

LESSONS LEARNED FROM DEVELOPMENTAL AND
OPERATIONAL TURBINE ENGINE MONITORING SYSTEM

REAFFIRMED

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(FURTHER LESSONS LEARNED IN PREPARATION)

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1. PURPOSE:

The purpose of this Aerospace Information Report (AIR) is to document some of the valuable lessons learned from several developmental and operational turbine engine monitoring programs.

This AIR is not intended to be used as a standard or legal document but rather provide an objective statement of the more important lessons learned during the development and operation of engine monitoring systems with widely varying operational requirements. It is through the use of ARP1587 "Aircraft Gas Turbine Engine Monitoring System Guide," and SP-478 "Aircraft Gas Turbine Engine Monitoring Systems," an awareness of prior lessons learned and a clear definition of engine operational maintenance concepts that future engine monitoring systems can be developed to meet the specific needs of the user.

2. APPROACH:

The approach selected in preparing these lessons learned was through the review of available technical reports and papers covering the development work and personal interviews conducted with knowledgeable government and industry personnel directly involved with each of the programs. In most cases, the responsible project engineer from the government and/or the program manager from industry collaborated in preparing the initial draft for each program. The Lessons Learned Panel then worked jointly with these individuals to edit and prepare the final draft of each Lessons Learned. This final draft was then reviewed by the participating organizations prior to release for publication to insure technical accuracy and clarity of content.

3. SCOPE:

The scope of the information provided for each Lessons Learned includes (but is not limited to) the following:

- I. Brief TECHNICAL DESCRIPTION of the Engine Monitoring System
- II. DESIGN REQUIREMENTS and System Objectives
- III. ACCOMPLISHMENTS and Problems Encountered
- IV. LESSONS LEARNED
- V. PROBLEM AREAS
- VII. REFERENCES (If available for general distribution)

The pertinent questions that were asked to capture the essence of the Accomplishments, Lessons Learned and Future Recommendations were as follows:

1. What are the real benefits and liabilities of an EMS from a management perspective in terms of operating economy, cost avoidance and improved engine/aircraft availability?

3. (Continued):

2. Based on past experience, what would you do differently in the design, development and implementation of an EMS?

The responses to these questions were based on the documented results of the development work accomplished and the professional opinion of the project personnel involved.

4. REMARKS:

The Accomplishments, Lessons Learned, and Future Recommendations are considered unique for each of the programs and cannot be readily generalized. Consequently, the information reported for each system in each of these categories is considered configuration dependent and is not intended to be universally applicable to other flight systems. It is, therefore, suggested that all lessons learned and recommendations for engine monitoring systems contained in this AIR should be reviewed in the context of the operational environment of the aircraft (military or civil), the aircraft configuration (transport, fighter, helicopter, single or multi-engine, etc.), and the maintenance concept that the engine monitoring system was designed to support.

Early development programs pioneered new frontiers in turbine engine monitoring system development and consequently had to face many of the difficult technical challenges with limited resources and the lack of opportunities for adequate testing in a service environment. Nevertheless, engine monitoring systems have demonstrated the ability to reduce engine removal rates and unsubstantiated component removals and decrease engine related maintenance man-hours per flight hour.

The development of an engine monitoring system can best be described as an evolutionary process requiring:

1. The full support of management both in the industry (supplier and user) and the government,
2. Sufficient funding to develop the system and support the hardware/software in service and
3. Flexibility within the overall system hardware and software to respond to the evolving requirements imposed by lessons learned and emerging maintenance concepts.

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5. LESSONS LEARNED:5.1 Lessons Learned: Condition Monitoring Program for T700-GE-700 Engine (Report Covers Period 1967 to 1976):

- I. Technical Description: The technical objective was to design and develop an engine Condition Monitoring System (CMS) that was compatible with the Army's concept of on-condition maintenance for the UH-60 (BLACKHAWK) and AH-64 (APACHE) helicopters using the T700-GE-700 and T700-GE-701 engine. A total of 22 parameters were initially selected for the CMS, but this list was reduced to 16 as a result of a re-direction of development effort to incorporate only the most useful and affordable CMS provisions. The following list shows both the original and the final quantities of signals/parameters:

	<u>Original Number</u>	<u>Final Production Number</u>
Pressures	2	2
Temperatures	3	2
Speeds	2	2
Mechanical Position	6	5
Accelerometers	2	0
Other (torque, chips, etc.)	7	5
TOTAL	22	16

- II. Design Requirements: The design of the CMS was an evolutionary effort beginning with various basic requirements as follows:

- o A capability to detect incipient malfunctions by prognosis.
- o A capability to detect and fault-isolate a malfunction to an engine module or to a line replaceable unit (LRU) by diagnostic methods.
- o A capability to inspect installed engine and subsystems for acceptability, thus providing on-condition maintenance and minimizing removal and replacement by periodic preventative maintenance, such as time between overhauls (TBO).

