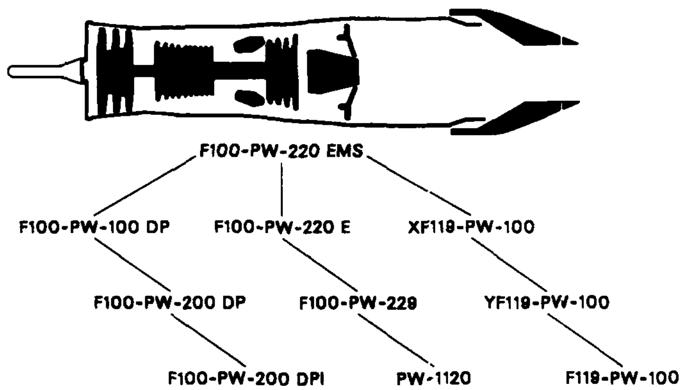


Figure 10. *EMS Applications*

LE CALCULATEUR DE POTENTIEL
SUR LE REACTEUR M53

SPRUNG Claude - SNECMA
B.P. 83 - 91003 - EVRY CEDEX - FRANCE

0 - Résumé

1. Définition des besoins utilisateurs

2. Description des matériels

   2.1. Matériel embarqué sur avion

   2.2. Matériels d'environnement au sol

3. Utilisation et philosophie d'emploi

4. Premiers résultats d'exploitation chez l'utilisateur

5. Conclusion

1 - Définition des besoins utilisateurs

L'heure de fonctionnement d'un réacteur, bien que comptabilisée avec précision n'est pas très représentative de son vieillissement réel.

Sans faire, dans un premier temps, de savants calculs, on imagine qu'un moteur qui subit un vol de convoyage ne se fatigue pas de la même façon que celui qui réalise un vol de combat.

Le premier qui est à régime constant, n'utilise pratiquement pas la pleine puissance alors que le second est soumis à tous les sévices :

- changement de régime,
- utilisation fréquente de la pleine puissance,
- fonctionnement sous fort facteur de charge.

Un décollage peut se réaliser de deux manières extrêmes très différentes.

- Décollage long, configuration légère, puissance minimale,
- Décollage court, configuration lourde, puissance maximum.

Ainsi, il faut fournir à l'utilisateur un moyen d'intégrer dans l'heure de fonctionnement (que nous appellerons heure horloge) la sévérité de la mission et définir d'abord l'unité de comptage.

La première idée qui vient à l'esprit serait de définir des unités qui seraient des cycles complexes :

- cycles thermiques,
- cycles de fatigue mécanique, olygocyclique, ou autre.

Afin de ne pas bouleverser les habitudes des utilisateurs et de toujours conserver la notion de potentiel en heures et de faciliter la gestion de tous les éléments du moteur, ceux qui vieillissent en fonction du temps réel indépendamment de la sévérité de la mission et ceux qui, au contraire, sont sensibles à cette sévérité, nous avons défini le concept :

HEURE DE MISSION MIXEE

L'unité de comptage étant définie, le matériel permettant de calculer le vieillissement du moteur doit être aussi peu contraignant que possible au niveau de l'utilisateur et en particulier ne doit pas autoriser de faire des erreurs.

Avant d'aborder la description des matériels, définissons l'unité de comptage.

Le tableau ci-après représente la consommation relative de potentiel pour chaque type de mission.

Si l'heure de vol de convoyage représente 1 heure, on constate que l'interception à partir de l'alerte au sol représente 39 heures de vol de convoyage et que la mission plastron représente, elle, 81 heures.

. CONVOYAGE	1
. INTERCEPTION ALERTE AU SOL	39
. INTERCEPTION BASSE ALTITUDE	5
. PLASTRON	81
. PENETRATION BASSE ALTITUDE	1,50
. VOLTIGE	2,75
MISSION MIXEE	16

L'unité de compte ainsi définie "MISSION MIXEE" représente 16 heures de vol de convoyage.

C'est avec cette unité que la SNECMA définit les potentiels et les durées de vie des éléments du moteur, sans pour autant connaître la sévérité réelle à laquelle est soumis chaque moteur, en attribuant à chaque mission un taux d'occurrence et un pourcentage de temps dans le fonctionnement du moteur.

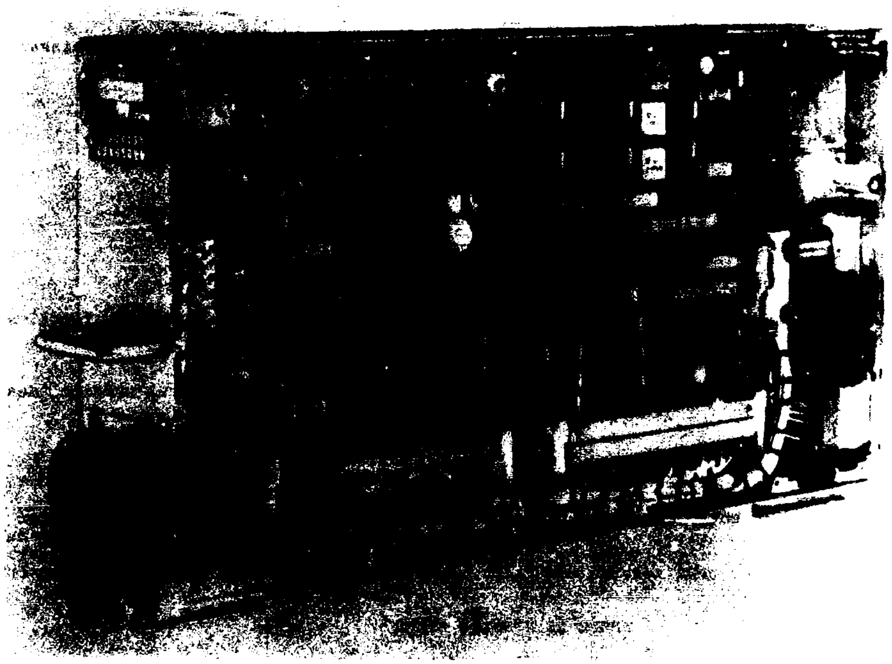
Ces deux dernières données n'ont pas été choisies au hasard. Elles représentent une moyenne des missions dans l'Armée de l'Air Française sur un type d'avion déterminé.

2 - Description des matériels

2.1. Matériel embarqué sur avion

Il se compose d'un calculateur de potentiel qui enregistre les paramètres de fonctionnement du moteur et calcule le potentiel en heures de missions mixées.

Ci-dessous une vue du calculateur ouvert.



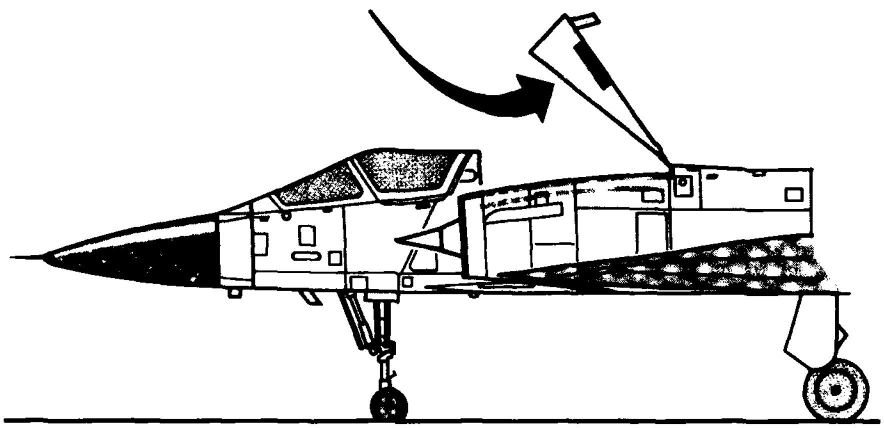
Vue avec l'une des cartes d'éléments électroniques

La vue ci-dessous permet d'apprécier les dimensions de cet équipement.

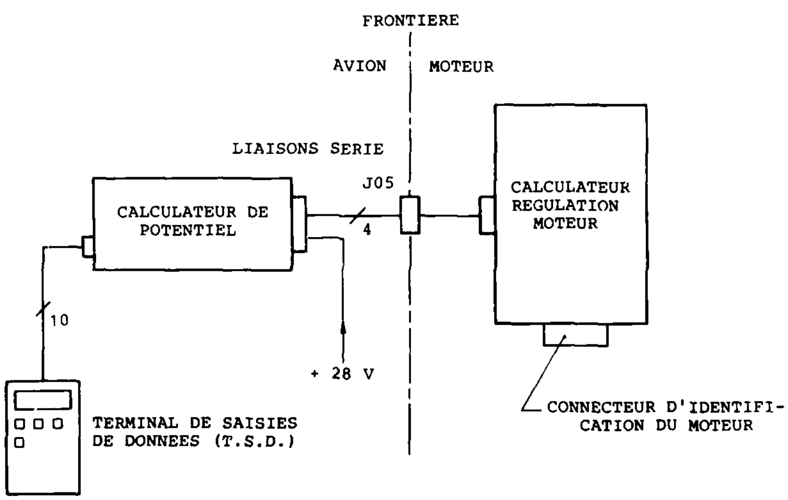
Ce calculateur est installé dans une soute de l'avion, qui pourra d'ailleurs être différente suivant le standard de la cellule de chaque client.

Ci-dessous est présentée une solution pour un standard donné de cellule.

Le choix de l'emplacement doit, bien sûr, résulter d'une discussion entre l'avionneur et le client.



Le principe de l'installation sur l'avion restera cependant toujours le même comme il est indiqué sur la planche ci-dessous.



Apparaît également le terminal de saisies de données (T.S.D.).

Ce matériel est un matériel d'environnement qui reste au sol et sur lequel je donnerai plus de détails dans le paragraphe suivant.

Pour terminer la description du matériel embarqué, nous avons ajouté sur le calculateur de régulation du moteur un connecteur codé d'identification lié au moteur qui permet au calculateur de potentiel de lire le numéro du moteur.

Ceci évite des erreurs lors des déposes moteur du fait que le calculateur de potentiel est sur la cellule.

Si le numéro du moteur ne correspond pas à celui programmé dans le calculateur de potentiel, ce dernier se déclare en panne.

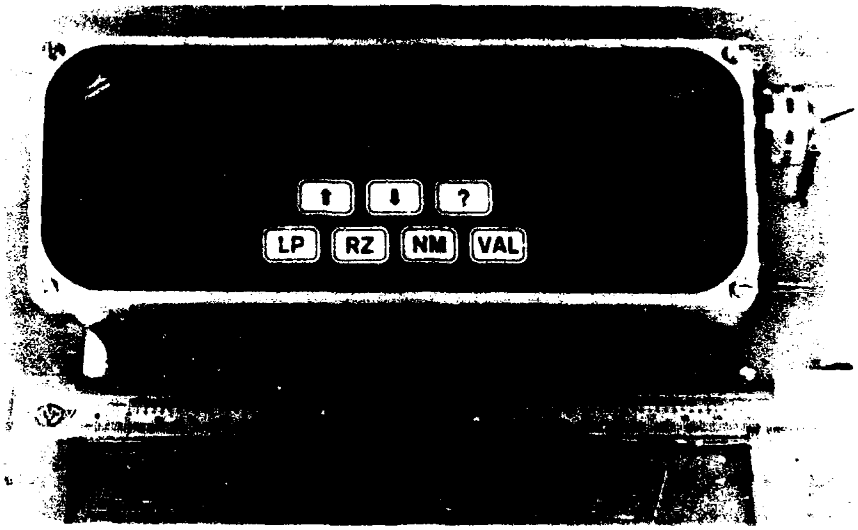
2.2. Matériels d'environnement

Pour éviter toute erreur, le chargement et l'extraction des données du calculateur de potentiel sont réalisés automatiquement sur l'avion au moyen du terminal de saisies de données (T.S.D.).

Il est connecté au calculateur de potentiel pour :

- extraire les données élaborées et traitées par celui-ci,
- initier ce même calculateur lorsqu'on change de moteur ou de calculateur de potentiel.

Voici cet équipement représenté avec le calculateur de potentiel.



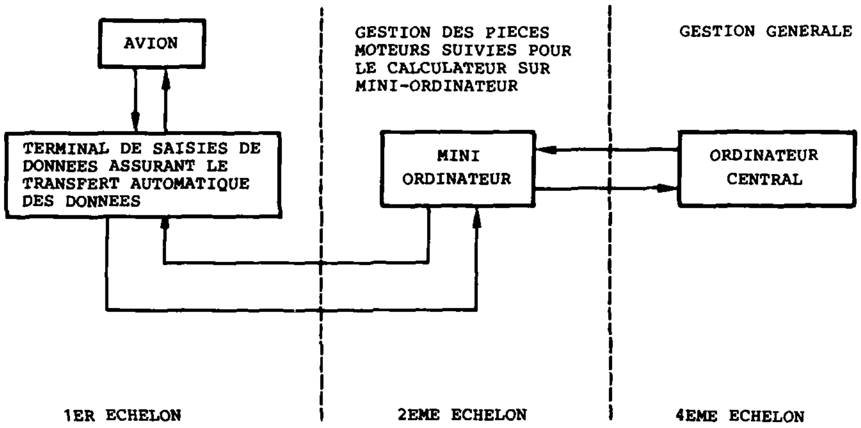
Je m'étendrai un peu plus sur son utilisation lorsque j'évoquerai les problèmes de gestion liés à l'emploi du concept calculateur de potentiel et les solutions que nous proposons pour les résoudre.

Les informations ainsi extraites sont introduites dans un micro ordinateur de gestion au niveau de la base aérienne, de manière automatique, pour éviter toute erreur de transcription.

Une liaison vers un ordinateur central peut également être établie.

Ainsi doit exister une circulation permanente et en temps réel d'informations, comme le montre le schéma ci-dessous, entre :

- l'avion,
- le terminal de saisies de données (T.S.D.),
- le micro ordinateur de gestion et retour vers l'avion, via le T.S.D.



3 - Utilisation et philosophie d'emploi

Une bonne gestion de parc moteur doit permettre une meilleure utilisation des moteurs et pour cela il est nécessaire de :

- mettre à jour la base de données des pièces suivies par le calculateur de potentiel,
- faire les prévisions à court et moyen terme des déposes de moteurs pour envoi à l'atelier 2ème échelon,
- faire les prévisions de retour de modules au 4ème échelon,
- faire des analyses statistiques de consommation de pièces en fonction de la sévérité des missions et des heures de vol réelles,
- connaître l'historique des pièces suivies.

3.1. Maintenance

Pour atteindre cet objectif, il faut s'assurer du bon fonctionnement du calculateur de potentiel.

Au niveau de l'avion, la maintenance se résume à :

- la signalisation,
- un diagnostic sur allumage du voyant PR (perte de redondance du calculateur moteur).

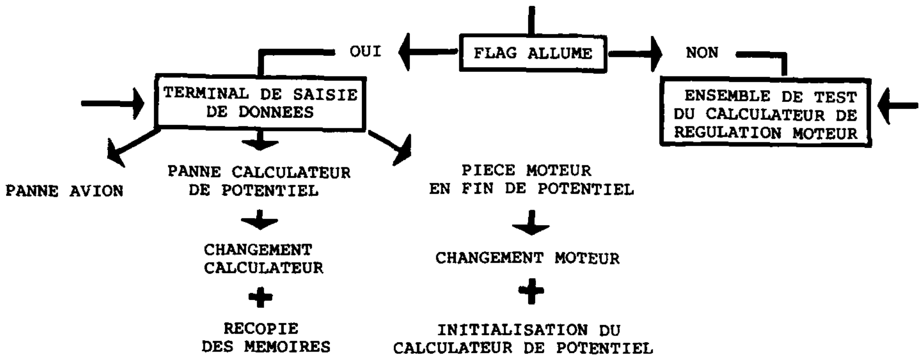
L'allumage de ce voyant doit être interprété suivant le schéma ci-dessous du fait qu'il a deux fonctions :

- perte de redondance du calculateur de régulation moteur,
- demande d'intervention sur le calculateur de potentiel
    - soit parce qu'il est en panne
    - soit parce qu'une pièce moteur est en limite de fonctionnement.

SIGNALISATION : VOYANT EN SOUTE MECANICIEN

- FIN PR DE POTENTIEL D'UNE PIECE MOTEUR
- PANNE DE LA CHAINE DE CALCUL

DIAGNOSTIC : (SUR ALLUMAGE VOYANT PR)



Pour distinguer l'une ou l'autre fonction un "flag" s'allume sur le calculateur de potentiel.

3.2. Impératifs à respecter

Le mode d'emploi étant établi, les impératifs à respecter sont les suivants :

Au premier échelon

- Prévoir la dépose du moteur pour limite atteinte.
- En aucun cas ne dépasser la limite de fonctionnement. La lampe PR citée à l'instant nous le garantit.
- Mais aussi ne pas se laisser surprendre par cette limite pour des raisons opérationnelles évidentes.

Il faut donc définir la périodicité d'extraction des données traitées par le calculateur de potentiel.

Au deuxième échelon

Si les impératifs cités pour le premier échelon sont respectés, les prévisions de retour des modules au 4ème échelon pourront être correctement réalisées au 2ème échelon.

3.3. Fréquence d'extraction des données

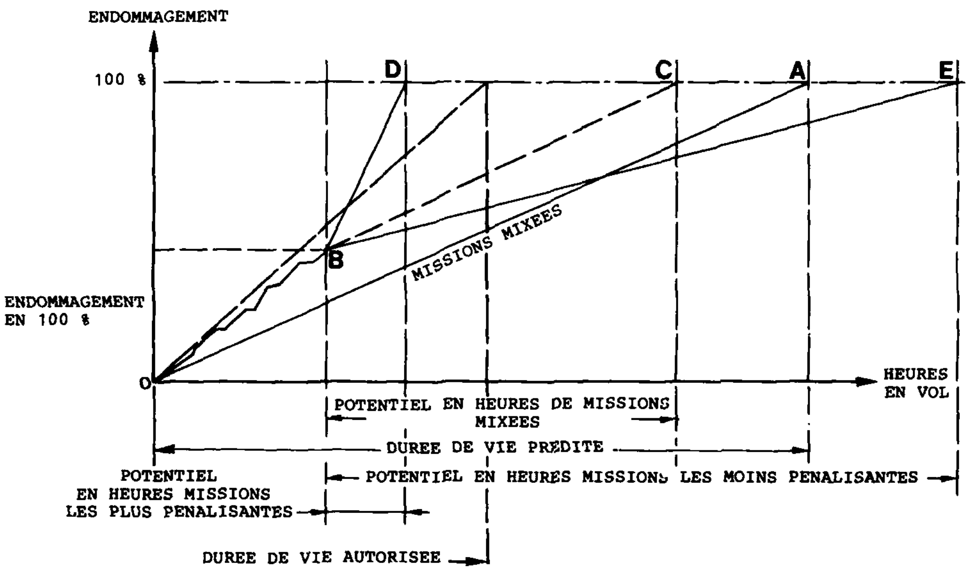
Compte tenu de ces impératifs, quelle doit être la fréquence d'extraction des données ?

La question reste posée et peut être différente pour chaque utilisateur suivant les conditions d'emploi des avions.

Voici simplement quelques éléments qui doivent permettre à chaque utilisateur de déterminer cette fréquence en fonction de leur organisation et des impératifs opérationnels qui leur sont spécifiques.

Le graphique ci-dessous précise les différentes données pour répondre à cette question.

- En ordonnée, figure l'endommagement en "pour cent" ainsi, lorsqu'une pièce arrive à limite, son endommagement est dit de 100%.
- En abscisse figurent les heures de vol réelles (temps horloge), dont on distingue :
  - Durée de vie prédite de la pièce moteur. Elle est définie en heures de missions mixées montrant que si l'avion faisait ce type de mission, telles qu'elles ont été indiquées par leur taux d'occurrence, verrait ces pièces moteur arriver à limite au point A.
  - Durée de vie autorisée : durée de vie libérée par le constructeur par méconnaissance de la nature réelle et exacte des missions de chaque moteur.
  - Potentiel en missions les plus pénalisantes.
  - Potentiel en missions les moins pénalisantes.
  - Potentiel en heures de missions mixées à un instant donné, résultat fourni par le calculateur de potentiel.



Deux cas se présentent :

3.3.1. L'utilisateur n'a pas de calculateur de potentiel.

- Il est obligé de rebuter la pièce du moteur qui a atteint sa limite de vie. La durée de vie autorisée par le constructeur est dans ce cas égale à la moitié de la durée de vie prédite par le calcul.

  La différence entre ces deux valeurs couvre les aléas dus à la sévérité des missions qui n'est pas connue du constructeur.

3.3.2. L'utilisateur possède le calculateur de potentiel.

Si l'on considère une pièce qui a vieilli suivant le processus représenté en OB, au point B, on fait une extraction de données du calculateur de potentiel. Ce dernier nous indique le potentiel en heures de MISSIONS MIXEES qui reste à faire sur moteur (représenté par la droite BC).

Dans le cas d'exécution de MISSIONS LES PLUS PENALISANTES, cette pièce ne pourra être maintenue en utilisation que pour un potentiel représenté par la droite BD.

Dans le cas d'exécution de MISSIONS LES MOINS PENALISANTES, cette pièce pourra être, par contre, maintenue en utilisation pour un potentiel représenté par la droite BE.

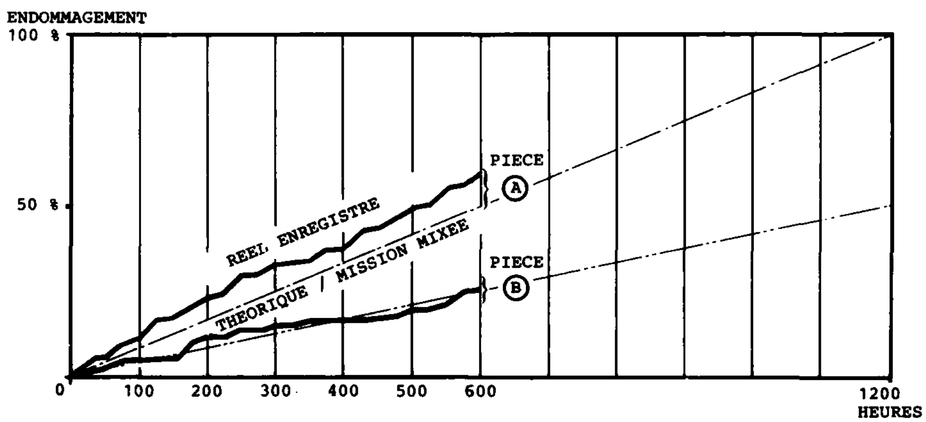
Par cette représentation graphique, on peut apprécier la dispersion d'utilisation que peut avoir une pièce considérée. C'est le domaine représenté ici par le triangle BDE.

Pour concrétiser, prenons l'exemple de deux pièces moteur dont la durée de vie prédite est de 1200 heures.