During development of the engine, the cost and complexity of each portion of the CMS was evaluated against the initial requirements and the changing engine characteristics to determine the cost effectiveness of the CMS hardware item. As will be noted in the Accomplishments section, this evolutionary process resulted in modification to, and deletions from, the original CMS. An example of one of the modifications that was made is related to the redesign of the Engine History Recorder (EHR). Instead of recording each engine start and each engine over-temperature event, it was decided to record low cycle fatigue (LCF) counts in order to more accurately document the usage of certain items of engine hardware that were suspected of being susceptible to low cycle fatigue. Many items that were deleted are discussed individually in the Accomplishments section.

III. Accomplishments: The T700-GE-700 engine condition monitoring and diagnostic program was approximately a ten-year effort that was initiated with the award of a 1500 shaft horsepower demonstrator engine contract in 1967 and concluded with the selection of a final production engine configuration in 1976. Many hours of engine test cell running and flight evaluation were accomplished prior to the eventual selection of BLACKHAWK and the Advanced Attack Helicopter condition monitoring equipment.

System: During the development of the T700-GE-700 engine, the Condition Monitoring System (CMS) was continually being optimized and simplified to reduce engine cost, weight, and complexity. An additional important consideration was the recognition that the Army battlefield environment and capability would probably limit the effectiveness of a complex system. A further consideration involved the expected difficulty of maintaining complex diagnostic equipment which was installed in Army helicopters or even on the ground in the case of ground support equipment. After spending considerable R&D funds on several of the items during engine development/testing, the overriding consideration that led to the elimination of some items was the cost of further development and the cost of including the item on production engines or support for production engines.

Hardware: The following is a list of the hardware/monitoring techniques that were evaluated during the T700 engine development program and shows which items were retained and which were deleted:

<u>CMS Item</u>	<u>On Production Engine</u>	<u>Delete During Development</u>
Engine History Recorder (EHR)	X	
Borescope	X	
Radiographic Inspection		X
Oil Level Sensor		X
Lube Temp Sensor	1	
Lube Press Sensor	X	
Oil Sight Gage	X	
In-Line Oil Analyzer		X
Oil Filter Impending By-Pass	X	
Oil Filter By-Pass	X	
Magnetic Chip Detector	X	
S.O.A.P. Provisions		X
Fuel Filter Impending By-Pass	X	
Fuel Filter By-Pass	X	
Accelerometer (on #3/4 Bearing Housing)		X
Accelerometer (on #6 Bearing Housing)		X
Thermocouple Harness (Individual Readout)		X
Erosion Indicator		X
FOD Impact Detector		X

<u>CMS Item</u>	<u>On Production Engine</u>	<u>Delete During Development</u>
Torque Sensor	X	
Ng Speed Sensor	X	
NP Speed Sensor	X	
Diagnostic Connector	X	
Accessory Gearbox Analyzer		X
Bearing/Unbalance Monitor		X
Engine Health Monitor (EHM)		X
Anti-Icing/Bleed Valve Indicator	X	
Control Systems Analyzer	0	

0 Recent Development for Ground Use With Engine

1 Not included on the T700-GE-701

The following explanations are provided relative to the CMS items that were changed or deleted during the engine development program:

1. Engine History Recorder (EHR):

- o Deleted over-temperature counts and start events counts.
- o Substituted LCF1 counts (excursions of Ng from start to above 95%) to monitor significant rotor speed changes.
- o Substituted LCF2 counts (excursions of Ng between 86 and 95%) to monitor significant thermal cycles.
- o Retained time-temperature index counter and elapsed time (engine operating hours) counter.
- o No requirement for field units to report LCF data. Contractor personnel acquire and manually tabulate data periodically.

2. Radiographic Inspection:

- o Deleted due to development time and effort (cost) required to optimize procedures.
- o T700 modules can be separated for inspection in less time and with less trouble.
- o Even good X-rays are of questionable use.

3. Oil Level Sensor:

- o Deleted due to cost, complexity, reliability, etc.
- o Substituted oil level sight gage.

4. In-Line Oil Analyzer:

- o Deleted due to cost and weight and lack of success in detecting bearing spalls plus difficulty in establishing limits for oil degradation due to variations in oils.
- o 3 micron oil filter and magnetic chip detector were more useful and less costly.

5. Spectrographic Oil Analysis Program (SOAP) Provisions:

- o Deleted because 3 micron oil filter removes particles that would normally be used by SOAP procedure.
- o SOAP procedure is after the fact and often too late to prevent T700 bearing failure.