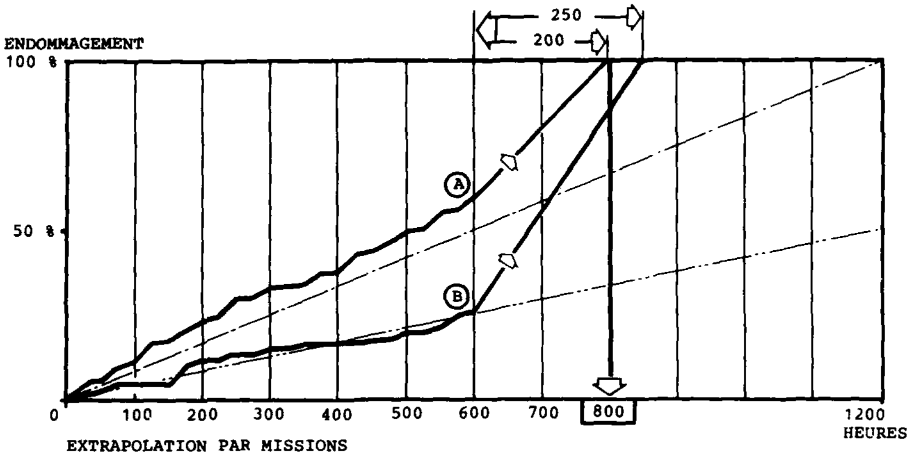
Elles pourraient donc voler 1200 heures si le moteur ne faisait que des missions mixées. Sur ce moteur la lecture du calculateur montre qu'il y a :

- une pièce A qui a vieilli un peu plus vite que ne le prévoit la mission mixée,

- une pièce B qui a vieilli un peu moins vite que la mission mixée.



En prolongeant les lignes qui représentent l'endommagement des pièces dites A et B, suivant les missions les plus pénalisantes pour ces pièces, nous obtenons respectivement pour les pièces A et B, 200 et 250 heures de vol réel restant à accomplir avant limite de fonctionnement.



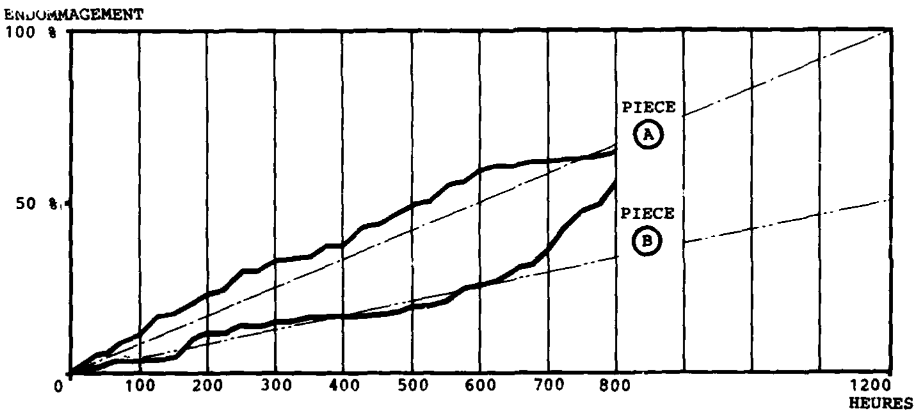
EXTRAPOLATION PAR MISSIONS

MISSION A : LA PLUS ENDOMMAGEANTE POUR LA PIECE (A)

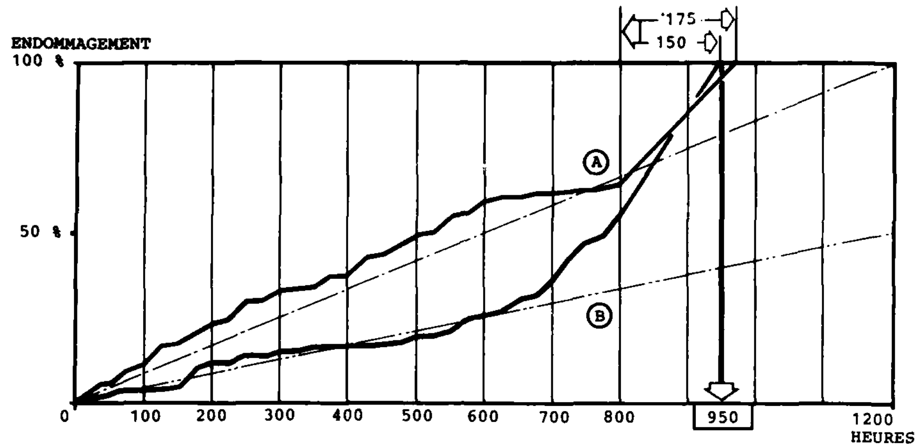
MISSION B : LA PLUS ENDOMMAGEANTE POUR LA PIECE (B)

Dans ce cas précis, il faut aller vérifier le potentiel affiché par le calculateur avant 200 heures de vol.

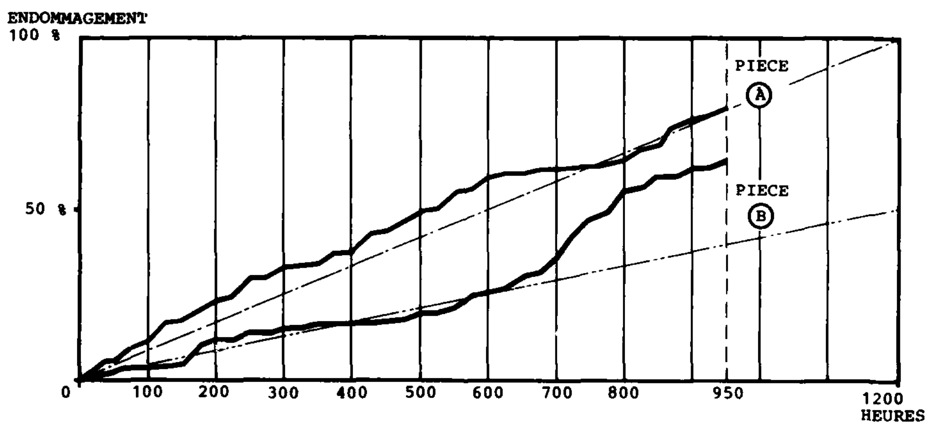
Ce même moteur continue de vieillir et les missions sont telles qu'au stade de fonctionnement 600 heures, la lecture du calculateur montre que la pièce B a eu un vieillissement accéléré (pente accentuée). Par contre, la pièce A est passée sous la ligne de sa "mission mixée théorique".



En faisant le même raisonnement que précédemment, le potentiel autorisé avec les missions les plus pénalisantes - courbes prolongées avec les mêmes pentes respectives - c'est la pièce B qui, avec 150 heures de potentiel restant, provoquera la prochaine extraction de données à 950 heures.

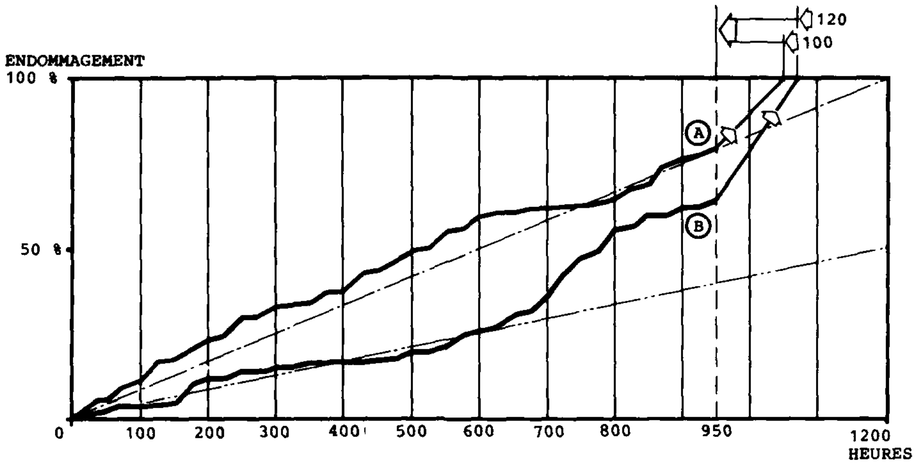


Continuons le raisonnement et faisons une lecture à 950 h.



Au stade de fonctionnement 950 heures, nous constatons que le vieillissement des deux pièces A et B s'est stabilisé.

En prolongeant les courbes comme précédemment, avec respect des pentes des missions les plus pénalisantes, c'est la pièce A qui cette fois provoquera, avec 10ᵤ heures de potentiel restant, la prochaine lecture.



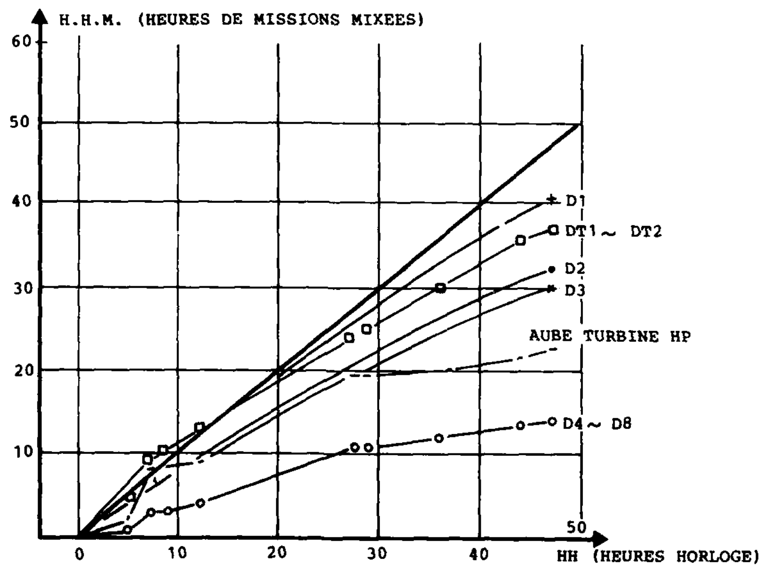
On constate qu'il faut donc augmenter la fréquence d'extraction au fur et à mesure qu'on se rapproche de la limite d'endommagement maximum.

Tout ce raisonnement est bien entendu bâti, pour un moteur "mature", pour lequel la durée de vie autorisée se rapproche plus et a même atteint la durée de vie prédite : ce qui n'est possible qu'avec un calculateur de potentiel.

4 - Premiers résultats d'exploitation chez l'utilisateur

Ces résultats donnés à titre d'exemple sont parfaitement corrélés avec les profils de vol. Sur les graphiques, il y a en ordonnées les heures de missions mixées en abscisse les heures horloge.

4.1. Premier exemple. Utilisation moyenne de l'avion



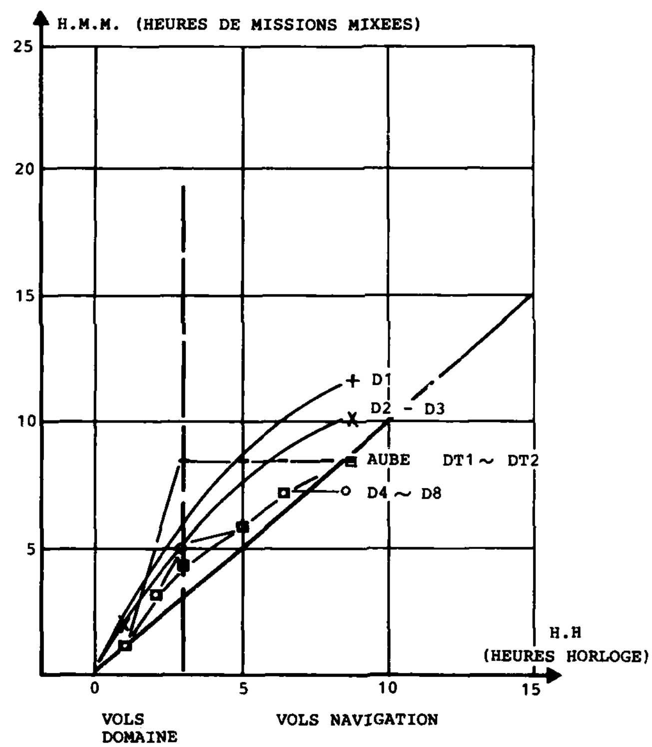
Légende : D_1, D_2, D_3 ... D_8 : disques compresseurs
DT_1, DT_2 : disques turbines 1 et 2

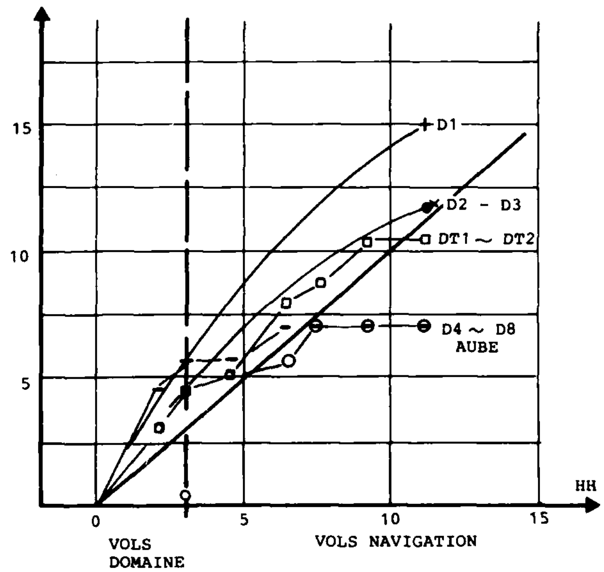
Si l'utilisation de ce moteur se poursuit de la même manière, le calculateur de potentiel permettra de réaliser plus d'heures de vol horloge, et dans ce cas précis on constate que l'endommagement des aubes de turbine HP est égal à la moitié de ce qui est prévu en moyenne.

4.2. <u>Deuxième exemple</u>

Les deux graphiques suivants représentent la vie de deux moteurs sur lesquels on a pu distinguer deux périodes différentes :

- une première où l'avion a plus largement exploré le domaine de vol et en particulier la zone haute altitude et fort Mach.
- une deuxième où l'avion n'a réalisé que des vols de navigation. On constate très nettement que les courbes d'endommagement s'infléchissent et en particulier pendant cette deuxième période, le vieillissement de l'aube de turbine HP se stabilise.





5 - Conclusion

Le calculateur de potentiel est parfaitement au point et est en service dans l'Armée de l'Air Française pratiquement depuis un an.

Il intègre très fidèlement la sévérité des missions ce qui permet donc de gérer les matériels de manière plus sûre, plus intelligente et plus économique.

Pour montrer l'intérêt de ce calculateur, je choisirai comme exemple une des pièces les plus chères du moteur qu'il surveille :

L'AUBE DE TURBINE HP

Aujourd'hui, le critère de rebut d'une aube est son fluage maximum autorisé jusqu'à la prochaine visite périodique de la turbine.

La valeur de ce critère est celle obtenue par différence entre le fluage à partir duquel il peut y avoir rupture de l'aube, et celui que subirait l'aube pendant le temps jusqu'à la prochaine visite périodique (soit 300 heures aujourd'hui), avec le critère de sévérité le plus dur.

Si nous n'avons pas de calculateur de potentiel, nous devons donc rebuter un jeu d'aubes qui n'est pas à sa limite réelle de fluage.

Et cette limite de rebut est d'autant plus basse que la périodicité de visite est plus grande, but recherché par l'utilisateur.

Indépendamment des autres pièces qui sont surveillées par le calculateur, les économies réalisées sur l'utilisation optimale des aubes de turbine HP justifient à elles seules le calculateur de potentiel.

DISCUSSION

P.J. JENKINS

Do you calculate engine life based on a statistical mean of sortie types or do you calculate engine usage directly based on engine speed and temperature changes?

Author's Reply:

L'heure de mission mixée est une unité de compte qui pourrait s'écrire ainsi

Heure de mission mixée = (hr de vol horloge) x (sévérité de la mission)

Ainsi on calcule le potentiel du moteur en fonction des différents paramètres de vol(régime, pression, t°)

P. CHETAIL

With all the progress made in the military applications for life usage evaluation, I wonder, as a commercial user, when this will be applied in the world of civil engines?

Author's Reply:

Il n'y a aucun problème pour adapter un calculateur de potentiel sur un moteur civil ou militaire. Encore faut-il que ce soit utile.

En principe, sur un moteur civil, à l'inverse d'un moteur militaire on connaît bien la mission. Mais dans le cas où l'on change souvent la mission (ex:détarage du moteur pour économiser du potentiel) le calculateur prend toute sa valeur.

MILITARY ENGINE CONDITION MONITORING SYSTEMS
THE UK EXPERIENCE

by

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SUMMARY

The desire to monitor exactly how engines are used in service is probably as old as the gas turbine engine itself. However, it was not until the mid-seventies that the concept of engine monitoring really became viable following the appearance and general availability of affordable digital electronics, including the mini-computer which is now commonplace in most engineering organisations. Since then, the proliferation of engine condition monitoring has resulted in the development of many different systems and it is now customary for defence organisations to include it among their requirements for new military aircraft.

The functional requirements for engine condition monitoring, as stated in the specifications for new aircraft and engine programmes, are usually defined in very general terms, but for one notable exception. The exception is for the life usage monitoring of major rotating components, these being the discs and the turbines. The level of importance afforded to the monitoring of these components is attributable to safety and economic factors which are too great to be ignored in the world of modern high technology aircraft engines.

To the engine designer, a monitoring system can simply mean extra mass, which in terms of today's performance goals is more critical than ever. If it is considered that a monitoring requirement is impracticable or that it will be ineffective, the mass argument will prevail in an effort to have the requirement withdrawn. There are few, however, who would challenge the requirement for engine usage monitoring, not only because it is stated unequivocally in the paragraphs of engine specifications, but moreover because life usage is an inevitable consequence of engine operation.

Engine condition monitoring in the UK military has been built on the foundations of usage monitoring. It is interesting to note that except for one or two very specialised functions such as vibration and oil system monitoring, the engine parameters required for usage monitoring can provide enough data for many other condition monitoring functions. Thus, by starting with usage monitoring, the UK has acquired a useful experience base from which it has been possible to expand into other areas of engine condition monitoring, at the least additional cost.

All the programmes described in this paper have been supported and funded by the Procurement Executive of the UK Ministry of Defence, primarily for the purpose of monitoring Rolls-Royce engines in service with the Royal Air Force.

USAGE MONITORING

Of the many different parts which make up a gas turbine engine, only a small number actually qualify for life usage monitoring. Indeed, the majority have no need for any form of monitoring at all. On the other hand there are some parts that would benefit immensely if a practical monitoring technique could be developed.

To qualify for usage monitoring, the requirements are straightforward; they are to improve safety or reduce costs. Analysis shows that this means discs and turbine blades, all of which are life-limited. The fact that a part is life-limited has nothing directly to do with engine monitoring. A part is life-limited because in time it is liable to fail as a result of the environment and the stresses imposed on it during service operation. It is the variability of operation which makes monitoring necessary.

The principal life usage monitoring functions are low cycle fatigue (LCF) and creep. LCF is predominant in compressor and turbine discs where the consequence of cyclic stress is critical, such that in the event of a failure a serious safety hazard would inevitably result. Unlike the failure of a blade which can be contained by the engine structure, the containment of a disc failure is impossible and since many military aircraft engines are buried in the fuselage, it is not difficult to understand why it is so critical. The fact that an aircraft has two engines can offer little additional comfort in the event of a disc failure.

An LCF cycle is usually defined as an excursion from a state of zero stress up to the maximum design stress and back to zero, making a complete cycle. The stresses that cause LCF increase proportionally with the square of the rotational speed and are usually at their greatest at peak engine rpm. It follows that a small change in speed at a higher rpm will involve a much greater change in stress than a corresponding change in speed at a low rpm. This is broadly the situation that pertains to the first few stages of the engine compressor system. However, in the later stages of the compressor and particularly in the turbines, the situation is quite different. The difference is that the discs in these areas of the engine are also affected by thermally induced stresses which, depending on the circumstances, can either augment or abate the rpm based stresses. These thermal stresses arise from temperature gradients that develop across the affected component. Thus, the computation process becomes increasingly more involved as engine components are required to operate at higher and higher temperature levels.

Temperature and stress are also the main contributors to creep which is particularly evident in parts of the engine that are totally immersed in the hot gases downstream of the combustion chamber. The conditions for creep are most prevalent at high power ratings when rotational speed and temperature are closest to their operating limits. Unlike LCF, where there are no visible signs of distress until the onset of cracking shortly before failure, creep can be measured in units of length as it progresses. Indeed, special gauges have been developed just for this purpose, a typical example being shown in Figure 1.

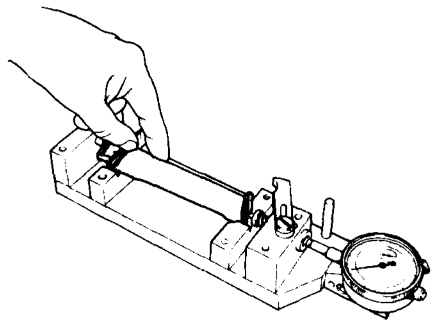

Fig.1 Turbine Creep Checking Gauge

In theory, it should be possible to plot life usage as it happens, but in practice it is not so simple. Nevertheless, the propensity to develop electronic black boxes has continued with strength for a market where the emphasis on life cycle costs is growing in significance.

Before proceeding with a description of the systems that have been developed for military engine life usage monitoring, it is worth pausing for a moment to consider the question; 'why bother?'. For years, gas turbine engines have been operated on the basis of flying hours and indeed the majority still are. Are we therefore in danger of just inventing or fabricating a need to develop yet another box to occupy space somewhere in an already crowded aircraft avionics bay. The arguments for and against usage monitoring almost always revolve around a common set of questions regarding safety, cost and cost benefit. It has already been said that an engine can be operated without any form of life usage monitoring device that is capable of counting cycles or time at temperature. However, there is no guarantee that a fleet of engines will be operated in accordance with the assumptions originally used to estimate the service lives. This introduces the problem of uncertainty and the requirement to apply safety factors. Although it would be possible to make the safety factors so large that the probability of a failure in operation would be virtually zero, the cost of doing so, in spare parts alone, would be astronomic.

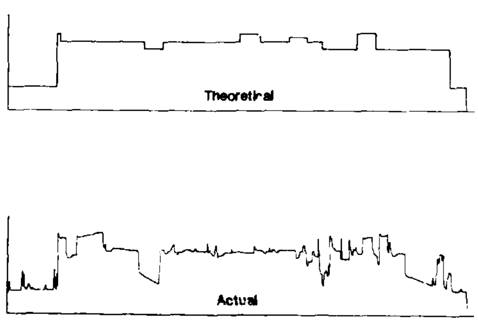

Fig.2 Mission Profiles (rpm)

There are some good examples that usefully illustrate the problem of uncertainty. The problem is really due to many factors, two of the more obvious being; the variance between theoretical and actual mission profiles, and variation within the same mission type. Figures 2 and 3 provide an indication of both problems respectively. The engine rpm profiles in Figure 2 clearly show that there is a vast difference between a theoretical mission profile and a recording of actual service operation for the same mission type. This is not really surprising since the theoretical profile is constructed by simple point to point connection, ignoring the many throttle movements which naturally occur in flight. However, because it is known that real flying is more complex, safety factors are applied.

So, although initially it might seem that gross underestimates of life consumption are possible, in practice the service life predictions are generally conservative.

Perhaps the best example of this is the Adour Mk 151 engine in operation with Royal Air Force Hawk training squadrons, where less than five years after entering service the assumed LCF life consumption rates were revised downwards by a factor of 2.3. Correspondingly the service life limits of many components were increased by the same factor. The projected life cycle cost savings resulting from this achievement alone were estimated in 1984 to be around fifty million pounds.