6. Accelerometers (No. 3/4 and 6 Bearing Housings):

- o Deleted due to cost and poor reliability/maintainability of internal accelerometers and especially electrical leads.
- o External accelerometers mounted on the accessory gearbox and exhaust frame (installed for testing only) were selected as a cost effective alternative to internally mounted sensors for detecting engine unbalance caused by blower failures, compressor rubs or improperly balanced rotors.
- o Chip detector was deemed satisfactory for detecting bearing problems.

7. Thermocouple Harness:

- o Original design allowed monitoring of individual thermocouples to detect abnormal burner outlet temperature pattern and to detect a failed thermocouple which would allow high engine operating temperature.
- o Deleted capability due to cost and complexity and excellent experience with combustors and thermocouples during development and maturity programs.
- o Retained ability to test harness for shorts or open circuits.

8. Erosion Indicator:

- o Compressor erosion patterns are not symmetrical or repeatable, especially relative to circumferential location of erosion.
- o The two erosion indicators were deleted as not a meaningful measurement device.
- o Instead, use of a borescope was adopted.

9. FOD Impact Detector:

- o Original intent was to utilize the No. 3 BRG accelerometer.
- o FOD detection by this means was eliminated when No. 3 BRG accelerometer was deleted due to cost and lack of reliability.
- o FOD damage on this size engine can be detected by audible and/or performance changes.

10. Accessory Gearbox Analyzer:

- o This was intended to be a special piece of ground support equipment (GSE) to check accessory gearbox (AGB) vibration.
- o Deleted from further consideration due to cost and complexity and due to excellent experience (lack of problems) with the T700 AGB.

11. Bearing/Unbalance Monitor:

- o This was deleted when the No. 3/4 and 6 internal bearing accelerometers were deleted.

12. Engine Health Monitor (EHM):

- o Deleted due to cost and complexity and the expectation that the T700 engine would have a low rate of performance degradation. Use of early (1970's) analog circuitry technology resulted in excessive cost, weight, and complexity of EHM.

Added: This following component was added during the T700 development and early production stages. Although it is a piece of ground equipment and not usually considered a part of a condition monitoring system, it is included here because of its importance in the overall T700 engine condition monitoring program.

Control Systems Analyzer:

- o Excessive replacement of easily removable T700 electrical control units (ECU), hydromechanical units (HMU), and other control system components from aircraft in service dictated the need to develop the analyzer.
- o The analyzer consists of two units: (a) sensor/harness circuit tester and (b) ECU system tester.
- o The Circuit Tester checks component resistance and shorts to aircraft ground; the ECU System Tester performs functional checks of the dynamic performance of the control system.

- o Two prototype sets are being successfully used with aircraft in service to reduce the number of unnecessary/unconfirmed removals and to troubleshoot aircraft/engine interface electrical problems.
- o Twenty additional sets are to be supplied to Army operational units for further evaluation.

IV. Lessons Learned:

1. The simple method is better for some items of condition monitoring in view of the Army field environment and human factors involved.
 - o The use of a simple sight glass to observe oil level not only reduced the cost of the T700 engine, but increased the reliability and eliminated the problem of maintaining the oil level sensor in calibration and working order.
 - o Use of a 3 micron oil filter and a magnetic chip detector in lieu of the more complex in-line oil analyzer not only reduced the cost and weight of the T700, but provided other benefits of increased reliability and decreased maintenance.
 - o The deletion of accelerometers on bearing housings inside the T700 engine reduced the cost and avoided the difficult task of maintaining the internal sensors, and especially the lead wires. It is still possible to obtain engine vibration data, when necessary, by installing external accelerometers such as during an acceptance test or a maintenance test.
 - o Small high-performance engines are subject to performance loss in the Army field environment. An EHM would have proven useful by providing more accurate engine monitoring and simplifying troubleshooting procedures.
2. Each engine type, size, design configuration, and installation dictates different requirements for a condition monitoring system.
 - o The combustor on the T700 engine proved to have a dependable burner outlet temperature (BOT) pattern which made it possible to simplify and reduce the cost and weight of the thermocouple harness by deleting the capability to read the output of each thermocouple individually. Other gas turbine engines may not have a combustor that is as well developed and monitoring BOT pattern could be important in preventing damage to the turbine(s).