As mentioned already, it is not just the variance between theory and practice that is important. Variation between sortie types and variation within a specific sortie type are equally important. The reasons for this variability are manifold; they include pilot-to-pilot differences, engine-to-engine differences due to performance or modification state, and aircraft stores configuration. A striking example of the degree of variation that can exist is shown, albeit in somewhat extreme circumstances, in Figure 3.

The rpm traces shown are produced from data recorded by monitoring systems fitted to two of the Red Arrows formation flying team. The difference is clearly visible, with the wing man using up LCF life almost forty times more quickly than the lead man.

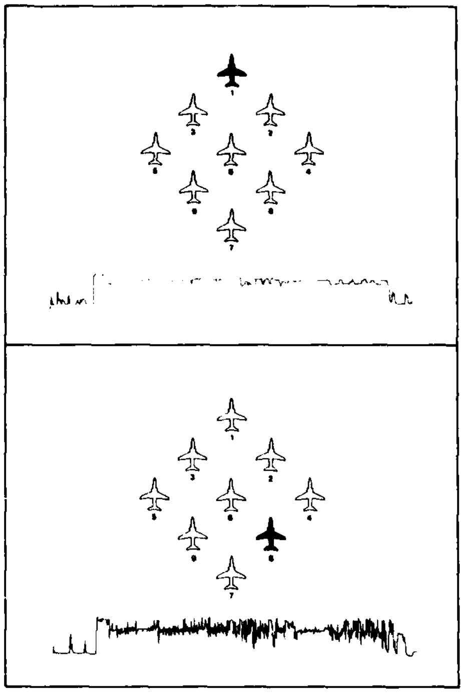

Fig.3 Red Arrows rpm Traces

USAGE MONITORING SYSTEMS

Several systems have been developed in the UK for military engine usage monitoring, some specifically for the purpose, others for more comprehensive engine condition monitoring. These systems range from relatively simple data recorders to real-time data processors.

Pegasus Engine Life Recorder

All marks of Harrier aircraft incorporate a facility for metering the life usage of HP turbine blades. In the later AV8B/GR5 series of aircraft, this is performed by an engine monitoring system while earlier aircraft are fitted with a purpose designed 'engine life recorder'. There are, however, significant differences between the algorithms used in each of these systems.

The engine life recorder function is based on an exponential law which uses an averaged exhaust gas temperature measurement to estimate the rate of creep life usage. To account for the cooling effect of water injection on the turbine blades, a 'wet law' is applied which reduces the count rate for a given exhaust gas temperature. However, the accuracy of the engine life recorder relies on an implicit relationship between exhaust gas temperature and turbine blade temperature, and so lacks the sophistication that is possible with more modern digital computing devices. For example, centrifugal stress is not included because shaft speed is absent from the simple life recorder function.

The limitations of the engine life recorder have not gone unnoticed. As more capable electronics have become available, the opportunity has been taken to improve the methodology for calculating creep for use in later generation monitoring systems.

Engine Usage Monitoring System

The development of special-to-type life usage monitoring systems is an expensive business. Ideally, therefore, it would seem worthwhile to develop a standard monitoring system that could be used for a multitude of aircraft types with minimal changes to its configuration.

Such a system was developed in the early seventies, known as the Engine Usage Monitoring System, or simply *EUMS*. The primary aim of *EUMS was* to provide a better knowledge of the usage, in particular LCF life usage, of engines in service. In its original form, EUMS provided a simple and effective monitoring capability.

The system, described by Figure 4, simply records data from an array of engine and aircraft sensors onto a tape cassette in a digital format. The tape cassette recordings, one for each flight, are then processed on computers using complex stress algorithms to calculate the amount of LCF life usage incurred by each of the major engine components.

The power of EUMS, when fitted to a large enough sample of aircraft, covering the spectrum of operating roles, is such that the life of major engine components can be controlled with greater confidence and significant cost benefits. At the same time, the system enhances flight safety by providing a more accurate assessment of life usage rates. However, these benefits can only be realised when sufficient data has been accrued to build a data base consisting of hundreds or even thousands of flights, depending on the role of the aircraft type concerned. The actual amount of data required before a cyclic usage rate can be determined will depend largely on the observed scatter in the life usage results. As a broad indication of the scale of EUMS, to date more than 60,000 hours of data have been recorded from more than sixty aircraft installations covering a dozen different types.

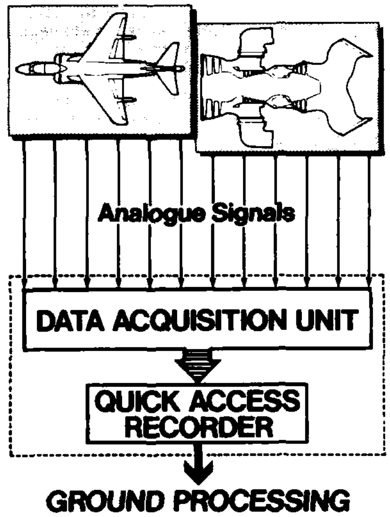

Fig.4 Engine Usage Monitoring System

As implied earlier, EUMS has been the subject of further development. Indeed by 1980 there was a EUMS Mk.2, incorporating a microprocessor for executing life usage algorithms in real time. Although never employed on the scale of the original system, EUMS Mk.2 has successfully provided a valuable service as a development tool in support of other important engine monitoring programmes.

LCF Counter

The obvious limitation of EUMS is that it can only serve to provide a small window on the overall service operation of a fleet of aircraft, unless of course it is fitted to each and every one. Although the natural conclusion might be to do just that, there are two major factors against doing so. EUMS, although a low cost option for a small number of aircraft, would be too expensive for fleetwide use. Moreover, the amount of recorded data from a fleet of aircraft could conceivably overwhelm the resources available to support its operation in the service environment. If then, the maximum life is to be obtained from all major components, a system that is both cheap and simple to manage must be a requirement.

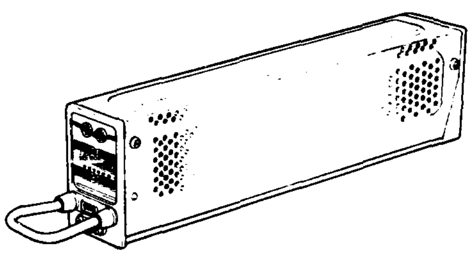

Fig.5 Smiths LCF Counter

A system that met these criteria was developed, primarily for the Royal Air Force.

This was the LCF counter, illustrated in Figure 5, which incorporates a microprocessor, memory and display devices that enable it to calculate and store life usage counts for later interrogation by maintenance personnel. It has been fitted to several military aircraft types on a limited basis, but never fleetwide.

Since its introduction, development of the LCF counter has continued in order to enhance its performance and the number of functions it can accommodate. From its initial capability of calculating LCF life usage from the bare minimum of input parameters, the latest derivatives are capable of executing virtually any life usage algorithm, plus a host of other engine condition monitoring functions.

HEALTH MONITORING

Following the success of EUMS, support grew in favour of investigating the potential of health monitoring. Accordingly a programme, designated Air Staff Target 603, was sponsored by the Royal Air Force to trial a condition monitoring system on Hawk trainer aircraft. AST 603 was originally conceived in 1976 and emerged finally, ready for evaluation, in 1980. An important objective of the trial was to demonstrate that a condition monitoring system could reduce maintenance and support costs. The technical objectives were:

> To determine the correlations between engine condition and measurable engine operating parameters; and

> To develop a practical means of presenting condition monitoring data in a form which could be used for maintenance purposes.

Twelve aircraft and engines were duly fitted with special instrumentation to sense and record a total of fourteen parameters as shown in Figure 6. The system, both the airborne and ground based elements, was based largely on EUMS.

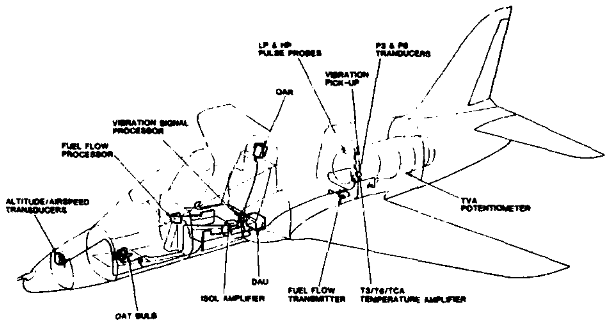

Fig.6 AST 603 Hawk Instrumentation

Engine and airframe parameters were recorded on EUMS equipment and processed on the ground, but unlike EUMS the whole operation was to be managed within the Service environment by Air Force personnel. The life usage functions merely replicated EUMS, though the additional health monitoring parameters were utilised where beneficial. The engine health monitoring objectives called for several functions including vibration, gas path performance monitoring and fuel system diagnostics. However, it was performance monitoring which received the most interest and attention during the trial.

Performance monitoring was pursued as a two-stage process; performance trending and trend analysis. The development of trending techniques was relatively straightforward, but the interpretation of trends proved much more difficult for several reasons. Firstly, the Adour engine has a reputation for good performance retention. Secondly, the engine has no history of single module degradation. Thirdly, the number of performance parameters was significantly less than used for test house performance measurement. Finally, the appearance of long, wavy trend lines offered little meaningful indication of engine condition to anyone but a performance expert. However, by the time the trial ended in March 1985, a number of techniques had been proposed to provide a simple, meaningful indication of the cause of performance changes. Two of these were developed further. Both relied on small change (one percent) performance matrices based on fixed compressor speed and exhaust gas temperature reference parameters. One of these produced graphical results, the other produced plain English and used an expert system.

In more than 2000 hours of monitoring, none of the engines involved in the trial was removed for performance problems, neither did any of the engines give any indication of performance problems. Although this was viewed by some as a failure to demonstrate the worth of condition monitoring, others pointed to success as the data consistently correlated with the good condition of the engines that were monitored.

Many important lessons were learned from AST 603 which have already been put to use in a later production monitoring system. There can be little doubt that some of the problems experienced in AST 603, if encountered in a production programme could seriously undermine confidence in the credibility of engine condition monitoring.

ENGINE CONDITION MONITORING SYSTEMS

The most recent equipment developments have been, of necessity, forced to provide a wider range of functions, following the trend towards comprehensive engine condition monitoring. In keeping with the philosophy to produce a mostly common equipment standard, the requirement arose for a standard engine monitoring system (EMS) that could satisfy all condition monitoring requirements. The EMS which subsequently emerged from this requirement was developed with one application already planned. This was for RAF Harrier GR5 aircraft which began service operation in the second half of 1987.

Development of the EMS hardware was the responsibility of Plessey Avionics under contract from the Ministry of Defence (Procurement Executive). Rolls-Royce was contracted to define the functional requirements and provide the engine transducers. When defining the requirements, Rolls-Royce was very cautious, not wanting to create an over-sophisticated system that would be unsupportable. The basic functions include:

- LCF Life Usage Counting
- Turbine Life Usage Counting
- Operational Limit Exceedance Detection
- Hot Start Detection
- Surge Detection
- In-Flight Relight Detection
- Vibration Frequency Analysis
- Incident/Exceedance Recording
- Pilot Initiated Event Recording

It was fortunate that the GR5 would incorporate a MIL-STD-1553 data bus which could provide most of the data required to satisfy the functional requirements. This was an important advantage in favour of minimising weight penalties, which is always of concern to aircraft designers, but even more so when the aircraft is designed for VTOL operations. Only two extra transducers were required; an accelerometer to sense vibration and a pressure transducer for compressor delivery pressure. Much of the EMS data provided via the aircraft data bus is alternatively available from the digital engine control system which is standard fit on Pegasus engines in the Harrier GR5. This offers a straightforward means of data validation by comparing the values of parameters that are common to both data sources.

Not all of the functional requirements are of prime concern to first or second line maintenance. For example, the fact that an in-flight relight occurred is certain to be reported by the pilot. The reason that this function has been included in the EMS is to provide more information to the engine manufacturer in the hope that with a better knowledge of the circumstances and engine behaviour relating to the incident, improved maintenance procedures might be developed. A similar situation also applies, but to less extent, to the other functions, enabling the engine manufacturer to build up a data base of incidents that hitherto could only be recorded as pilot observations. With more detailed information it is possible that some of the limits applied to basic engine operation, such as top temperature limits, could be relaxed to the benefit of the operator. Initially however, the EMS will only provide better information relating to existing limitations which will help to determine, with more confidence, the maintenance action to be taken.

The requirement for vibration frequency analysis did not originate from Rolls-Royce. Previous experience with vibration monitoring systems on Rolls-Royce engines had proved to be the cause of numerous false warnings. However, none of those systems attempted to do very much with the transducer output other than to illuminate a warning lamp in the cockpit when the vibration level exceeded a preset limit. This was not to be the case for the Harrier EMS. The US Marine Corps, as the major customer for AV8B Harrier aircraft demanded that vibration monitoring should be incorporated in the EMS, in keeping with US Navy policy to equip all fighter aircraft with a facility to monitor engine vibration and the capability to analyse the frequency components. This concept not only improves the ability to identify the cause of vibration within the engine, but also improves the ability to check out the transducer itself. In order to implement this requirement, Rolls-Royce chose to specify a comb filter comprising of fifteen narrow band frequency filters. These were appropriately distributed to span a bandwidth of 5 KHz to cover the operating ranges of the engine spools as well as higher frequency levels normally associated with gears and bearings.

Every time an engine abnormality is detected, as defined by the EMS logic, whether it be vibration, overtemperature, surge, etc., or if the pilot chooses to record data, two records are automatically stored in memory. The first of these is a high level summary of the incident giving the salient details of the incident, the time at which it occurred, the duration and the peak values of associated parameters. The second is a time history record of all EMS parameters for the period of the incident including four seconds before and afterwards.

The purpose of the summaries is to provide maintenance personnel with sufficient data to make GO/NOGO decisions between flights while the time history records are intended to provide detailed engineering data for troubleshooting the causes of problems.

The means to interrogate the EMS have been provided in several ways as shown in Figure 7. Information can be accessed from the cockpit using the display systems available to maintenance personnel during after-flight inspection. Alternatively, there is a compatible data retrieval unit for reading exceedance/incident summaries and life usage counts or for transferring all of the data stored in the EMS to a ground computer for bookkeeping and analysis.

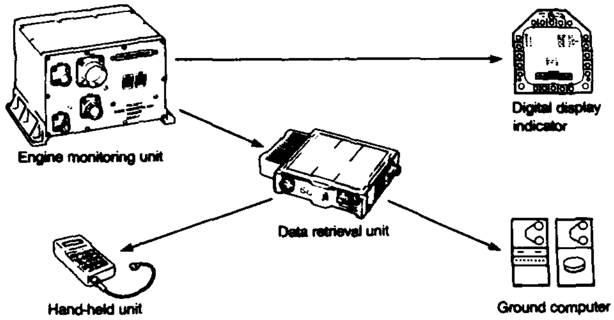

Fig.7 Harrier GR5 EMS Maintenance Interfaces

There is an obvious connection between engine condition monitoring and diagnostics. The approach taken in the UK is to store data when there is an abnormal engine operating condition and then to analyse that data on the ground to assist maintenance decisions. However, unless there is a clear strategy for data management, the amount of data produced from a fleet of aircraft will overwhelm maintenance resources. For this reason, a special information management system has been developed in parallel with the engine monitoring system which can be deployed to all Harrier operational units in the Royal Air Force.

FULFILLING THE OBJECTIVES

All of the monitoring systems described in this paper have succeeded in meeting their functional objectives, though the degree of application has been slight in some cases. Compared with the enormous success of the EUMS programme, the LCF counter may seem insignificant, being fitted to no more than a few UK military aircraft, including the Red Arrows. However, this is through no fault of the equipment; it is more a reflection of the changing requirements and technology developments in the rapidly expanding field of engine condition monitoring. It is only fair to point out that the LCF counter has found greater success in other markets outside of the Royal Air Force.

It is highly significant that a monitoring system has to justify its way onto a fleet of aircraft, and the most direct means of doing so is to demonstrate its effectiveness on the basis of cost benefits. Unfortunately though, the cost benefits are increasingly difficult to realise if the system is not incorporated during the aircraft design and development phase. This is primarily due to the high cost of retrospective installation, compounded by the loss of savings resulting from the absence of a parts life monitor at the commencement of service operation of the aircraft. Consequently, with new military aircraft programmes few and far between, the opportunities for commissioning fleetwide monitoring systems are correspondingly small in number. Thus, the chances of a new system being fitted to a new aircraft type tends to depend on there being a requirement and the state of technology available at the time. The circumstances relating to the decision to fit an engine monitoring system to Harrier GR5 aircraft illustrates these points very well.

In the future, as avionics technology progresses, it is likely that engine condition monitoring will find itself integrated with other aircraft monitoring functions in multi-function processing systems, making the most recent engine monitoring systems obsolescent. However, this prospect should not discourage further development of independent systems, since without them, the importance ascribed to usage monitoring could elude some of the less established engine condition monitoring functions.

The views expressed in this paper are those of the author and do not necessarily reflect the views of Rolls-Royce plc.

DISCUSSION

M. HOUILLON (Commentaire sur les communications n° 19 et 20)

A la suite des deux derniers exposés je tiens à apporter les précisions suivantes:

-La philosophie retenue en France est identique à celle retenue au Royaume Uni et dans les autres pays participants.

-En ce qui concerne le calculateur de potentiel du M53 un doute s'est installé au cours de l'exposé. Il est nécessaire de préciser que les algorithmes de calcul utilisés sont semblables dans le principe à ce qui a été exposé par les autres participants. L'endommagement est calculé pas à pas en fonction des paramètres moteur, les résultats sont comptabilisés et mémorisés dans le calculateur.

-La différence et l'incompréhension apparue en séance provient de la confusion apportée par la notion de mission mixée. Cette notion est utilisée, à la demande de l'Armée de l'Air Française, afin de communiquer au technicien chargé de la mise en oeuvre de l'avion, un résultat facile à interpréter.

-Cette notion n'intervient absolument pas dans le calcul lui-même et dans la comptabilisation de l'endommagement.

MILITARY ENGINE MONITORING STATUS AT GE AIRCRAFT ENGINES CINCINNATI, OHIO

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SUMMARY

This paper describes the design and development by GE Aircraft Engines of recent military engine monitoring systems. In particular, the systems for the F101-GE-102 engine in the B-1B aircraft and the F110-GE-100 engine in the F-16C/D are used as examples. Since both of these systems have recently been introduced into service, this experience is discussed together with operational status.

These present systems are compared with future evolutionary trends which are affected by the development of miniaturized, rugged electronics and by the desire to minimize the unique hardware and software required for engine monitoring. A discussion of interfaces, both airborne to the flight crew, and, through support equipment and ground analysis programs, to the ground crew, is included.

INTRODUCTION

The aircraft engine manufacturers' involvement in engine monitoring has varied but, with recent emphasis on supportability features, participation in total system integration throughout the engine design and development phases is now the normal modus operandi. As will be seen from the two examples cited, the means of achieving the end result of a fully integrated system can vary significantly and will continue to evolve as aircraft with fly-by-wire techniques, which include data bus architecture, become the standard.

Military monitoring systems have emphasized go/no-go decision making more than long-term engine performance trends. GE Aircraft Engines is developing military monitoring systems which include instrumentation of the engine, airborne diagnostic algorithms, and ground software/hardware combinations. GE has developed the total system for the F-16 aircraft with the F110-GE-100 engine, and similar ground systems are being developed for the F110-GE-400 (Navy) and F101-GE-102 (Air Force/SAC). The systems for the F101-GE-102 in the B-1B and the F110-GE-100 in the F-16C/D have been selected as examples of systems which are in service and accruing operational experience.

The system for the B-1B/F101-GE-102 is known as the Central Integrated Test System (CITS) which has its origins in the early '70s with the B-1A. Extensive factory and flight testing led to diagnostic logic changes but the system remained essentially unchanged even with the advent of the B-1B in 1982. Additional factory and flight testing has brought the system to the operational point described in this paper with almost all of the 100 B-1Bs assembled by the end of 1987.

With respect to the F110-GE-100 system, GE received a contract from the USAF in early 1983 for the full scale development of that engine. Included in this contract was the requirement for a Engine Monitoring System (EMS). At that time it was recognized that for the EMS to become an integral part of the engine maintenance concept, it needed to be keyed to the existing USAF maintenance organization.

System design was initiated in January of 1983, and complete system operation was demonstrated during development engine testing in December 1984. The EMS was available for the first flight of the F110-GE-100 engine in an F-16C aircraft (May 1985). Production deliveries of EMS equipment started in March 1986 and at the end of 1987, the EMS was "on board" over 250 GE powered F-16C/D aircraft that had entered service.

CITS Major Equipment

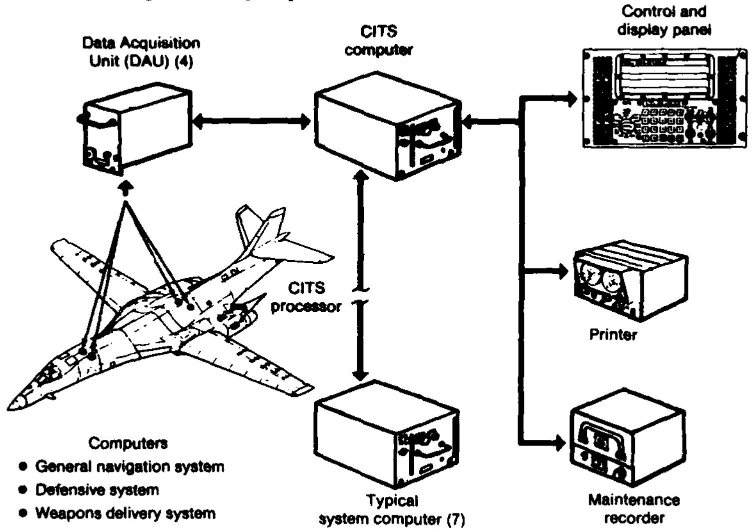


Figure 1

SYSTEM DESCRIPTIONS

F101-GE-102 Engine Monitoring

The Monitoring system for the F101-GE-102 engine in the B-1B is part of the Central Integrated Test Systems (CITS) - See Figure 1. Engine control parameters from the analog electronic Augmentor - Fan - Temperature (AFT) Control are digitized by the on-engine CITS Processor, which also performs the engine cycle counting functions. This cycle data can be downloaded directly to a portable

Engine Sensors/CITS Interface

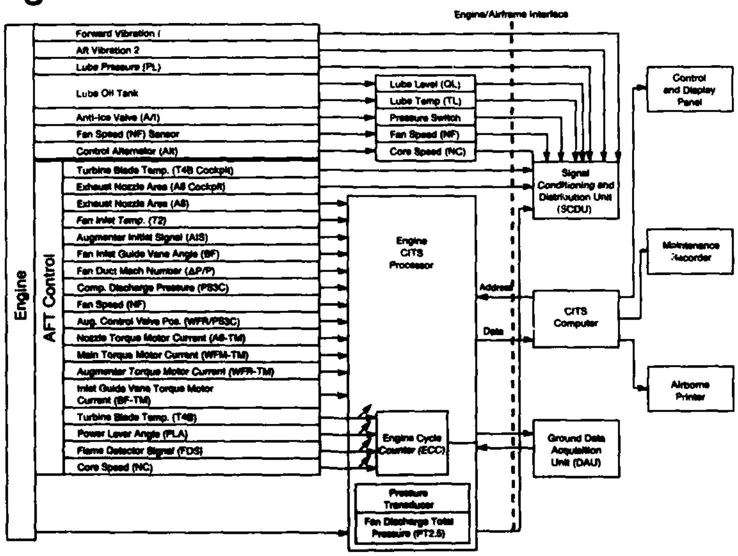
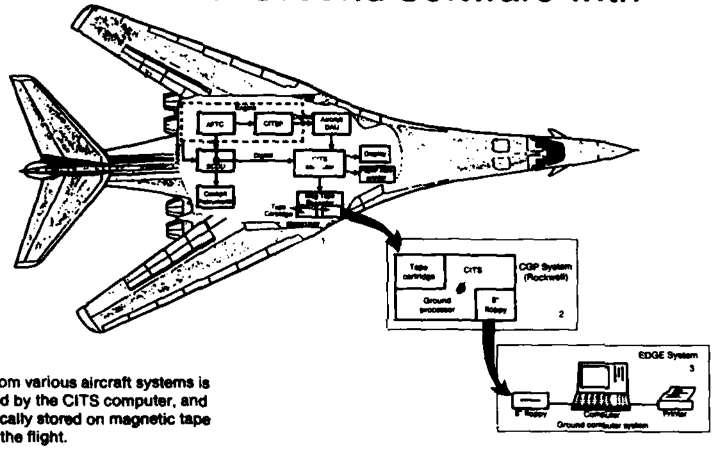


Figure 2

ground support Data Acquisition Unit. Other sub-system analog signals, e.g., vibration, anti-ice and lube parameters, are transmitted to the aircraft Signal Conditioning and Distribution Unit (SCDU) for digitization. Both sets of digitized parameters are then sent to the aircraft CITS computer which performs the data acquisition, event detection and fault isolation functions. The CITS computer communicates with the aircraft Control and Display panel, the maintenance recorder and the airborne printer - See Figure 2. A Record Initiate Switch is in the cockpit which permits the pilot to manually request the CITS to record data.

The aircraft maintenance recorder stores data on a magnetic tape. A cartridge is physically removed from the aircraft and is read by the CITS Ground Processor (CGP). All data is available, either in total or selectively, from the CGP in hard copy form. In addition, engine data is separated and stored on an 8" floppy disk. A ground software program is in the latter stages of development which will take this engine data and process it in an Air Force Personal Computer (Z-248) to provide information such as fault parametric data, trends and maintenance history in an easily accessible and understandable form - See Figure 3.

Integration of New Ground Software with CITS



1. Data from various aircraft systems is sampled by the CITS computer, and periodically stored on magnetic tape during the flight.
2. The magnetic tape cartridge is removed from the aircraft, and the data applicable to the engine is transferred to 8" floppy by the CGP.
3. The 8" floppy is delivered to the EDGE system at flight line maintenance, and EDGE is used for engine fault analysis and trending.

Figure 3

The present CITS engine logic is intended to detect 95% of the faults which would result in a 10% or greater power loss. Further, it then should correctly isolate at least 75% of those faults to the LRU level. The crew is informed of these fault detection/isolations on the control and display panel and a printed paper tape. At the same time, data snapshots are recorded on magnetic tape. Each of the detection/isolation messages identified in the logic has been assigned a unique code number (which also identifies the engine position). These codes are listed in a table in the engine troubleshooting manual. The table identifies the appropriate troubleshooting procedure for each of the codes. Additionally, each of the troubleshooting flow charts has a list of the CITS codes which relate to it.

It should be recognized that the limitations of the CITS automated diagnostics (and, for that matter, other systems) are:

- CITS detects 95% of the faults. The 5% which are the most difficult for human troubleshooters are also the most difficult for CITS.
- A CITS LRU includes cables and plumbing. The repair technician is still required to diagnose interconnection faults.

- When the CITS logic is confronted with two or more possible LRU's and has insufficient information to choose among them, they are ranked according to failure probability.

- The CITS logic designers have attempted to compensate for the interaction of multiple failures, however, all of the possible ramifications and interactions of multiple failures are not known. The limitations of CITS is mentioned in order to emphasize that CITS was designed to be a tool to aid a human diagnostician, not a way to replace him, and not a diagnostic panacea.

A considerable amount of data can be recorded by CITS. It is grouped in the following data blocks:

- Identification data (engine S/N, aircraft S/N, etc.) entered through the control and display panel.

- Failure messages or CITS Maintenance codes (CMCs) - 150 per engine or 600 per aircraft. (6% of total aircraft which possesses 10435 unique CMCs).

- Snapshot data taken at event detection, power up and every 30 minutes. Consists of three scans, 30 seconds apart. A single snapshot is recorded when the Record Initiate Switch is activated. It should be noted that any aircraft event results in a complete set of aircraft data, including engine, being recorded. This data can only be separated into sub-systems by the CGP on the ground.

- Trend data, eight scans taken over a two second period.

- Continuous recording of fan speed, core speed and T4B in the event of an exceedance.

- Parts Life Tracking Data.

- Engine status (total run time).

As part of the trend data block some additional data is taken associated with T4B levels and significant engine anomalies such as power loss.

The B-1B CITS is, as its name implies, a total aircraft monitoring system with the engines being a sub-system. GE's involvement has been in the engine CITS Processor, the ground support DAU, the on-board diagnostic logic and the future ground software program. The ground software program did not commence until 1985 whereas the aircraft and engine CITS were designed in to the original B-1A system which led to the B-1B.

F110-GE-100 Engine Monitoring System

The primary interface for the F110 EMS parametric inputs is also the engine AFT electronic control. This full authority control provides some 23 analog inputs and five discrete values. Parameters are also available from other non-control areas such as the anti-ice and lubrication sub-systems. The aircraft avionics system provides an additional six inputs relating to flight conditions.

The EMS configuration consists of three hardware components; an engine mounted EMS processor (EMSP), an airframe mounted EMS computer (EMSC) and a Data Display and Transfer Unit (DDTU) - flightline equipment. Additionally, EMS software is provided for the ground station computer. The relative locations of this equipment are shown in Figure 4. The functional relationships and interfaces are illustrated in Figure 5. A full description of the F110 EMS can be found in Ref. 1.

The system generates four types of data: Diagnostic Data, Parts Life Tracking Data, Trend Data and Pilot Initiated Data.

F110 Engine Monitoring System

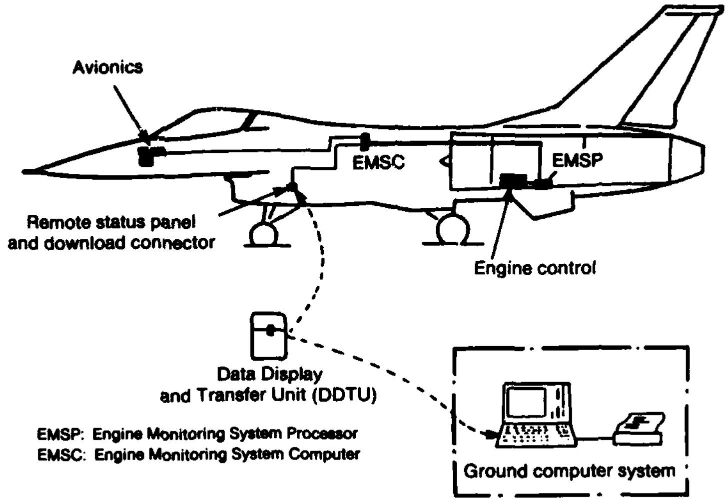


Figure 4

Component Interfaces

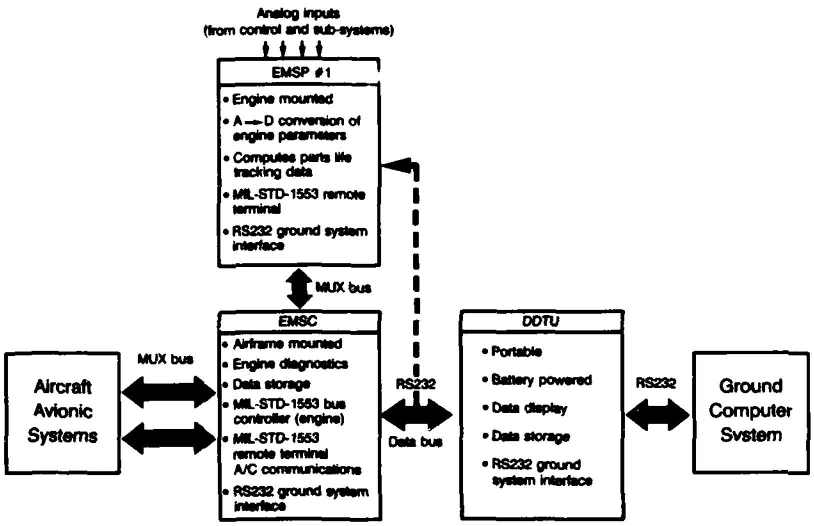


Figure 5

Diagnostics Data

The EMSC incorporates extensive fault detection and isolation logic to provide a "real time" diagnostics capability. The logic for the F110 was based on the original F101 logic. The EMSC continuously assesses all inputs and compares them to stored criteria. When a parameter or a set of parameters exceed these stored values indicative of a fault, the EMSC transmits an appropriate status flag to the aircraft avionics for storage, cockpit display and/or pilot alert.

Concurrently the EMSC stores a pre-programmed amount of parametric data in its non-volatile memory for post flight retrieval. The EMSC diagnostics is structured to enable isolation of a fault to an engine Line Replaceable Unit (LRU) wherever possible. The parametric data is also available to aid further troubleshooting if required.

The EMS has the capacity for detecting/transmitting up to 80 different fault flags to the aircraft. This fault status summary is known as the Maintenance Fault List (MFL) for the engine. A small subset of the MFL comprises the Pilot Fault List (PFL). The PFL consists of specific faults which warrant caution messages and alerts to the pilot.

Parts Life Tracking Data

This data is computed by the EMSP and stored on a cumulative basis. The data reflects the total operating times and cycles on the engine and is used by the ground computer system to track life limited engine components. This tracking allows predictions for maintenance planning and spares provisioning.

Trend Data

The EMSC automatically acquires and stores a pre-programmed amount of parametric data during the take-off sequence. The data is subsequently transferred after the flight and processed/displayed in the ground computer system. Selected parameters are plotted over a period of time in order to identify any detrimental trends in overall engine health.

Pilot Initiated Data

In addition to the EMS automatically saving data for detected faults etc., the capability exists for the pilot to request a data save by activation of a cockpit switch. When so commanded the EMSC will save a pre-determined amount of parametric data which can then be retrieved post flight and analyzed.

All of the EMS stored data is retrieved via a single connector, conveniently located on the aircraft Remote Status Panel. This panel, which is housed in the left hand side of the inlet structure, also incorporates two EMS status indicators. The DDTU is used to accomplish the data transfer. Fault and isolation summary messages are displayable on the DDTU together with the associated engine/aircraft documentary information. The DDTU can be used to download multiple aircraft prior to returning to the maintenance facilities/ground computer system for data entry and processing.

OPERATIONAL EXPERIENCE

F101-GE-102/B-1B

Since the CITS is a fully integrated system, it was not possible to run the total system during factory testing of the F101. Instead the airborne algorithms were programmed into a slave computer and airframe parameters were simulated permitting exercise and development of the algorithms during factory engine test. This proved to be an invaluable tool. Flight testing of the B-1B which has been continuing since mid 1983 provided a source for continuing development but it is since delivery of the first aircraft in mid 1985 that excellent progress has been made. It must be remembered that engine monitoring represents approximately 10% of the Rockwell CITS program and approximately 6% of total aircraft CITS. Thus software block updates must consider many factors, not only the engine, and can take longer with this integrated approach. On the benefit side, once software design and test is complete, the update to the latest version happens quickly, since it is an upload by tape of software rather than firmware as in the case of the F110 EMS.

At the time of writing there are approximately 85 B-1Bs in service and the maturation process is proceeding. CITS has not, to date, driven maintenance but has been used for verification and substantiation of flight crew reports. As problems are solved and confidence in the system is built up, this will change. Progress in the last year on engine-related airborne CITS has been good. A formal evaluation performed in November 1987 over a period of 33 flights on 13 aircraft showed that, of the 132 engine flights, 125 were fault free, seven real faults were correctly identified and one false fault indicated. False alarms are driven primarily by four factors - tolerances, operational considerations and flight envelope considerations, all similar to the F110 and discussed in more detail in the F110 section.

The false alarm rate has been reduced from a potential of 25 per flight, 18 months ago, to the current potential level of two per flight. "Potential" means that these faults do not occur every flight but could possibly occur, depending on the mission. Elimination of these three faults along with other improvements are planned for 1988.

It is generally agreed that maturation of the engine-related CITS has been significantly advanced due to regular quarterly coordination meetings attended by all contributors yet small enough so that effective decisions can be made. A preliminary version of the enhanced ground software is about to be released so it is not possible to comment on its effectiveness but it is hoped that it will encourage the use of CITS airborne data and aid those who maintain and manage the F101-GE-102 engines.

F110-GE-100 EMS

The F110-GE-100 EMS has accumulated significant operational experience and widespread usage around the world. As of the end of 1987 approximately 50000 flights had been flown and the "fleet" had grown to over 250 aircraft. The discussion that follows summarizes that experience.

EMS False Alarms

The first F110-GE-100 powered production F-16 aircraft entered operational service in mid 1986. Up to that time the EMS had been developed and "matured" primarily as a result of factory engine test experience and 12 months of flight test at Edwards AFB. The latter involved experience with one aircraft and two different engines. Although it might be considered that the EMS had been sufficiently exposed to an operational environment, with over 200 flights accumulated, initial service experience was to suggest otherwise.

Ramstein AB in West Germany was the first operational base for the F110-GE-100 powered F-16 aircraft. After some early flight experience it became evident that the EMS was producing far more unjustified fault messages (known as false alarms) than had been expected. During the latter stages of flight test, a false alarm rate of approximately one per ten flights had been noted, whereas at Ramstein it was near one per three flights. Despite several significant successes the EMS performance was soon overshadowed by this false alarm rate and the reduction thereof became a top priority.

Several factors were soon identified as driving the false alarm rate and they are similar to other engine monitoring programs such as the F101. Most could be related to a "real world" environment versus a "test" environment as indicated below:

o Tolerances

Incorrect or insufficient range/tolerances existed in the EMS diagnostic routines to allow for engine-to-engine variations.

o Engine Operational Considerations

Certain engine transient operations or combinations of transients appeared during initial operations and requiring modifications to the diagnostic logic.

o Flight Envelope Considerations

Certain areas of the flight envelope (i.e., mach/altitude/engine power combinations) generated unexpected faults which also required logic modification. As with the previous category, these combinations are difficult to predict and there is probably no substitute for service experience.

EMS Component Performance:

Overall, EMS component performance has been satisfactory. Several minor problems have been experienced, however, together with a number of EMS interface related anomalies.

o Non-Volatile Memory Performance

Both the EMSP and the DDTU use Electrically Erasable Programmable Read Only Memory (EEPROM) as non-volatile storage medium and both have experienced some problems with these devices. Soft failures resulted in built-in-test (BIT) failure indications being output randomly.

o EMS Interface Anomalies

Failure to transfer data from the DDTU into the ground computer system has been experienced for two primary reasons. One involves a "time-out" by the sending device (DDTU) while the ground computer is attempting to write data to its hard disk. This has now been overcome by the introduction of a new computer and the creation of a RAM disk for initial data storage. The second problem is one of "corrupted" data being stored in the DDTU and then transfer to the ground computer being prevented. This "locks-up" the DDTU, which then requires special maintenance to resolve. This problem is to be addressed in a proposed update to the DDTU operating software.

Demonstrated EMS Benefits

Despite the above problems, significant benefits have been demonstrated.

o EMS/Aircraft Integration

By far the most significant EMS impact during this initial service period has been the improvements in single engine safety as a result of integrating the EMS diagnostics outputs into the F-16 aircraft fault reporting system. This is particularly true for the Pilot Fault List (PFL) function.

In late 1986 and early 1987 a number of problems related to the lubrication oil system were experienced. The availability of the engine PFL allowed the EMS to report these faults to the cockpit directly, thus providing the pilots with earlier warning of the problem, allowing extra time to react and take appropriate action. This integration feature will undoubtably continue to pay big dividends over the years.

o Line Replacement Unit (LRU) Fault Isolation

With the higher than expected false alarm rate output from the EMS, the correct fault annunciations have tended to become somewhat overshadowed. The EMS has, however, provided a correct diagnosis on many occasions. These have included, not only faults with electrical components, such as sensors, ignitors, engine controls, etc., but also mechanical components such as actuators and pumps. The diagnostic coverage of the system is biased towards the electrical components and the majority of the detected faults have been of that type. Additionally a number of faults have been correctly detected by the EMS, but incorrectly isolated due to limitations either in the diagnostics or in the available data to the diagnostics.

During this initial service period it is estimated that approximately 70% of all real faults detected were also correctly isolated to the proper LRU. Continued refinement to the diagnostics is expected to improve this figure to approximately 90%. It is to be noted also, that even with an incorrect LRU fault isolation, the faulty sub-system is identified and some reduction in maintenance man hours costs can still result.

o Engine Manufacturer Benefits

The data saved by the EMS has been of significant benefit to GE. It has aided in the identification and resolution of early service problems. Pilot initiated data has been used to refine the augmentor operability envelope and to aid in analysis of problems. Trend data is used to check overall engine health during acceptance flights at General Dynamics.

Additionally, because the EMS is on-board all F110-GE-100 powered aircraft, the capability is provided to compare any engine with others in the fleet.

Operation Summary

The F110-GE-100 EMS has had a mixed response during its initial service exposure. In general the pilot community like the system and recognizes its benefits to them. The maintenance community gave it a somewhat negative reception initially partly because it was new to them and partly due to the false alarms and the work impact on them in clearing the alarms. This attitude is changing with the introduction of improved EMS diagnostic software and ground processing software/hardware. The latest "block" release of EMSP/EMSC's is demonstrating a false alarm rate of 1 in 14 flights (previous version was 1 in 3). Also, some newly added diagnostic functions are already indicating their worth.

The EMS will continue to be matured by a combination of improving what is already in use (both hardware and software) and by adding new capabilities. Current activity at GE Aircraft Engines involves development of the next "block" of EMSP/EMSC software. The diagnostics improvements currently identified are hoped to reduce the false alarm rate to one in 200 flights, as well as improve the LRU isolation accuracy.

Additionally, several enhancements to the GE Aircraft Engines supplied EMS ground processing software are being evaluated together with improved methods of data retrieval, display and transfer.

LESSONS LEARNED

Single contractor responsibility, in the case of the F110-GE-100/F-16, enabled the development of the EMS in a relatively short period of time (concept to flight test in 24 months). Additionally, system interface problems were minimized and problems that did arise were resolved quickly.

There is no substitute for operational experience. The majority of the false alarms generated upon initial service flying were identified within the first month or so and in general were not seen during flight test. A 3-6 month service evaluation period (utilizing several aircraft/engines) would have yielded significant benefits and should be considered for future systems (and system updates), prior to production introduction, if at all possible.

The benefits of aircraft integration, discussed earlier, make this area vital for future systems. The level of integration achieved on the F-16C/D and the B-1B reflects the importance General Dynamics and Rockwell attach to the integration of sub-system diagnostics.

It was recognized that because the F110-GE-100 EMS would still require some maturation after service introduction, a means of building some flexibility into the formal Organizational Level T.O.'s was necessary in order to overcome any system shortcomings. This flexibility was provided by the creation of an EMS Fault Isolation Manual (FIM). This document remains under GE control (allowing rapid revisions) for an agreed-to time period. At the end of this period it then becomes the basis for a formal T.O.

The availability of this manual has allowed the EMS to direct flightline maintenance whenever possible and provides a way to cope with false alarms and other system limitations. The "formal" use of the EMS at the flightline has provided significant visibility and thus impetus for the maturation process.

Much has already been learned from both programs with respect to the diagnostics design, the impact of false alarms and the techniques necessary to minimize them. Although some of this experience is unique to the engine application, a significant portion can be considered generic, and is being incorporated into future designs.

FUTURE SYSTEMS

The F101-GE-102/B-1B CITS described above was designed as a fully integrated system in that it is one sub-system sharing computer space and operating system software with other sub-systems. The sheer complexity of this task creates a certain inflexibility and inertia resulting in extended maturation of the system during service. On the other hand the F110-GE-100/F-16 EMS was designed as a stand-alone system with the capability of communication interaction, a form of integration, with the avionics system. In fact, much more integration has occurred than originally envisaged. Maintenance procedures for the F110-GE-100 engine are largely dependent upon the EMS thus providing impetus to fix any problems affecting aircraft availability. In future, it is believed that there will be increased reliance on engine monitoring systems and more integration with the aircraft resulting in more real time diagnostics and less raw data.

The F110-GE-100 EMS is the first production system to be integrated into an engine maintenance concept and largely drive the flightline maintenance effort. The lessons learned on this and the F101 program to date are already impacting GE Aircraft Engines' designs for future monitoring systems and have significantly increased awareness of the benefits of integrated diagnostics and engine monitoring as a whole.

Digital controls provide tremendous advantages to engine monitoring. There is more electronic information available in a form which can be rapidly utilized. Control schedules are self-adjusting closed-loop incorporating some form of engine model. Some degree of redundancy is included which makes many Line Replaceable Unit (LRU) defects more identifiable. Many functions which required a separate electronic unit can be performed within the control.

Future trends can be sub-divided into short and long term. In the short term, on-engine boxes such as the CITS Processor for the F101 and the EMSP for the F110, which provide signal verification, cycle counting, digitization and communication functions will become part of the control and thus be fully integrated. Data will continue to be transmitted over digital data bus links to off-engine computers for further analysis. Some parameters such as accelerometer vibration signals will continue to require an analog interface.

In the long term much of the event detection and fault isolation will be performed on-engine and only fault messages and small segments of relevant data will be sent to the aircraft for transmission to ground systems. Separation of software and the avoidance of throughput penalties in the control due to monitoring functions (e.g., vibration) continue to be of paramount importance and may dictate some degree of separate processors or even separate on-engine units. Most current monitoring systems have been added to the engine and/or aircraft at a later date. Future systems are addressing monitoring requirements at a conceptual stage and are basing instrumentation complement on requirements and Failure Modes Effects and Criticality Analysis (FMECA) both of which may demand that unique instrumentation is added to the engine.

Future integrated diagnostics must address all elements of a weapons system such as propulsion, support equipment, flight control, software, avionics, sensors and mechanical systems. A cost-effective approach must be utilized which improves diagnostic effectiveness, improves fault detection/fault isolation accuracy, reduces dependence on ground support equipment, reduces unscheduled maintenance and is designed in from inception. Future systems will present demanding electronic, mechanical systems and rotating machinery challenges. These can only be met by an integrated design approach which incorporates input from mechanical and aerodynamic designers, logistic support analysis, reliability and maintainability studies and include a high degree of coordination between engine manufacturer, airframe manufacturer and users.

REFERENCES

1. The F110 Engine Monitoring System. AIAA-84-2754

Ashby & Dyson

DISCUSSION

C.A. KIRK

With regard to the F101 engine monitoring sustem, could you elaborate on why three scans are taken at 30 second intervals when an event is detected?

Author's Reply:

The logic relating to event data storage was probably driven by airframe requirements. Since the central CITS airborne computer treats all CITS maintenance codes the same way, the engine data is treated similarly.

I should stress that this is not an ideal situation and if we had to design this system to-day we would hope to influence data retention more along the lines of the F110-GE-100 EMS.

G. TANNER

Will there be a conflict in criticality when integrating engine monitoring functions into the control system?

Author's Reply:

We are adopting an integrated but separate approach. A "CPU" is dedicated to engine monitoring within the same box as the control.

COMMERCIAL ENGINE MONITORING STATUS AT GE AIRCRAFT ENGINES CINCINNATI, OHIO

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SUMMARY

This paper describes the design, introduction and development of expanded commercial engine monitoring systems by GE Aircraft Engines. The history of present systems is outlined starting from the introduction on the CF6-80A3 engine for the A310 aircraft of the Propulsion Multiplexer (PMUX) which has led to similar systems on the CF6-80C2 engine. The impact of the full authority digital control on future system is also discussed.

The introduction and application of the Ground-based Engine Monitoring (GEM) software developed by GE in conjunction with several airline users is recounted. This is an on-going team effort with the users playing a key role and where individual airlines have added unique features, integrated with GEM, into their own operations. The original software development occurred in parallel with the expanded sensor complement and digitization of data. A description of the functions of a typical ground software program is provided together with proposed improvements and future directions.

INTRODUCTION

The introduction of "on condition" maintenance concepts for high bypass turbofan engines encouraged the use of advanced engine monitoring techniques. Although GE had participated in several monitoring programs to support the CF6-6 and CF6-50, the CF6-80A3 engine on the A310-200 aircraft for KLM and Lufthansa Airlines was the first to be equipped with expanded capabilities. These capabilities included sufficient instrumentation for modular performance assessments, an expanded aircraft data system and an analytical ground software program.

Many airlines have in fact utilized engine monitoring techniques for a number of years, driven by the introduction of "on-condition" concepts in the late 1960's. Initially, expanded instrumentation complements resulted in widespread systems problems, many associated with the transmittal of analog signals over long distances in aircraft. The introduction of the PMUX on the CF6-80A3 engine, with the associated transmittal of highly accurate, reliable digital data, was a key factor in making the expanded engine monitoring approach work. The functions of the PMUX are now being incorporated into the new generation of full authority digital electronic controls with resultant reduction of unique monitoring hardware and software, yet with a further expansion of capabilities.

The ground-based engine condition monitoring (GEM) software for many GE and CFM International powered aircraft is described. This GEM system provides the capability to monitor and analyze a wide range of engine thermodynamic and mechanical measurements with a single, flexible computer program.

Measurements acquired with the standard engine instrumentation as well as extended monitoring instrumentation if available, are recorded during normal engine operation. These data are generally stored for subsequent retrieval using an on-board data acquisition system. The data recorded during flight, along with test cell performance measurements, are input into the airline's computer system for ground-based processing with the GEM system. The results from the GEM processing are made available to various airline organizations in order to monitor and manage the engines within their fleet.

The GEM monitoring system is designed to provide an airline with a valuable tool with which to manage its aircraft engines relative to such concerns as safety, availability, maintainability, fuel costs, and improved performance.

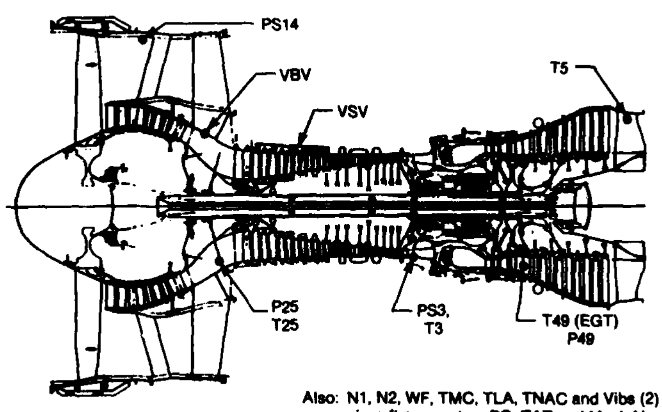
Directions for the future show that some of the functions which are presently performed on the ground will be performed airborne where useful to flightline operations. Airborne diagnostics will be enhanced and results, rather than raw data, will be transmitted across the avionics data bus thus making available to the line mechanic useable information for accomplishment of his maintenance tasks. The paper concludes with a discussion of these future plans for commercial engine monitoring and current operational experience.

SYSTEM DESCRIPTION

On-Engine Hardware

The PMUX was developed to provide consistent, accurate data suitable for gas path analysis or modular fault isolation. It is a convection-cooled, microprocessor-based unit which houses pressure transducers, signal conditioning and analog to digital conversion. It has extensive built-in-test and signal validity checks. All of the signals critical to the gas path analysis/modular fault isolation function are routed through the PMUX to maintain consistent, accurate data, other than N1, TMC and TLA, which are processed by the Power Management Control (PMC) and made available on the digital data link.

CF6-80 Condition Monitoring Parameters



Also: N1, N2, WF, TMC, TLA, TNAC and Vibs (2) plus aircraft parameters PO, TAT and Mach No.

Figure 1

The instrumentation complement for the CF6-80A3 engine is shown in Figure No. 1. Instrumentation for the CF6-80C2 is essentially the same. These sensors can be sub-divided into the following categories:

A. Signals required for indication/control purposes and routed through the Propulsion Multiplexer (PMUX) or Power Management Control (PMC):
   - Fan Speed (N1)
   - Core speed (N2)
   - Throttle Lever Angle (TLA)
   - Fuel Flow (WF)
   - Main Fuel Flow Torque Motor Current (TMC)
   - LP Turbine Inlet Temperature (T49)

B. Additional signals required for Engine Monitoring which are routed through the PMUX:
   - Fan Discharge Static Pressure (PS14)
   - Compressor Inlet Pressure (P25)
   - Compressor Inlet Temperature (T25)
   - Compressor Discharge Static Pressure (PS3)
   - Compressor Discharge Temperature (T3)
   - LP Turbine Inlet Pressure (P49)
   - LP Turbine Discharge Temperature (T5)
   - Variable Bypass Valve Position (VBV)
   - Variable Stator Vane Position (VSV)

C. Additional signals required for Engine Monitoring but not routed through the PMUX or PMC:
   - #1 Bearing (Fan) Internal Accelerometer
   - Alternate Fan Frame External Accelerometer (Optional)
   - Compressor Rear Frame External Accelerometer
   - Nacelle (core compartment) Temperature (TNAC)

D. Aircraft parameters required for engine monitoring (not including anti-ice and bleed discretes):
   - Pressure Altitude (PO)
   - Total Air Temperature (TAT)
   - Aircraft Mach No. (MN)
   - Other instrumentation available as part of the inflight data record consisting of oil temperature, oil pressure and oil quantity.

The interfaces with the PMUX and PMC are shown in Figure No. 2.

CF6-80C Fan Compartment Interface Wiring and Connector Schematic

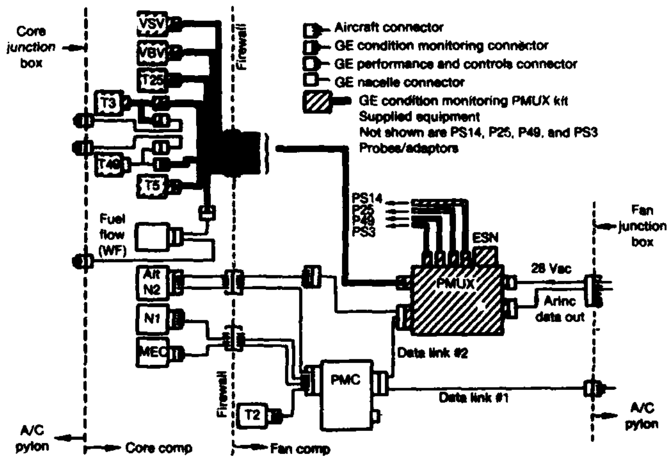


Figure 2

The PMUX is mounted on the engine fan case. Electrical leads are combined in a harness and routed from the core to the fan compartment and to the PMUX. The pressure sensors (sources) are connected by tubing to the pressure transducers which are contained within the PMUX unit. In addition a raw N2 (core) signal is routed to the PMUX and an ARINC data link connects the PMC to the PMUX. Thus, the PMUX accepts analog and digital inputs from various added and existing engine sensors. These inputs are conditioned, multiplexed, and converted to digital format (ARINC 429) for output to the Aircraft Integrated Monitoring System (AIMS).

In addition, an encoded Engine Serial Number plug (ESN), lanyarded to the fan case, interfaces with the PMUX and provides the means for "Tagging" acquired data with the appropriate engine serial number.

A more detailed description of the hardware is contained in Ref. 1.

Instrumentation for the Full Authority Digital Controlled (FADEC) CF6-80C2B 1F/DIF and CFM56-5 is similar to that described above, but the system no longer requires a separate PMUX. The functions of the PMUX are contained within the FADEC which provides the signal conditioning and the digital interface with the aircraft. The parameters which required an analogue interface (e.g. vibration) still require that interface in this first generation of FADEC controlled engines. It is anticipated that future applications, such as the GE36 engine for the UDF™, will possess a purely digital link with the aircraft. (See Figure No. 3). The majority of the engine monitoring, fault isolation and detection will be performed on engine. Space and flexibility considerations are presently dictating that there be two on-engine boxes, one for control and flight critical purposes and the other for engine monitoring.

Option for Proposed Advanced System

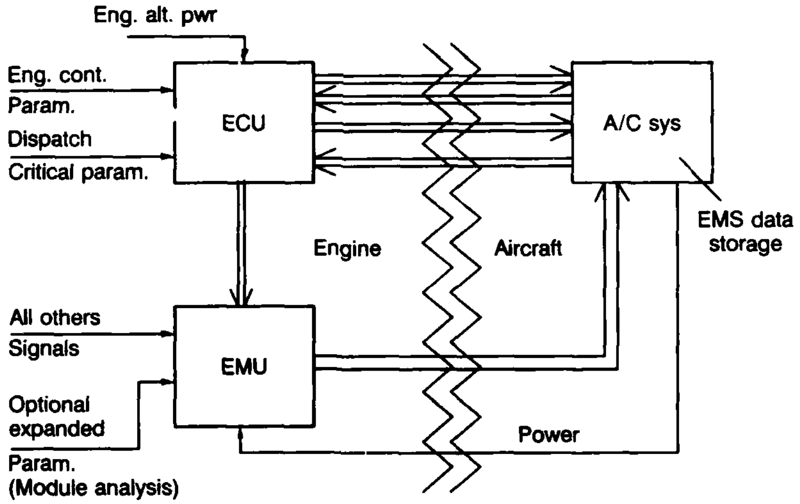


Figure 3

Ground-Based Engine Monitoring

The flow of engine monitoring data is shown in Figure No. 4. The Ground-based Engine Monitoring (GEM) system provides the capability of handling a wide range of engine thermodynamic and mechanical functions (see Figure No 5) within a single very flexible program. The software was developed as a co-operative effort involving GE and a group of airlines (originally KLM, Lufthansa and SAS). The resulting design is shown in Figure No. 6.

Schematic of Engine Monitoring Information Flow

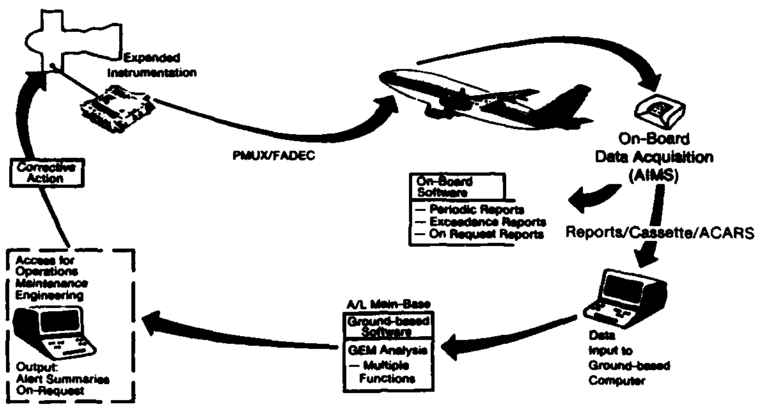


Figure 4

Ground-based Engine Monitoring System Analysis Functions

Function	Purpose
On-wing temper*	Analyze cruise gas path data to determine overall engine and module health
Test cell temper*	Analyze acceptance test gas path data to determine overall engine and module health
Takeoff margin assessment	Analyze takeoff data to determine the EGT margin of the engine
Control schedule analysis	Compare measured control variables to nominal schedules and limits
Vibration trend analysis	Compare measured vibrations to limits to identify potential imbalances
Fan rotor imbalance	Use measured fan vibration amplitude and phase angle to determine balance weights to correct fan imbalance
Fleet average	Compute fleet statistics for engine family and identify low performing engines

*For turbine engine module performance estimation routine

Figure 5

GEM Software System Architecture

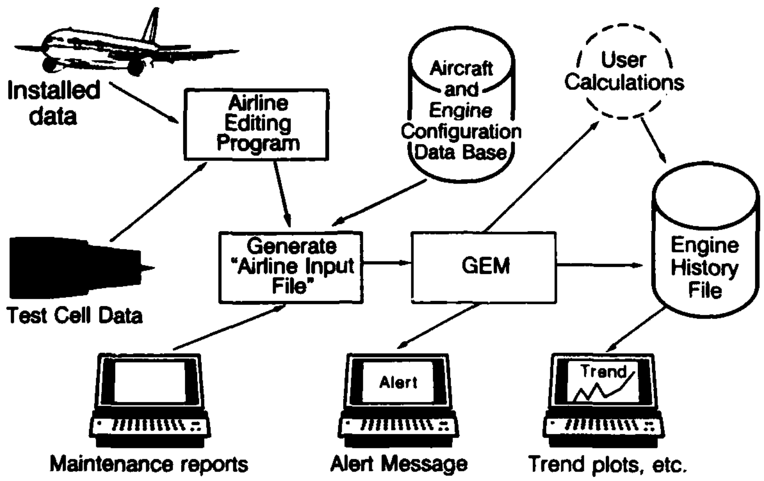


Figure 6

The GEM program monitors and analyzes performance trends, take-off margin, control schedules, vibration trends and fan rotor imbalances. In addition, it incorporates the Turbine Engine Module Performance Estimation Routine (TEMPER), a program used to diagnose engine modular performance in airline test cells. GEM extends the TEMPER program to the analysis of installed cruise data in order to provide modular performance estimates and trends.

The GEM system started as a GE/Airline team effort for the CF6-80A3 engine on the Airbus A310-200 aircraft. GE Aircraft Engines, KLM, Lufthansa and SAS, along with Airbus Industrie, worked together to define, develop, implement and refine this extensive monitoring system. CFM International and other airlines using GEM have joined this effort during recent years. GE's participation has included the development of the GEM nucleus of analytical functions, within a mutually agreed software structure, to manage the data flow. A general architecture for GEM is shown in Figure No. 7. On the airline side, each user has developed individual

GEM Software Architecture

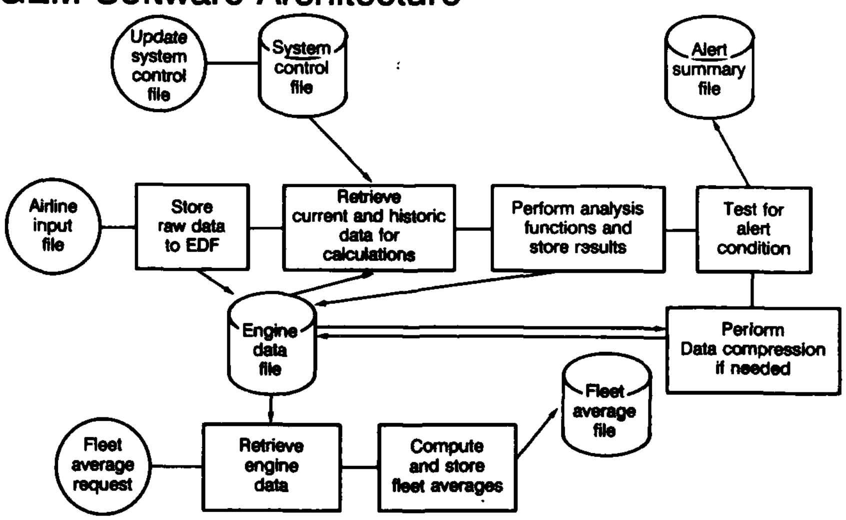


Figure 7

software to pre-process the engine data and has defined output display formats in a manner compatible with their own operation. Further, they have contributed to the overall design and implementation of the system. A description of implementation of GEM monitoring at KLM and Lufthansa can be found in Ref. 2 and Ref. 3.

As the GEM program has been implemented the airlines have started to rely on alert summary reports to monitor the engine trends for their fleets instead of daily examination of individual trend charts. The engine trend analyst at each airline interrogates the alert summaries and can obtain supplemental information using a menu of available plots in order to investigate any particular alert. Generally, previous trends for the engine are retrieved from the airline's history files, which might include codes indicating maintenance performed on the engine. Based on this examination, the analyst will recommend appropriate actions. Efforts continue to fine-tune the trend recognition routine in order to reduce some of the unnecessary alerts.

Another significant advance is the use of cruise acquired vibration data to perform fan trim balances without expensive ground runs. Lufthansa has successfully used this procedure to balance their CF6-80A3 fans to keep fan vibrations well below limits using an auxiliary PC program which they developed and which will be incorporated in GEM at a later date. The benefit to Lufthansa, in addition to the avoidance of ground runs, is extended life for accessories and parts (such as brackets) which are affected by high vibration. In this system, both fan vibration amplitude and unbalance phase angle are acquired during cruise. Back on the ground, these data are used to project appropriate weight changes; these are done by changing the configuration of the balance bolts. When fan vibration trends increase, the airline can make corrections based on cruise data alone, without extensive (and expensive) ground operation. Similarly, engine control parameters -- Variable Stator Vane (VSV) setting, Variable Bypass Valve (VBV) position, and torque motor current -- are monitored to promote maximum fuel efficiency.

Some Airlines have added a number of features to integrate the GEM system with their own operations. These include features to process, store and present GEM data automatically. KLM retrieves data from their on-board system using cassette tapes containing data sampled throughout the flight from which readings are selected for batch GEM processing. Lufthansa, on the other hand, uses optical scanners to read data from its on-board system's printed reports; these are then loaded into the main computer via their worldwide reservation system. Lufthansa has thus developed a virtual real-time system in which GEM results are available to their analyst within a few hours of the airplane's landing. These GEM results are also available to GE via a direct data link, provided by Lufthansa, between the GE Product Support Center in Cincinnati and Frankfurt, Germany.

GEM was originally designed for the CF6-80A3 in the A310-200 application but it has been expanded over a period of years to incorporate various GE/CFMI engines and applications, the latest of which is the CFM56-5 in the A320 (see Figure No. 8). The prime purpose of the latest software release is to include this first FADEC controlled engine as part of what is now known as "universal" GEM. Instrumentation limitations on certain engines do not allow for the implementation of all analytical functions to all engines. The functions available by engine model are shown in Figure No. 9.

OPERATIONAL EXPERIENCE

Considerable operational experience has been obtained from the CF6-80A3 engine. This experience is now being extended with the CF6-80 and CFM56 families of engines. A number of problems have occurred all of which have been addressed in latest releases.

- o Pressure transducers were affected by service generated contamination and moisture. Design changes to the transducer and pressure tubes were required in order to overcome the problem.

Latest GEM Engine/Aircraft Applications

	A300 -200	A300 -600	A310 -200	A320	B737 -300	B747 -200	B747 -300	B767 -300	DC-10 -30	A310 -300
CF6-80A3			X							
CF6-80C2		X	X				X	X		X
CF6-50C/C+	X								X	
CF6-50C2	X								X	
CF6-50E2						X	X			
CFM56-3					X					
CFM56-5				X						

Figure 8

Universal GEM Analytical Monitoring Functions

Analytical function	CF6-80A3	CF6-80C2	CF6-50C	CF6-50C2/E2	CFM56-3	CFM56-5
A) On wing performance analysis (1)	Yes	Yes	Yes	Yes	Yes (3)	Yes (3)
B) Test cell performance analysis	Yes	Yes	Yes	Yes	Yes	No
C) T/O EGT margin/ SLOATL (2)	Yes	Yes	Yes	Yes	Yes	Yes
D) SLOATL with cruise update	Yes	Yes	Yes	Yes	Yes	Yes
E) Engine controls (2)	Yes	Yes	N/A	N/A	N/A	N/A
F) Vibration trending (2)	Yes	Yes	Yes	Yes	Yes (4)	Yes
G) Fan rotor imbalance (2)	Yes	Yes (5)	N/A	N/A	No	No
H) Reduced fan speed summary	No	No	Yes	Yes	No	No
I) Oil monitoring (AIMS)	Yes	Yes	Yes	Yes	Yes	Yes
J) Limit exceedance	Yes	Yes	Yes	Yes	Yes	Yes
K) Trend recognition	Yes	Yes	Yes	Yes	Yes	Yes
L) Miscellaneous alerts (2)	Yes	Yes	Yes	Yes	Yes	Yes
M) Fleet average	Yes	Yes	Yes	Yes	Yes	Yes
N) Simulation	Yes	Yes	Yes	Yes	Yes (6)	No
O) Nacelle temperature	Yes	No	No	No	No	No

N/A Not applicable
(1) Instrumentation configuration limits level of module analysis
(2) On-wing only
(3) Trending capability (no module analysis)
(4) Two of four possible vibration signals
(5) Vibration amplitude and phasing characteristics not established
(6) Test cell only

Figure 9

- Low input impedance cockpit instrumentation affected the shared EGT signal.
- Incompatibilities were generated due to late and seemingly insignificant design changes between the LVDT sensor and the PMUX which provides excitation and signal conditioning.
- Initial software trend shift recognition and alerting features produced an unacceptable number of false or unnecessary warnings to the airline analysts. These continue to be refined based on operating experience.
- Initial cruise trends exhibited an unacceptable amount of scatter. Replacement cruise reference baselines were required which better matched the engine operating characteristics in revenue service.

Lufthansa are reporting quantifiable savings through diligent use of the system. It is reported that early failure detection, reduction in the number of line station removals, optimum scheduling, "cold" fan trim balancing and improved engine/module management are providing reductions in material, manpower, maintenance, fuel and overhaul repair costs. Other non-quantifiable benefits are also reported such as reduced out-of-service time, reduced secondary damage, improved flight safety standards, improved troubleshooting and the ability to handle large fleets.

A number of recommendations can be made in terms of general monitoring system activity:

Hardware:

- The engine monitoring program should be established up front. Design of auxiliary systems subsequent to design of the basic engine and configuration hardware adds expense and "less than best" compromises.
- The engine monitoring system, including the off-engine software, should be approached just like any other engine sub-system. It should be included on all factory and flight test engines and certified like any other engine sub-system.
- A thorough analysis of electrical characteristics both between components within the system and between the various interfacing aircraft systems is essential. Certain sensors and instruments are sometimes derivatives from earlier systems and are included to maintain commonality of hardware. Their operation in the new system can prove to be incompatible. Use of cockpit instrumentation with low input impedance characteristics must be avoided.

Software:

- Sufficient time must be provided to develop and check out such a software system between the definition of the specification requirements and the implementation in a production environment.
- Development of a new software system concept will benefit from initial prototype application to gain operating experience which can be used to finalize the software design.
- A design/development team with strong airline participation can address the real operating conditions and requirements for the monitoring system. The system's value will thereby be greatly enhanced.
- Too much initial flexibility and optional operating modes slows down development and can overwhelm new users.
- Standard and rigid interfaces are required for the software system.
- It must be possible to refine the system as operation experience dictates.

FUTURE

Military and commercial operators have traditionally taken different approaches to engine monitoring. The airlines have historically been interested in performance monitoring. They ask, "Is the engine performance trend changing, and if so, what maintenance will we need to schedule?" The military, on the other hand, has been more interested in Line Replaceable Units, fault isolation and engine go/no-go decision-making using existing indication and control parameters. They ask "Is the engine available and will it complete a mission; if not, what do we have to do to fix it?"

Today's monitoring systems have improved to the point where both groups are finding them cost-efficient and effective. As with many good things, success does not come without a major contribution from the users themselves. Today GE's customers know what they want and why they want it. They are prepared to dedicate personnel who will understand, maintain, and utilize the system.

In the future, analysis of on-wing modular performance promises to better manage engine maintenance. Some organizations envision the time when shop refurbishment workscopes might be largely defined prior to engine removal based on the assessment of modular performance changes. This would be far more efficient than the "once-we-get-it-apart-we'll-know-what-we- have-to-do" method of engine analysis. Future airline plans might include the reduction or avoidance of test cell acceptance runs, refined cycle counting, APU health monitoring and improved integrated aircraft performance monitoring.

The success of the A310/CF6-80A3 GEM system has led to expansion of the monitoring capabilities to other applications. Universal GEM includes monitoring capabilities for the CF6-80C2, CF6-50, CFM56-3 and CFM56-5 in addition to the CF6-80A3. It provides a single monitoring system to use with all the CF6 and CFMI engine models. Refinement of the monitoring software continues based on airline operational experience. Use of GEM has been restricted to a limited but expanding number of airlines during this development period. At the beginning of 1988, GEM is operational at Air Frame, KLM, Lufthansa and SAS with efforts underway to install the system at Air Inter, Air Portugal (TAP), Quantas and Thai International later in the year.

Engine monitoring systems are coming of age. Recent advances have included:

- o Development of miniaturized electronics which can exist in a harsh environment.
- o Introduction of digital controls on an increasing number of engines such as the CFM56-5 and CF6-80C2. Digital controls reduce the need for unique monitoring instrumentation, provide highly accurate, reliable digital data and perform improved fault isolation.
- o Development of software analysis techniques and availability of computer facilities to guide troubleshooting, maintenance, logistic support and planning.

Military and commercial philosophies will come together in the next generation of advanced engines which will incorporate performance monitoring, modular health analysis, Line Replaceable Unit fault isolation, vibration monitoring, fan trim balance and control system programs. Such systems can reduce ground support, make the engine easier to support, track warranty provisions, control, and reduce the cost of ownership for all users.

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DISCUSSION

H.J. LICHTFUSS

You have mentioned many airlines which are using your system and others which are interested. But all these airlines are European. Why are the US airlines not interested in this system?

Author's Reply:

The observation is correct that only European airlines are currently using GE Aircraft Engine's expanded monitoring capabilities. Additional European, Asian and Australian operators are implementing the expanded monitoring capability.

On the other hand, the US airlines use "basic" engine trending procedures. It is important that individual airlines select approaches to monitoring which are consistent with their own engine maintenance practices. Additional airline resources are required in order to introduce and maintain the extended monitoring capabilities.

M.J. SAPSARD

1. What differences, if any, have you found between instrumentation requirements for performance and control?
2. What "snapshot" length do you use for the three windows you describe?
3. Can you correlate the data collected during the cruise, the take-off and testcell conditions?
4. What is your diagnosis success rate, are there modules particularly difficult to diagnose?
5. Is your system a ground based system which can accept data from any EMU supplier, rather than a combined airborne/ground system?

Author's Reply:

1. In the current systems providing expanded measurments for monitoring, PMUX and additional sensors were designed to yield accurate, reliable and repeatable data for monitoring. Similar sensors are included in the new digital engine controls (FADEC) which provide suitable signals for monitoring.
2. The onboard DMU's (data management units) have been programmed with different criteria used to acquire appropriate T/O readings and stable cruise measurements. The T/O readings are taken over a relatively short period of time due to the transient conditions. These are generally triggered to provide consistent conditions near the maximum EGT. At cruise conditions, the consistent data quality is sought by establishing a criteria requiring stable engine and aircraft cruise data at the airline's desired frequency. Thus an overly restrictive selection criteria might result in insufficient monitoring data, while wider tolerance bands or shorter time frames might produce inacceptable data scatter.
3. Monitoring data collected at various operating conditions (cruise, takeoff and testcell) generally are not correlated in the current version of the GEM software. However there is a GEM feature which produces estimates of T/O EGT margin (or outside air t° limit - OATL) based on changes in EGT trends.
4. The GEM modular analysis routine is designed to statistically provide the most probable assessement of engine health based on measurements of the expanded instrumentation. Our experience has been that deviations in the performance of the high pressure components can be detected more readily than the separation of the low pressure component deviations between the fan and low pressure turbine.

5. The data input to the GEM program is required to be in a specific format that was mutually agreed upon by GE and the participating airlines. GEM is not linked with any particular acquisition system. It is assumed, however, that the input measurements have been accurately acquired under appropriate conditions.

THE ADVANTAGE OF A THRUST RATING CONCEPT USED ON THE RB199 ENGINE

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SUMMARY

The control system of the RB199 engine was designed for a rating, using the HP-turbine inlet temperature as a limiter. The engine has now been in service for seven years and still uses the original concept throughout all fleets in United Kingdom, Italy and Germany, although new digital engine control units are being introduced which will allow considerable improvements.

For some fleets a thrust rating concept based on the original control system design has been installed recently. In this paper the concept is described and the procedure explained. A comparison is made between the existing full thrust concept at the maximum cleared HP turbine temperature and the applied thrust rating concept. Besides the basic behaviour of seal gaps, the influence of thrust rating in view of the life usage of life-limited parts as well as in the change of the maintenance material costs is explained. The assumptions for the comparison with their backround are decribed. Finally, a refined thrust rating concept is introduced. This concept is based on the existing turbine blade temperature schedule but trimmed so that with the existing DECU, an automatic thrust compensation setting for engine deterioration and varying ambient temperatures is possible for take-off and in-flight conditions. The basic assumptions for the refined system are explained and the fundamental control laws for verification are described.

SYMBOLS

DECU	Digital engine control unit
DF	Deterioration factor
EFH	Engine flying hours
F	Engine thrust
FAR	Fuel air ratio
LCF	Low cycle fatigue
M_{FM}	Fuel flow, main engine
M_{FR}	Fuel flow, reheat
MECU	Main engine control unit (analog system)
MMC	Maintenance material costs
NL	Low-pressure spool speed
NI	Intermediate-pressure spool speed
NH	High-pressure spool speed
OLMOS	On-board life consumption monitoring system
Pso/Tso	Static atmospheric pressure/temperature
Pto	Total ram pressure
PLA	Pilot's lever angle
Tt1	Total temperature at engine inlet
TBT	Turbine blade temperature (IP turbine)
R/H	Reheat
SOT	HP-turbine stator outlet temperature

INTRODUCTION

The owner of a fighter fleet demands that the thrust offer of the engine, the flight readiness, and the cost of ownership are well balanced and optimized for the individual mission requirements. The thrust setting influences these parameters considerably.

The customer may decide to run engines over their lifetime to full available thrust (i.e. constant cleared SOT) in order to fulfil specific mission requirements. The thrust rating concept however best fulfils the demands for easier mission planning and better flight readiness at lower cost of ownership.

The RB199 engine and its control system has been designed for a limiting HP turbine stator outlet temperature rating. This concept was maintained thoughout the whole development programme and in the production phase. Although nowadays fleets in the United Kingdom and West Germany are being equipped with digital engine control units the basic control laws of the main engine control unit (analog system) have been maintained for simularity and interchangeability reasons.

With a careful choice of suitable existing engine parameters and the definition of a manageable procedure however a thrust rating concept has been established, which is now in use at several wings.

In this paper the applied thrust rating procedure and its benefits are explained. With the use of a DECU with its flexibility and capacity a refined thrust rating and automatic setting procedure can be introduced, which maintains the specific RB199 control parameters but ensures a constant thrust offer for take off and in flight, which in turn influences mission planning and flying beneficially.

The RB199 ENGINE (Fig. 1)

The RB199 engine is a three-spool, turbofan with an afterburner and is of modular construction. The bypass ratio is $\sim$1.2. The engine delivers more than 70% of reheat boost and is cleared for more than 1600 K stator outlet temperature at combat conditions.

The engine was initially designed in the late sixties, but has been repeatedly uprated in order to meet changing performance requirements because of higher aircraft weight and changed mission demands. The engine is being developed from the existing 70 kN combat thrust level and is approaching the 80 kN class, where requirements such as a specifically high DRY rating at certain flight conditions with thrust increases of more than 25% can be offered.

The main features of the uprated versions are

- Redesigned upflowed LP/HP compressors and HP/IP turbines
- Use of single-crystal HP/IP turbine blades
- Brush seals
- Digital engine control unit
- Extended jet pipe for improved reheat boost (optional)

None of these features with the exception of the DECU's and the extended jet pipe for some wings are actually in service yet. Consequently the considerations in this paper exclude the engines with the later features but concentrate on the existing engine fleet which since 1980 has accumulated more than 700,000 engine flying hours. For example the life factor of turbine blades relates exclusively to equiaxed high-temperature-resistant alloy.

The basic control system concept is shown in Fig. 2. The dual-lane control system is characterized by linear control of the high-pressure spool speed i.e. a pilot's lever angle conforms to a high-pressure spool speed. Besides several limiters, such as N_L, $N_L/\sqrt{\theta}$ and N_H the IP turbine blade temperature is used to control the HP turbine stator outlet temperature limit.

In the normal usage range the maximum SOT is limited by two independent and individually set IP turbine blade temperatures which are measured by optical pyrometers and processed in separate amplifiers and separate channels in the MECU for the maximum fuel flow limitation.

The TBT is scheduled over T_{t1} as shown in Fig. 3. The slopes are designed so as to

- give a SOT increase over T_{t1} as required for the mission (L/H slope) in view of thrust
- give an absolute temperature limit to avoid extreme life usage or overheating
- restore SOT with falling P_{to} (L/H, upper region of the flight envelope)
- on combat selection, raise the TBT by a ΔTBT combat to gain max. thrust conditions

The limiting parameter at normal conditions is therefore always the SOT over the TBT as the control parameter.

The TBT can be measured relatively close to the combustion chamber as the pyrometer can be installed outside the main gas stream in the turbine casing. The TBT as a control parameter measured by a pyrometer ensures a quick response and avoids detrimental overswings during engine transient conditions. This is not only advantageous in view of life usage of turbine and LCF parts due to temperature and speed peak suppressions, but also ensures more stable control parameters for the reheat nozzle area and the fuel flow during accelerations to reheat conditions, which is required especially during the ignition phase. Special care had to be taken in order to avoid excessive sooting of the pyrometer lens, which occurred in the early phase. With the present configuration, slight lens sooting still occurs but its influence on the TBT readings is known and severe interference to the TBT control concept can be avoided by corrective maintenance.

The basic engine rating concept is a constant temperature limiting concept with a decreasing thrust over time depending an engine deterioration. Fig. 4 shows the fundamental dependence between HP turbine temperature, thrust, N_L and N_H speeds over time when the engine is set at constant SOT. The basic deterioration curve is characterized by a slope, which initially has a steeper gradient but flattens at longer running times. The degradation in the first period is the result of blade tip and labyrinth seal wear caused by thermal expansion and dynamic deflection of rotors and structural parts under manoeuvre loads. These effects diminish after the 'rub-in period'. At longer running times, a small but normally constant degradation process follows, which results generally from

a) Erosion of seal coatings, resulting in diminished efficieny of the seals

b) Higher roughnesses on gas-washed parts caused by foreign particles in the air and/or attack by constituents such as sulphur, vanadium and chlorides.

c) Compressor blade fouling

Bearing these basic relationships in mind, it has to be ensured that the actual thrust in flight is always above the minimum acceptable level. Performance checks are therefore carried out periodically to ensure that the thrust requirements are met and that the temperature (TBT) limit is set correctly. Between these checks the engine health is monitored by pre-flight 'placard checks' at which the N_H has to be within a set placard tolerance.

The performance check is carried out on the basis of correlation curves as shown in Fig. 5. The basis for the check of the dry performance is the N_L/F relationship and its dependency on T_{t1}. Using these parameters for individual engines, the accuracy of thrust setting is within 1% initially and does not exceed 1.5% at high flying hours. The N_L over T_{t1} line in Fig. 5b decribes the N_L for a constant SOT setting i.e. it gives a varying thrust over T_{t1}. With the deteriorating engine the SOT limit shifts the N_L line downwards where it crosses the N_L minimum acceptance line, which represents the minimum acceptable thrust of the engine. The reject limit needs to be defined correspondingly.

For the reheated engine the fuelling (FAR) of the reheat burners is scheduled over the nozzle area such that the required fan working line is achieved. For a fleet of engines such as the RB199 which is in service since seven years (stabilized conditions), the reheat thrust over the dry thrust can be expressed accurately over the reheat fuel/air ratio (see Fig. 5c).

In fact, the flight personnel use tables and formulae for the execution of the performance checks and settings.

THRUST RATING CONCEPT

With the given control system concept an entirely nominal thrust rating (Fig. 6) cannot be verified, but a good approximation is possible.

Subject to the performance checks being satisfactory, a lower setting based on the deterioration curve (Fig. 4) plus resetting in the field at appropriate intervals leads to the conditions shown in Fig. 7. The intervals in this stepped deterioration curve need to be defined so as to achieve a maximum in SOT saving at a minimum of setting effort. The temperature savings over time indicate the potential life usage reduction.

The actual setting and check procedures for the dry and reheated engine are executed as described and shown in Fig. 5a and 5c. But in this case the determining setting value is not the SOT, but the minimum acceptable thrust plus an increment for the setting tolerance and for the expected deterioration over time until the next setting and performance check. Fig. 8 shows the limiting N_L versus T_{t1} for this procedure. For the deteriorating engine the SOT limit correlated over a N_L line cuts in the higher ambient temperature region first. The reject level is met when the minimum acceptable thrust is no longer achieved at the given day ambient temperature. The first resetting of a new engine after 50 hrs would be beneficial, but for the sake of a procedure common to all engines in service, resetting is carried out in 100 hrs intervals only throughout the life of the engine. The performance check and resetting are presently carried out as a scheduled maintenance activity.

The effect of the thrust rating compared with a temperature rating in view of seal gaps, low cycle fatigue and hot gas path parts and their influence on maintenance material costs is explained below.

SEAL GAP BEHAVIOUR

The experience shows that the slope of the deterioration curve (Fig. 4) is nearly independent of the level of thrust the engine is set initially. Thrust rating an engine reduces the wear on blade tip and labyrinth seals which contributes to the overall benefit. The lesser wear in the initial phase achieved by thrust rating thus gives a greater SOT reduction, which in turn increases the improvement in life.

In the following, the technical backround and the magnitude of benefit are illustrated by way of an example.

Fig. 9a shows the arrangement of the main air seal of the engine behind the HP compressor, which is a four-fin labyrinth-type seal with a pre-profiled static member. Fig. 9b shows the relative movement of one seal fin against the static member during acceleration, deceleration and at steady state running. The diagram shows that the rotating and static members could not be perfectly matched in their time-dependent movements. During acceleration the seal opens temporarily. On deceleration however the seal rubs in, which determines the permanent seal gap at steady state running.

Thrust rating of the engine reduces the centrifugal force and thermal expansion especially during the early running period due to the lower speeds and temperatures. A comparable situation indicates the dotted line of Fig. 9b. The lesser rub of the seal on an deceleration results in a steady state seal gap reduction. As Fig. 7 illustrates the benefit on temperature is diminishing over time but the speeds of the thrust rated engine do never achieve the absolute level of a fully rated new engine.

The effect on the smaller tip seal gaps of the total engine is worth 0,3 - 0,5% in thrust. As the thrust rated engine is set to a thrust figure the benefit appears as a SOT saving. (Note: What here appears as an advantage has a detrimental effect in cases where an engine uprating is by over temperature increases. The bigger seal wears have to be taken into account!)

INFLUENCE ON LIFED ITEMS

For life considerations the SOT setting is the determining parameter. A variety of settings is in use by the wings operating the RB199 engine depending on their thrust requirements.

The most significant are

- Setting to full cleared SOT over the lifetime and accepting a decreasing thrust according to engine deterioration
- Thrust rating as described above to different minimum acceptable thrust levels
- Derating the engine, for example, by a Δ SOT = 30K and keeping that SOT limit.

Derating an engine, for example, by 30K in SOT is a very good means of increasing the life of LCF controlled parts and hot gas path parts in particular, but the thrust-level must be adequate for the intended service use.

In the following, derating is ignored, only the thrust rating compared with the SOT rating concept is considered with regard to the influence on lifed items.

To enable the life benefits afforded by thrust rating to be quantified, comparable conditions need to be defined accurately. The principles underlying this paper are given in Fig. 10. The minimum acceptable thrust and maximum acceptable SOT are taken to be the same in both concepts. Whereas in the full SOT rating concept, such maintenance activities as compressor washing and module replacements, mainly because of

- life-limited parts
- defects
- performance loss

lead to restoration of the thrust level, such activities would result in a SOT reduction within the thrust rating concept (Fig. 10, bottom). The SOT reduction over the engine lifetime indicates the potential life saving.

EFFECT ON LCF LIFE

The basis for the design of RB199 LCF parts was missions defined by customers. According to the safe life concept, which clears life only up to a defined initial crack, the calculated life is confirmed by spin tests. Using sample parts from service, confirmatory spin tests are carried out to achieve and maintain full life clearance.

The calculated life usage based on the given missions is nowadays refined by life counting systems such as OLMOS, which are being introduced for TORNADOS in service with the German Air Force.

Fig. 11 shows an example of a mission plot. It can be seen that thrust rating results in the peaks being cut off. But there is another influence which has to be taken into account. With lower maximum thrust, the mission profile will change because for an acceleration from a certain flight condition to another, the lower thrust engine must run longer on maximum conditions, for example. A very detailed investigation would be required to quantify these influences. Whereas for 'cold' LCF parts, which depend only on centrifugal force and cycle, such changes have hardly any influence; with thermally-sensitive (i.e. 'hot') LCF parts, however, a longer soak period influences the life usage rate. An acceptable first approach however is a life calculation excluding the altered mission effect. The gain in LCF life can then be determined. It is 3 - 5% on 'cold' LCF parts, and 2.5% on 'hot' LCF parts on an average.

These life increases may not be economically usable in reality, because the various components of a module have different lives and consequently those parts with the shortest lives determine when parts have to be exchanged; meaning that the life of certain components may not be fully utilized. The usable life improvement depends very much on the basic lifes of the parts in comparison with the life of the engine. If the frequency of part exchanges in the life of the engine is not altered by the relatively small life increase quoted above, really nothing can be gained.

The introduction of a life-counting system such as OLMOS for the German wings will improve the determination of life usage drastically. It will indicate not only differences between the SOT and thrust rating, for example, but also the more significant effects of the different missions of all wings.

EFFECT ON HOT GAS PATH COMPONENTS

The hot gas path parts benefit directly from the lower temperature level, but also from the somewhat lower speeds. The life-usage reduction depends on the basic life of the parts, the deterioration slope of the engine (expressed by the gradient and in total), the failure mode of the relevant parts and the maintenance concept for the individual project. The RB199 utilizes the on-condition concept, i.e. there is no strict life limitation for the hot gas path parts. The condition of the parts is monitored and maintenance is carried out as required.

The gain in life is greatly influenced by the resetting interval. Fig. 12 shows the dependence of the life increase on the resetting interval, taking a HPT blade as an example. The figures are only valid for one engine standard or type with its specific deterioration rate and for one standard of blade with its specific failure mode. It shows the life improvement for the primary failure mode. The resetting interval of 100 hrs as applied in the German fleets for thrust-rated engines is a compromise between life benefit and maintenance effort. A considerable life potential could be utilized by shorter resetting intervals of 50 or 25 hours. As the gradient of the deterioration slope (Fig. 4) is steepest at the begin of service, shorter resetting intervals in this phase would have a significant effect. If the resetting intervals are normally 100 hrs, but if two 50 hrs resetting intervals are inserted after each maintenance activity the effect will be noticeable.

Fig. 12 was plotted using an average deterioration factor, defined as

$$DF = \frac{F_{in} - F_{300}}{F_{in}} \cdot 100 + 1 \quad (\%)$$

with

DF = deterioration factor (%)

F_{in} = thrust at start of service (kN)

F_{300} = thrust after 300 engine flying hours (kN)

The definition of the deterioration factor is based on the experience that after 300 hours the engine has achieved stable conditions and that the 1% allowance for further deterioration is on average adequate to cover the period up to the first maintenance activity.

Based on the assumptions described at the beginning of this chapter as well as on a resetting interval of 100 hrs throughout the life of the engine, the thrust rating concept results in life increases in the primary failure modes of the individual parts as follows:

Combustion chamber	6%	1)
HP turbine nozzle guide vanes	11%	1)
HP turbine rotor blade	18%	
IP turbine nozzle guide vanes	17%	1)
IP turbine blades	31%	
LP turbine blading	- %	2)

1) The life of the combustion chamber and HP/IP nozzle guide vanes is largely determined by the on-condition concept. These parts are most often not rejected because of having attained a primary failure mode life limit, but because of cracks, overheating, local burns etc., which do not allow the parts to be used for further service.

2) The LP turbine blade life is longer than the engine life, therefore there is no gain in the primary mode failure but only a saving in part-usage thanks to the reduction of secondary defects caused by the increased life of the parts of the preceding stages.

INFLUENCE ON COST OF OWNERSHIP

The total life cycle costs for a fighter engine are made up of

- Development and certification costs
- Production costs
- Operation and support costs

The influence of the changed life of the parts on the maintenance material costs which directly affect the operating and support costs, is illustrated below.

The maintenance material costs vary according to the project. They depend greatly on the production costs and the life of the parts. For a project like the RB199, the production costs are already established and therefore the biggest impact on the material costs can be gained by reducing the volume of the part requirements, i.e. by increasing the life of the individual parts.

Based on the life improvements gained by thrust rating, calculations were carried out for a fleet using engines at two different thrust levels

a) Using the max cleared SOT as a limit
b) Using a 30K lower SOT as a limit

Only the hot gas path parts are taken into account, since the LCF parts life increase does not have an impact for the reasons described above. The results are shown in Fig. 13. It can be clearly seen that the maintenance material cost reduction is highest at max SOT setting.

The absolute figures emphasize the significant influence on the cost of ownership. It is stressed again that the figures result from the comparison as described where the maximum SOT and the minimum acceptable thrust are the same in both methods, namely the constant SOT and the constant thrust rating concepts.

PROPOSAL FOR A REFINED CONCEPT FOR THE THRUST RATING

The introduction of the digital engine control unit means that a considerably improved and refined thrust-rating control concept can be employed without the need for hardware (instrumentation, control parameters) changes; only the DECU Software requires changing. Although the thrust can be described by different engine parameters such as HPC delivery pressure or turbine outlet pressure, which can be related to the nozzle pressure ratio, it is recommended to continue to use the well-proven N_L as the thrust parameter.

The basis of the proposed concept is

- To maintain the TBT control, which ensures quick and reliable readings and best represents the hot gas components life parameter (SOT)

- To use an individual $N_L = f\ (F)$ for engine deterioration compensation

- To schedule the TBT according to the in-flight requirements

- To trim the TBT for compensating the influence of ambient temperature on the thrust

According to the proposed concept

- On request the TBT is set automatically by a DECU logic on the ground to a value required to maintain constant thrust

- The TBT schedule is trimmed so as to maintain the required thrust over the Mach-number (within the flight envelope) irrespective of the ambient day temperature conditions. The required TBT trim is derived automatically and set in short intervals in flight by a DECU logic based on the comparison of the observed with the calculated ISA day engine inlet temperature.

- A fixed TBT 'tent' schedule as the final overall limiter ensures that the limiting SOT figures will not be exceeded.

Compared with the thrust rating procedure now in use, in the improved concept, the TBT it is set according to the deterioration level on request and there will be full day temperature compensation on thrust continuously on the ground and during flight.

Basically for the procedure, the thrust requirements on the ground and over the flight envelope at ISA conditions need to be defined and expressed in a TBT schedule. In this TBT schedule, the specific requirements of the aircraft user can be expressed as verified for the Tornado and shown in Fig. 3. The procedure is described in more detail on the basis of the TBT 'tent'-shaped schedule below. But fundamentally it can be applied to any schedule which has adequate distance to a limiting schedule, i.e. there has to be an adequate thrust margin for the concept for the specific application. A detailed feasibility study is therefore required for the individual customer to ensure correct predictions in view of the performance level and life situation in question.

<u>ENGINE DETERIORATION COMPENSATION</u>

The basis for the thrust on the deteriorating engine is the F/N_L relationship which remains adequately constant over the usage time as described. With the deteriorating, i.e. less efficient engine, the F/N_L relationship increases slightly, ensuring that the min. acceptable thrust is always achieved or slightly exceeded. (This effect derives from the lower energy transfer in the turbines on the deteriorated engine in relation to the constant exhaust nozzle efficieny. Deteriorated engines exhibit turbomachinery of lower efficiency, meaning that at a given thrust the SOT is higher, the N_L is somewhat smaller and the energy transfer in the exhaust nozzle is higher.)

To compensate for the engine deterioration, the TBT is set on the ground. From the basic relationship of N_L over T_{t1} at a constant thrust as shown in Fig. 14, the TBT for the ISA day can be derived and set as shown in Fig. 16. Consequently, this special point effects the complete TBT schedule for the engine in its existing deterioration level for the standard day.

The distance between the TBT schedule on the ISA day and the limiting 'tent' schedule indicates the TBT potential available for further engine deterioration on hot days. For the individual engine usage, the max. TBT for the standard day, which just ensures the required thrust at higher ambient temperatures, can be defined accordingly.

The whole procedure of setting the TBT-ISA schedule for the individual engine can be carried out automatically by the DECU on request if

- the N_L and TBT gradients over T_{t1} for constant thrust on ground are given
- the limiting TBT schedule is set and frozen
- the parameters for the floating TBT schedule are given
- the DECU is programmed accordingly

<u>AMBIENT TEMPERATURE INFLUENCE</u>

The aim is to maintain the thrust at any Mach number within the flight envelope irrespective of the day temperature changes. For this, the basic engine thrust setting has to be defined such that with a normally deteriorated engine, there is still a sufficient margin to cope with the expected highest ambient temperature level.

Thrust restoration at different day temperature conditions requires the definition of the T_{t1} deviation from the standard day. The ΔT_{t1} can then be used to define a TBT trim which will ensure that the thrust demands are met. The procedure is described below in greater detail.

In flight only the observed engine inlet temperature (T_{t1}) is readily available. The deviation of the observed T_{t1} from the standard day temperature has to be defined. With the given standard day Tso/Pso function the $T_{t1,ISA}$ can be derived iteratively from the observed Mach number. With the ΔT_{t1} resulting from the comparison of T_{t1} observed with $T_{t1,ISA}$ (see Fig. 15a) a ΔTBT for maintaining a constant thrust at that day condition can be defined (see Fig. 15b). The two lines in Fig. 15b result from the TBT schedule (Fig. 3) which has two different slopes over T_{t1}, the so-called tent. Consequently for one ΔT_{t1} the ΔTBT for the right hand slope needs to be higher than for the left hand slope.

The ΔTBT from Fig. 15b is then added to the ISA TBT (Fig. 16), restoring the thrust level for that day condition.

The limiting TBT schedule has authority against too high ΔTBT demands i.e. even excessively deteriorated engines will not be overheated, but they will not maintain the demanded thrusts on hotter days. The whole setting procedure is carried out automatically throughout the life of the engine in intervals as required.

The procedure calls for the existing engine and aircraft parameters. Programming of the DECU must be carried out as described and in accordance with the diagrams (Fig. 15 and 16). The reheat thrust setting is maintained as described and shown in Fig. 5c. By the way in the GAF, reheat setting is already being carried out automatically on demand. On combat selection, the above procedure applies, but at a slightly higher TBT threshold, i.e. $TBT_{combat} = TBT_{max\ dry\ R/H} + \Delta TBT_{combat}$.

In view of the life usage of life-limited parts a further positive effect in comparison with the present thrust rating concept can be expected as long as the engines are used on average under the same climatic conditions (high life usage on hot days is compensated by low life usage on cold days) and the same thrust level. The reason lies in the total compensation of engine thrust deterioration all the time, rendering a deterioration margin over the setting period of for example, 100 hrs unnecessary. For example, with the HP turbine blade shown in Fig. 12 for the applied thrust rating concept, the refined concept will result in the full life increase thanks to the very short intervals. This leads to a further reduction in maintenance material costs as expressed by the dotted line in Fig. 13.

In summary, the refined constant thrust rating concept uses existing engine parameters and maintains the TBT as a scheduled temperature limiter but trimmed for the restoration of the thrusts over the Mach number irrespective of the day temperature conditions.

With the DECU now available, setting on the ground and resetting in flight can be carried out automatically, meaning that field maintenance can be reduced.

The concept is not limited just to the RB199 project. Thanks to its flexibility in being able to accommondate various thrust parameters and to the use of various TBT schedule slopes as required, it can be applied generally.

CONCLUDING REMARKS

The investigations show that changing from a limiting temperature (SOT) concept to a thrust rating concept decreases the life usage of the engine generally but on hot gas path parts in particular which reduces the maintenance material costs considerably. The existing control system concept of the RB199 engine allows the application of a thrust rating concept without jeopardizing the advantages of the temperature limitation by a quick response pyrometer system for maximum power conditions. No additional maintenance effort is required because the required performance check and resetting intervals can be selected to be in line with already existing maintenance activities.

Further, with the introduction of the DECU a refined maximum thrust rating concept can be introduced which does not only provide an automatic re-setting system of the TBT to compensate thrust losses due to engine deterioration but also ensures a constant thrust offer irrespective of the ambient day temperature conditions. A further reduction in life usage of the engine and reduced maintenance efforts result.

The benefit of a constant maximum thrust offer of the engine in view of mission planning and execution as well as in respect of pilots training needs to be assessed and quantified by the customer.

The described thrust rating concepts are not limited to the RB199 engine but can be applied generally on engines for which the relevant basic conditions as the availability of

- suitable engine parameters for a thrust description
- a reliable, controllable maximum temperature limiting system
- sufficient thrust margin over the minimum requirements to cope with engine deterioration and hot day thrust requirements
- a suitable engine control unit

is given.

However, the conditions and requirements for the individual application of a suitable thrust rating concept need to be defined and scrutinized thoroughly to allow a prediction of the benefits and implications.

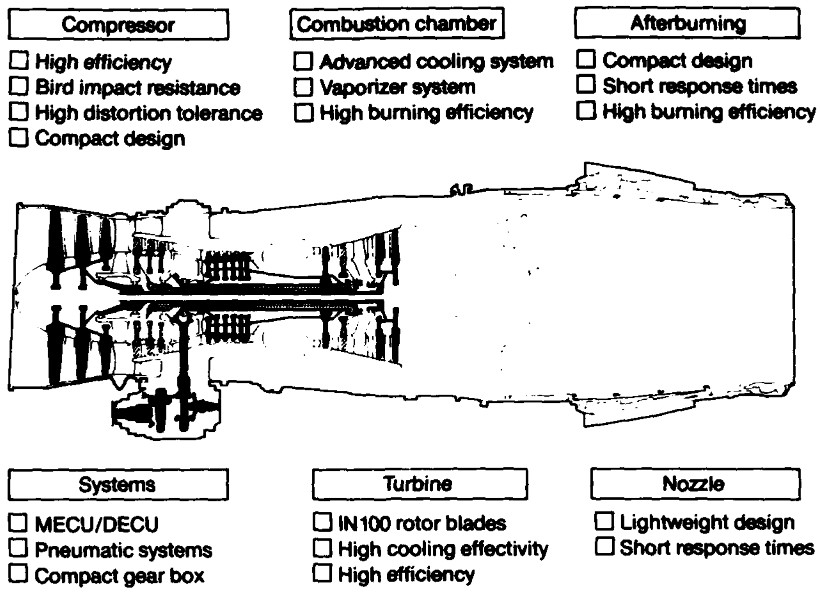


Fig. 1 Configuration of the RB199

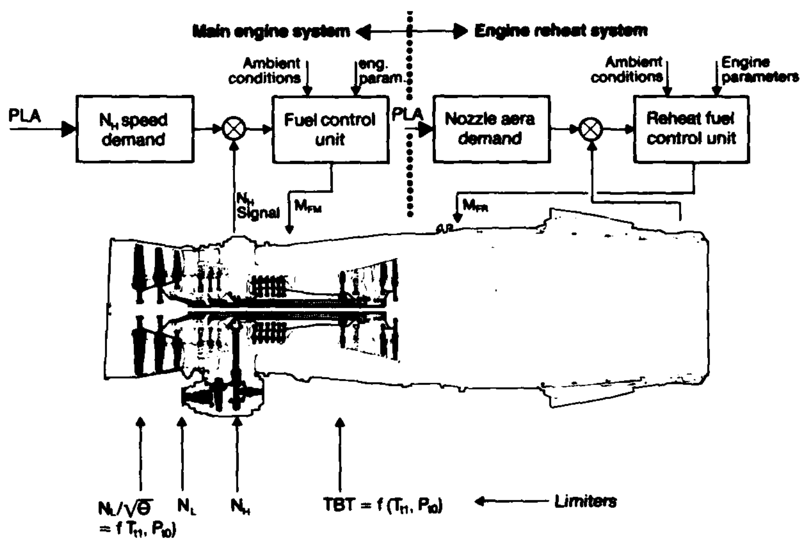


Fig. 2 RB199 control system concept

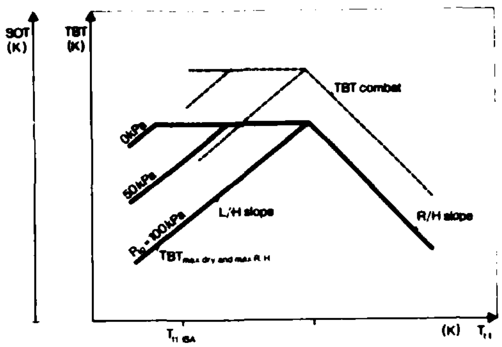


Fig. 3 RB199 TBT schedule (T?T tent)

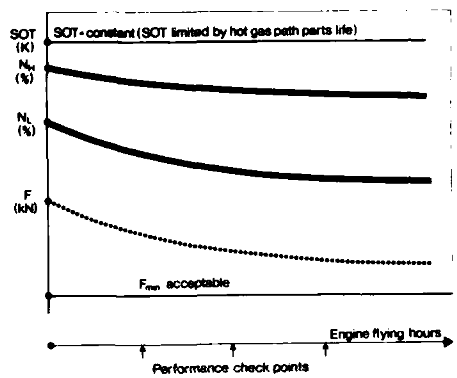


Fig. 4 Constant SOT rating concept

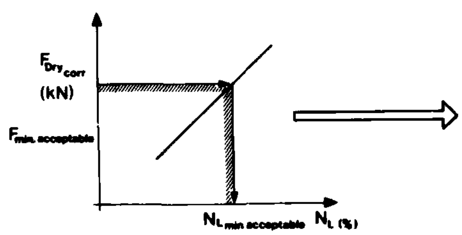
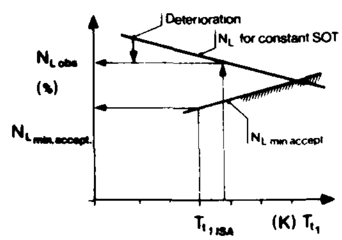


Fig. 5a Basic relationship for thrust check



$N_L > N_{L\ min.\ accept.}$ for const. SOT

Fig. 5b Performance check to ensure $F \geq F_{min.\ acceptable}$ at constant SOT

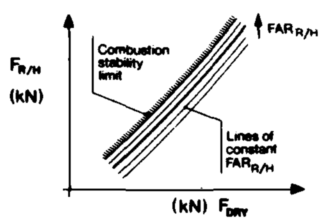


Fig. 5c Reheat performance check

Fig. 5 Min. acceptable thrust check at constant SOT

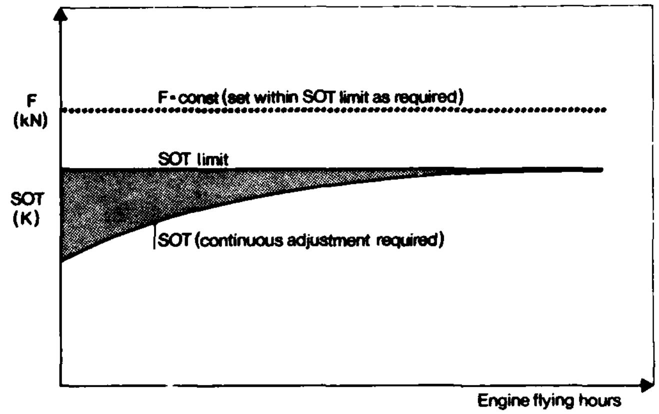


Fig. 6
Ideal thrust rating

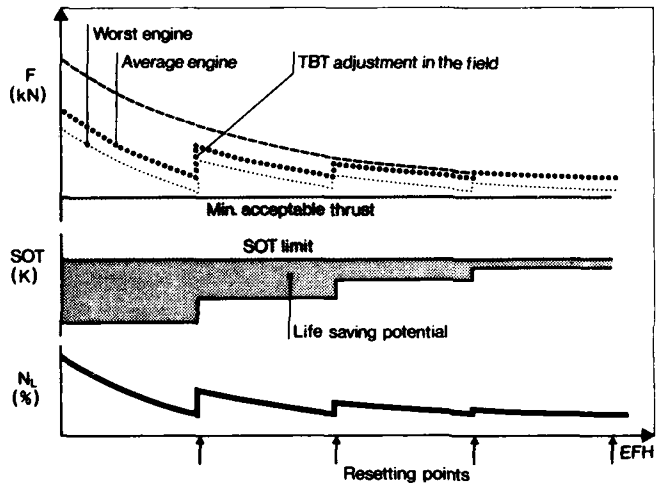
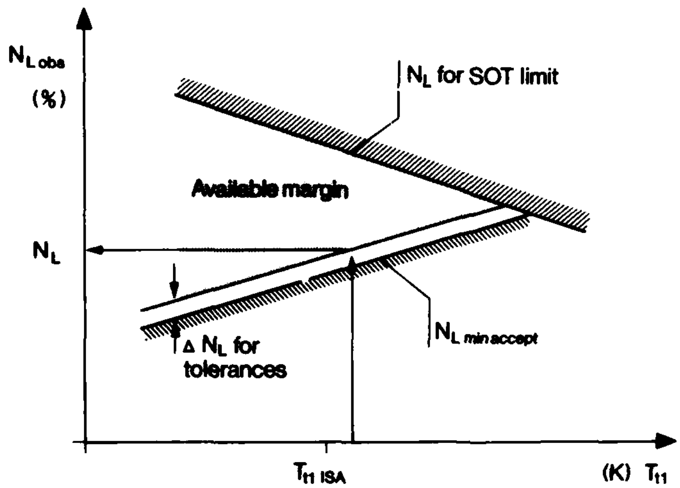


Fig. 7
RB199 thrust rating concept
(resetting at time intervals)



$F_{const.} = F_{min.\,acceptable} + \Delta F_{tolerances}$

Fig. 8
Performance setting or check to constant thrust

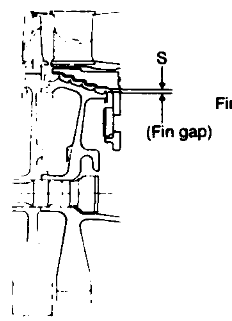


Fig. 9a Seal arrangement

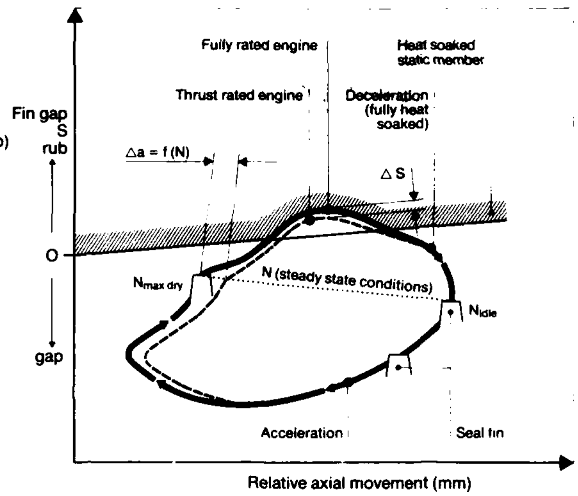


Fig. 9b Orbital plot of a seal fin movement

Fig. 9 Influence of thrust rating on seal gap

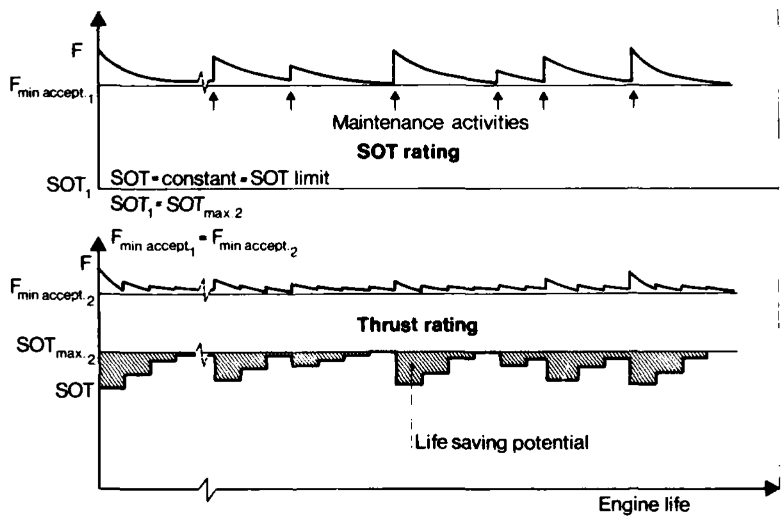


Fig. 10 Comparison of SOT rating and thrust rating

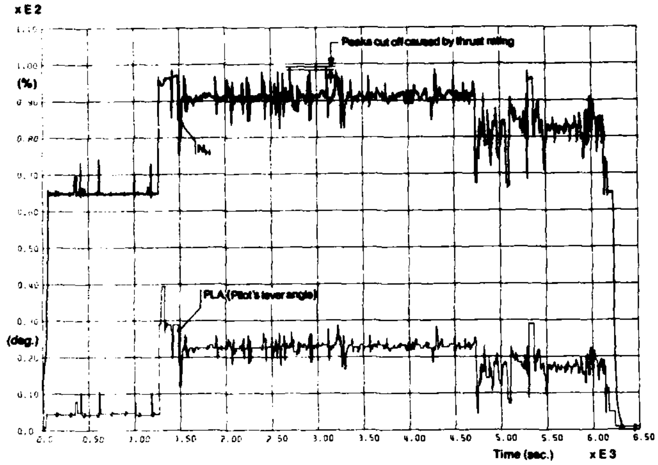


Fig. 11 Example of a mission plot (N_H, PLA)

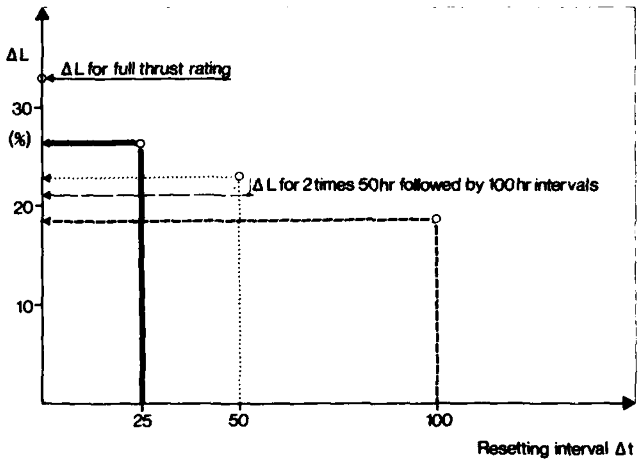


Fig. 12
Life increase of a HPT blade from thrust rating

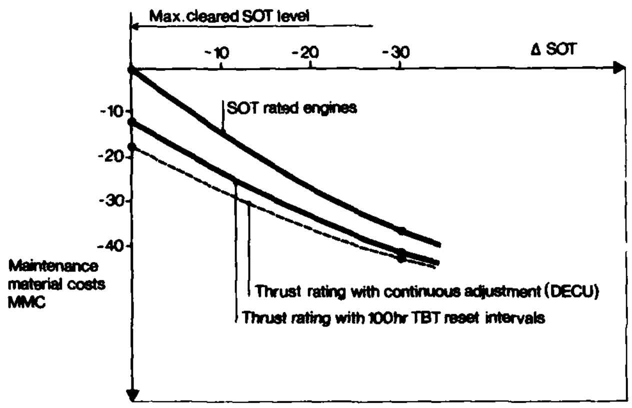


Fig. 13
MMC Reduction from thrust rating (Max. SOT and min. acceptable thrust are identical)

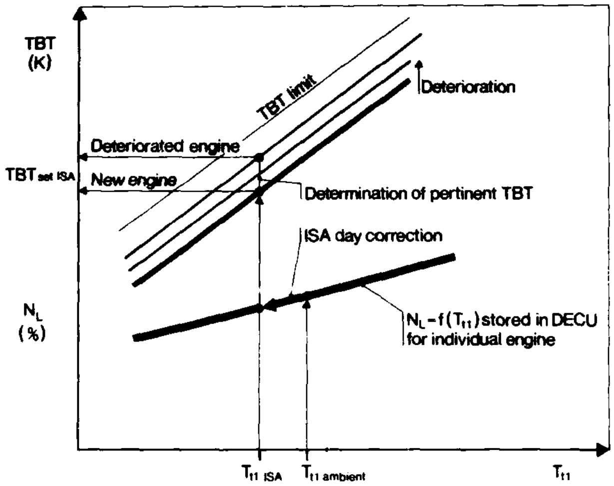


Fig. 14
Definition of TBT for standard day at constant thrust on the ground

Fig. 15a Definition of ΔT_{t1}

Fig. 15b Definition of Δ TBT as f $(\Delta T_{t1}, TBT_{tent})$

Fig. 15 Compensation for ambient temperature changes

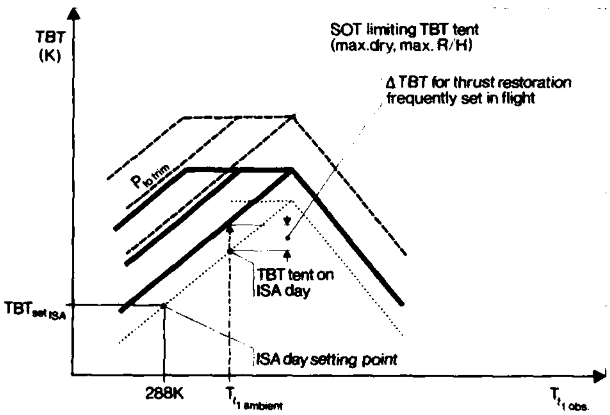


Fig. 16
Variable TBT for constant thrust at variable engine inlet temperatures

DISCUSSION

M. BEAUREGARD

How stable is N_L vs F_{dry} vs time (i.e. deterioration)? Why can a thrust gauge not be designed to reflect this concept?

What parameter does the pilot fly to? Is it temperature?

Author's Reply:

The relation is very stable. There is only a slight increase of thrust over time with engine deterioration due to the energy transfer in the turbomachinery and the thrust nozzle. The N_L is used on ground setting as a thrust description, not in flight because a reheated engines makes it very difficult. There are efforts ongoing to design thrust gages reliable enough for the difficult surroundings they have to work to. The pilot flies with the pilots lever to an aircraft speed and to a temperature limit which is set by turbine blad temperature and interacts

C. SPRUNG

Un des problèmes à résoudre est d'obtenir une bonne précision pour la saisie de la température des aubes de turbines surtout aux limites. Comment accédez-vous à cette température? Est-ce par mesure directe ou par calcul?

Author's Reply:

THE S.O.T. cannot be measured reliably because the newer fighter engines run at temperatures for which no reliable and accurate sensors are available. The S.O.T. on the RB 199 is calculated for the performance check. The Turbine Blade Temperature is then set accordingly for the temperature limit. The TBT controls the temperature limit on ground and in flight.

"TREND-MONITORING" DES TURBO-PROPULSEUR DE PETITE ET MOYENNE PUISSANCE

par

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1 - INTRODUCTION

Dans la recherche des méthodes propres à diminuer le coût de l'entretien des turbo-machines de petite et moyenne puissance, figure la tendance à supprimer les butées fixes que constituent les potentiels entre révisions des sections chaudes ou des sections froides, tout en conservant bien sûr un suivi des machines suffisant pour prévenir des avaries ou des dégâts graves en exploitation.

Certains Constructeurs (PRATT ET WHITNEY CANADA, GENERAL ELECTRIC, LYCOMING) ont donc proposé une méthode basée uniquement sur des relevés de paramètres moteurs en vol et présentée comme susceptible d'affiner le suivi technique et de permettre de déclencher les opérations d'entretien et/ou de réparation, au moins des sections chaudes, uniquement à partir des signatures de pannes.

L'introduction de ces méthodes en FRANCE est relativement récente et l'exposé suivant fait un point de sa mise en oeuvre chez les exploitants français.

2 - MATERIEL CONCERNE

Les moteurs dont il est question ici sont les turbo-propulseurs PRATT ET WHITNEY CANADA PT6 A et PW 120, et GENERAL ELECTRIC CT 7.

Les PT6 sont montés sur bi-moteurs BEECH 90 - 99 - 200, DHC 6, EMBRAER P110, PIPER PA 31 T et mono-moteurs PILATUS PC7. Ils sont dans une gamme de puissance allant de 400 à 700 kW.

Le PW 120 est monté sur l'ATR 42 - Puissance : 1 500 kW.

Le CT 7 a une puissance de 1 300 kW. Il est installé sur SAAB SF 340.

Tous ces appareils sont utilisés en transport régional, sur des lignes plutôt courtes, en moyenne de 1 heure, avec 1/2 heure mini et 1 heure 1/2 maxi, et à des altitudes de l'ordre de 3 000 à 6 000 m (niveaux 100 - 200).

Au point de vue flotte, il y a en FRANCE 6 opérateurs déclarés faisant du Trend Monitoring sur PT6, ayant de 1 à 7 appareils pour une flotte d'environ 20 bi-moteurs (soit environ 10 % de la flotte française) ; en PW 120, il y a 7 exploitants pour un peu moins de 20 avions. En SAAB SF 340 : 3 opérateurs avec 4 avions.

L'ensemble de la flotte mise sous surveillance Trend Monitoring représente, à ce jour, environ 80 000 heures moteur pour PT6, 50 000 pour PW 120 ; moins de 10 000 heures pour le CT 7. Le nombre d'heures augmente rapidement pour les PW 120.

3 - PRINCIPE

Le "Trend Monitoring" (en français "Surveillance de l'évolution des performances) consiste à observer, entre deux périodes d'entretien majeur, l'évolution d'un certain nombre de paramètres représentatifs de l'état physique du moteur, portée sur un graphique. En fait, on observe l'évolution non pas de la grandeur des paramètres, mais de la différence entre les paramètres de vol (ramenés en conditions standards) et ceux d'un moteur type défini par le constructeur. Les courbes observées représentent donc les évolutions de deltas.

Pour le PT6 et le CT 7, on observe les deltas sur 3 paramètres :

- vitesse du générateur,
- température inter turbine,
- débit carburant.

Pour le PW 120, qui est un triple corps, on observe en plus la vitesse du corps basse pression.

L'obtension de ces paramètres nécessite le prélèvement des données suivantes :

- vitesse générateur (haute et basse pression),
- débit carburant,
- vitesse de l'arbre porte-hélice et couple du moteur, ces deux paramètres donnant la puissance de référence,
- altitude - pression, vitesse indiquée et température extérieure de l'air, ces derniers paramètres servant à ramener aux conditions standards.

Les paramètres sont relevés par le pilote pour le PT 6 et le CT 7, par un enregistreur automatique embarqué (mini A.I.D.S.) pour le PW 120 (un dispositif analogue est à l'étude pour le CT 7).

Le traitement des paramètres se fait au sol, soit entièrement manuellement à partir de courbes données par le constructeur, soit à l'aide d'une calculette pré-programmée (T.I. 59 ou HP41), soit sur ordinateur IBM P.C. couplé à une imprimante éditant directement les courbes.

Le traitement manuel a été abandonné parce que trop imprécis et très contraignant.

L'avantage du traitement par ordinateur, selon programme informatique fourni par le constructeur, est d'obtenir directement la ligne de base de chaque paramètre et les valeurs lissées (lissage sur 10 points pour PRATT ET WHITNEY, sur 5 pour GENERAL ELECTRIC).

A titre de comparaison, il y a 8 paramètres surveillés pour un réacteur type JT8, la référence de base étant un rapport de pression caractéristique de la poussée (Engine Pressure Ratio) au lieu de la puissance :

- vitesse compresseur haute pression,
- vitesse compresseur basse pression,
- E.G.T.,
- vibrations,
- débit carburant,
- position manette,
- pression d'huile,
- température d'huile.

Une correction due aux prélèvements d'air sur le compresseur est également appliquée en plus des corrections d'altitude, température et vitesse.

A noter que si pour le JT8 l'ordinateur ne présente que les courbes lissées, pour les PW 120, PT 6 et CT 7 l'ordinateur présente en même temps les valeurs lissées et les valeurs du jour.

Comment sont surveillés ces paramètres ?

- d'une part, par un encadrement de seuils d'alerte à plusieurs niveaux sur la température et la vitesse de rotation pour les PT 6 et PW 120, par l'obtention d'une marge nulle en température pour le CT 7 ;
- d'autre part, par le sens de variation, la pente et les combinaisons de pentes pour l'ensemble des paramètres. Cet aspect de la surveillance est le plus délicat ; le constructeur donne des exemples de signatures de pannes (voir figures 1).

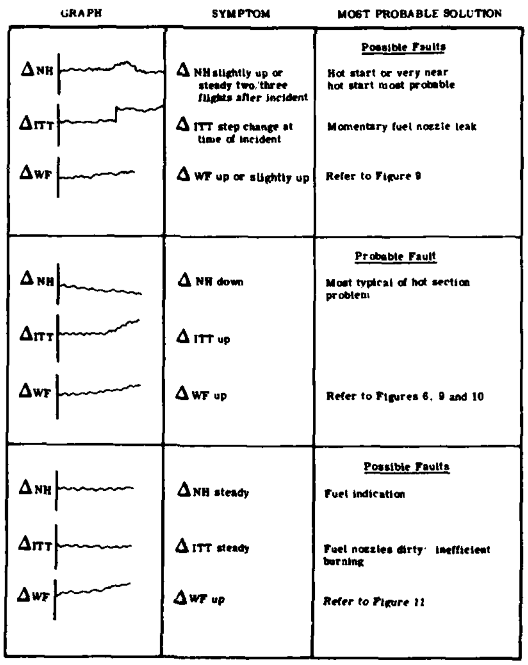

Figure 1 : PT 6 - PW 120

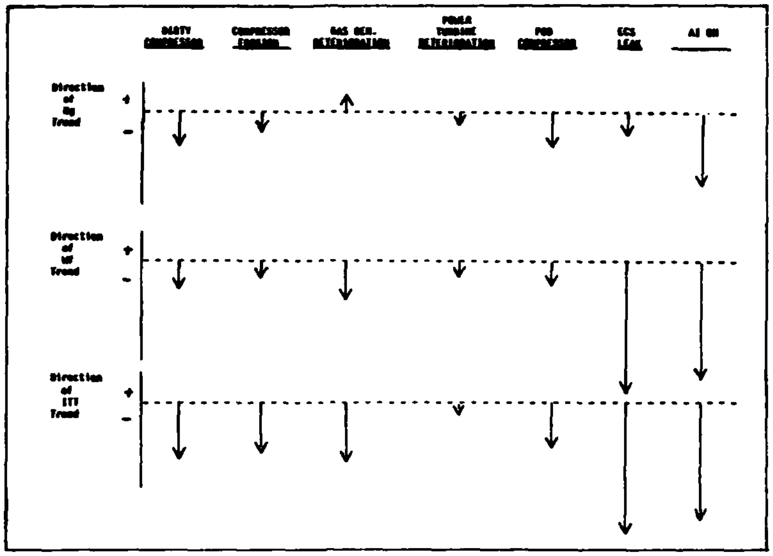

Figure 1 bis : CT 7

Champ d'application

Le principe de la méthode fait que seuls des paramètres thermo-dynamiques sont surveillés ; en conséquence, seules les usures ou défaillances ayant une conséquence directe sur l'écoulement dans la veine d'air et les performances seront détectables, aussi bien pour la section froide (c'est-à-dire les compresseurs) que sur la section chaude (turbines et chambre de combustion) :

- variation des jeux en bout de pales ou pertes d'étanchéités internes,
- variation des qualités de combustion,
- dispositifs de prélèvement d'air,
- et indirectement, les dérives ou les pannes des instruments chargés de cette surveillance, la dérive des instruments se traduisant pas une dérive apparente des paramètres surveillés.

D'un autre côté, le procédé n'a pas possibilité de surveiller l'état mécanique interne du moteur, ni certains phénomènes dans la veine d'air comme les criques, la corrosion, ou la sulfidation qui sont pourtant très courants et susceptibles de provoquer des dégâts ou des frais de remise en état importants.

4 - EXPLOITATION

En général, on utilise un relevé par jour. Chez certains exploitants, il peut y avoir plusieurs relevés par jour ; dans ce cas, le spécialiste chargé du dépouillement choisit le plus typique.

La Figure 2 montre un suivi fait en dépouillant les paramètres à l'aide d'une calculette T.I. 59 et en reportant manuellement les points calculés sur un graphe.

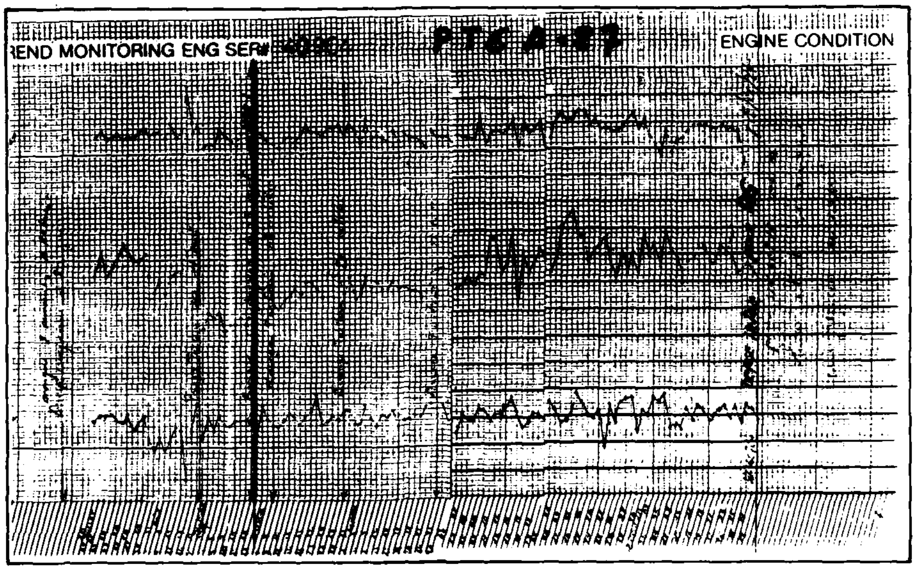

Figure 2

La *figure* 3 montre un suivi fait sur ordinateur IBM PC avec imprimante, suivant un programme fourni par le constructeur.

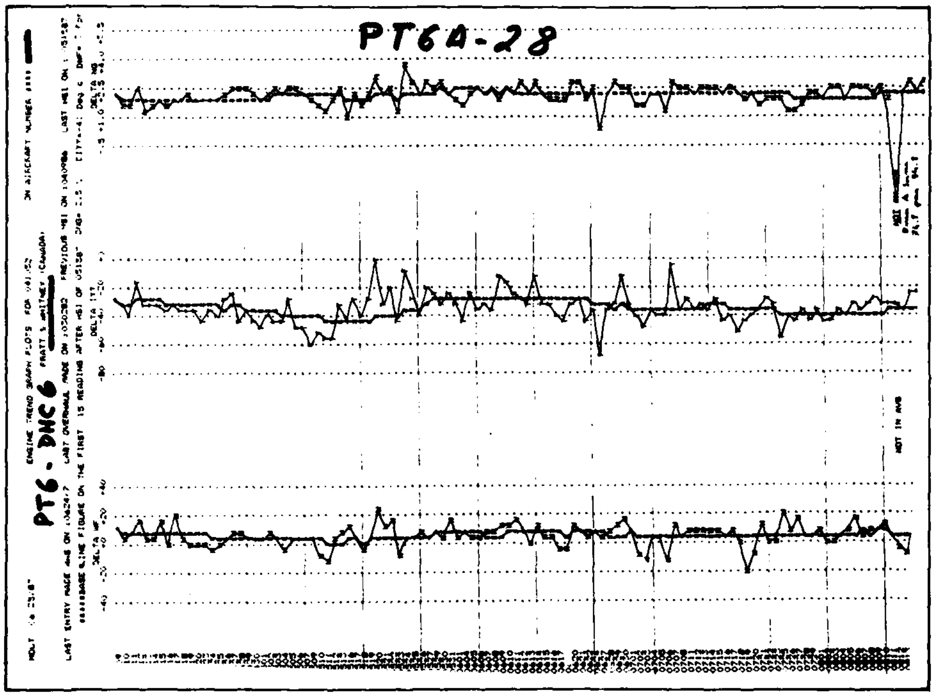

Figure 3

La figure 4 montre un relevé de moteur PW 120 d'ATR 42, fait à partir de l'enregistreur automatique embarqué (mini Airborne Integrated Data System) ; le bruit de fond avant lissage est particulièrement diminué.

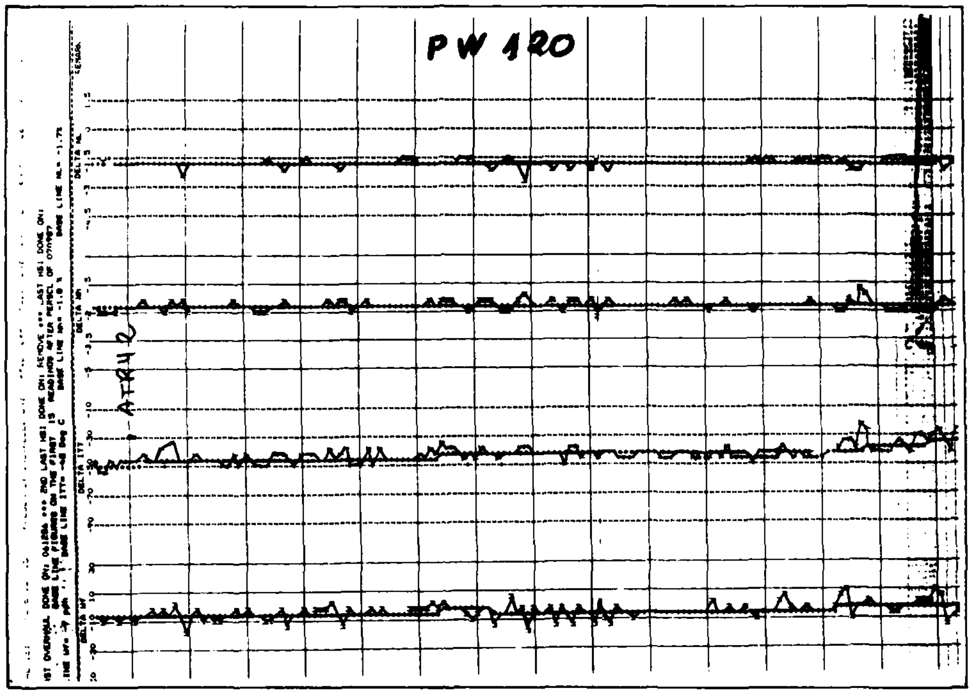

Figure 4

La figure 5 montre un suivi CT 7, avec ordinateur IBM PC.

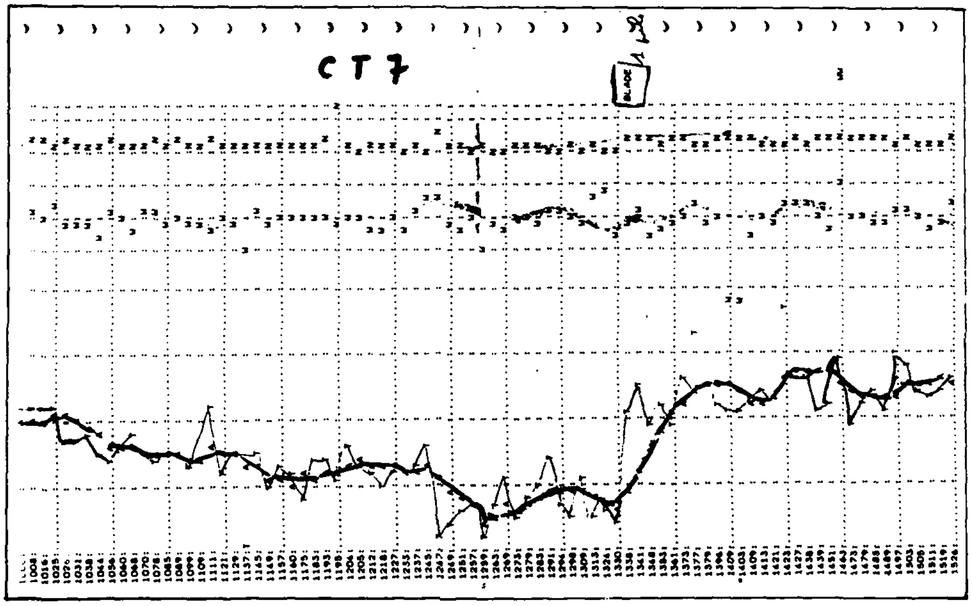

Figure 5

A titre de comparaison, nous montrons figure 6 un relevé de réacteur JT8 D.

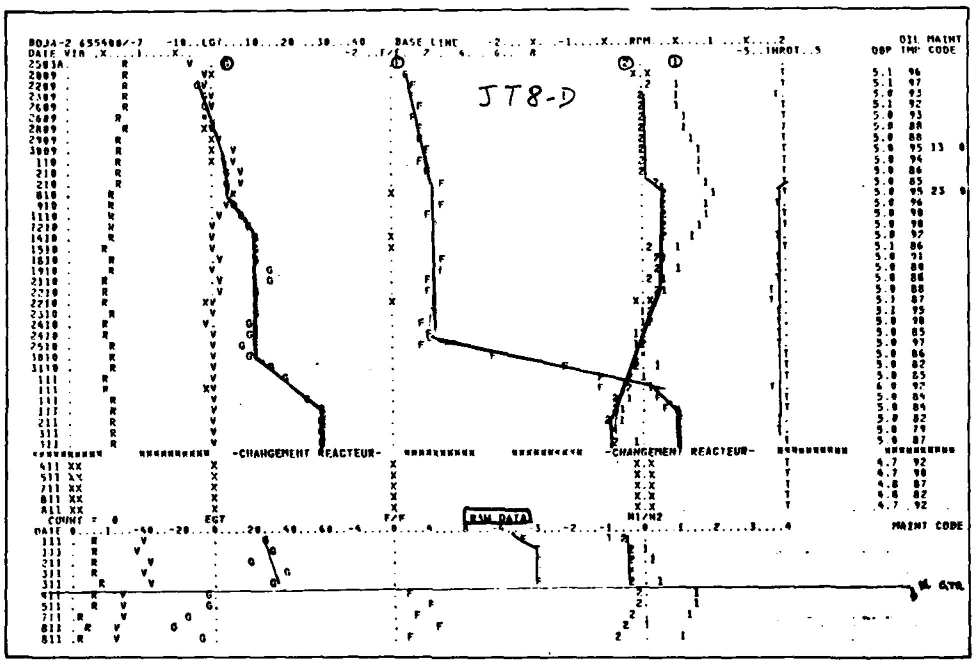

Figure 6