- o The size and configuration of the T700 engine was a primary factor in deciding that radiographic inspection was not a useful monitoring technique. The small size of the compressor and turbine blades resulted in considerable difficulty in noting minor defects or damage via radiographic methods with the engine assembled. In addition, it was found that the borescope and/or disassembly was more easily used for internal inspection.
 - o The characteristics of the T700 inlet particle separator and the compressor are such that the sand and dust erosion pattern was not symmetrical or repeatable. This led to the conclusion that simple erosion indicators were not meaningful. This was one instance when a simple device did not prove useful for this particular engine model.
 - o During the engine development effort, it was found that the Accessory Gearbox (AGB) was very reliable and that constant monitoring of the AGB was not required. Thus, the cost of developing/optimizing a complex monitoring device was avoided. Other engines may not have this same experience.
3. Engine maintenance personnel need adequate equipment to effectively troubleshoot engine and aircraft control system problems.
- o The design of the T700 engine control system components provided for relatively easy removal and replacement of electrical and hydromechanical controls and accessories. Thus, during early production it was found that many of these line replaceable units (LRU) were being changed unnecessarily.
 - o In order to allow better troubleshooting, an analyzer has been developed to check for aircraft and engine wiring and connector problems and to functionally check the controls. While the analyzer has proven to be effective in reducing the removal of satisfactory components and in detecting the faulty component on the T700 and/or the aircraft, it has not been approved for field use.
 - o One of the features of the analyzer is that it provides relatively simple signals of "fail" or "pass" so that maintenance personnel do not have to use complicated charts and/or calculations to determine whether a component is satisfactory or faulty.
 - o Other engines and aircraft equipped with more complete engine monitoring systems may not need this same type of ground support equipment.

V. Future Recommendations: The following lessons learned from the Army T700 Condition Monitoring Program may prove valuable in future engine development programs:

- o If an Engine Monitoring System (EMS) is to be developed in time for use in early production aircraft, definite requirements must be specified by the user before engine development/qualification testing is completed. This would allow an early effectiveness evaluation of the EMS. NOTE: This is a problem that is common to all the military services.
- o The "completeness" of an EMS for Army helicopters is strongly influenced by the Army field environment and human factors and the concern for low cost, low weight, and high reliability.
- o Cost and maintenance effectiveness of an EMS should be evaluated on engine(s) and aircraft as near to the final intended application and configuration as possible.
- o A full authority digital electronic fuel control on the engine increases the feasibility and enhances the design and development of an EMS. NOTE: The T700 does not have this type of control.
- o A strategically located "common" connector for engine parameters is useful for an EMS and/or control system troubleshooting.
- o A data processing capability needs to be established/implemented early, preferably along with engine and system development.
- o The ease of LRU replacement contributes to higher unsubstantiated removals of LRU's which may justify the requirement for better field level troubleshooting equipment.

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5.2 Lessons Learned: Inflight Engine Condition Monitoring System (IECMS)
(Report Covers Period 1970 to 1983):

- I. Technical Description: IECMS was developed for the TF41-A-2 engine installed in the US Navy A7E attack aircraft. The design objectives of the system were to increase flight safety and reduce maintenance expenditures. A multi-phased program has resulted since its inception in 1970, with a fleet retrofit program which began in 1983. The milestone chart (Fig. 1) summarizes the history of this program. IECMS was designed as a retrofit system consisting of the following major elements (Fig. 2):

Engine Kit:

Consists of sensors, transducers, wiring, plumbing, bracketry, and modification to existing control components. A total of 35 parameters are presently being monitored with 11 transducers added to engine.

Avionics Kit:

The Engine analyzer Unit (EAU) is an airborne computer. It provides signal conditioning and data management via software to give cockpit information, trip maintenance flags and send data to an airborne recorder. The Tape Magazine Unit (TMU) for data recording is integrated with a Data Display Unit which provides operational exceedance indication and parameter display.

Airframe Kit:

Consists of wiring, sensors, and compartment modification to enable interface with the engine kit and enables installation of the avionics kit. A total of 11 parameters are monitored. Cockpit modifications are also included to provide necessary information to the pilot.

Ground Station:

A computer to process tapes and provide maintenance data. Diagnostic routines are programmed in the ground station to isolate engine problems and provide substantiating data in a usable format. Historical data storage capability is also provided.

- II. Design Requirements: The primary design objective of the system was to reduce engine-caused aircraft losses by 50% through early detection and warning of engine problems. Secondary objectives were to reduce maintenance costs and improve aircraft availability. No specific goals were initially established, but as the system design evolved, a 20-25% reduction in maintenance costs and a 20% improvement in aircraft availability were deemed as desirable and feasible goals.

The only major design requirement was that the system be of a "bolt-on" configuration to enable retrofit with a minimum expenditure in man-hours. The preliminary reliability requirement was a mature system Mean Time Before Failure (MTBF) of 375 hours. Self-test protection was also required to assure that system failures would not result in false warnings or erroneous engine maintenance.

III. Accomplishments: Throughout the progressive evolution of this program, several major accomplishments have occurred, including:

1. Enthusiastic acceptance of the system and endorsement by the operating squadrons due to improved maintenance troubleshooting time resulting in increased aircraft availability.
2. Successful hardware qualification testing (Environmental, EMI, Reliability).
3. Documented reduction in engine removal rate (IECMS - 2.9/1000 FH's vs. Fleet - 4.9/1000 FH's).
4. Decrease in engine related maintenance man-hours per flight hour (IECMS - 0.323 vs. Non-IECMS - 0.809).
5. The time to transcribe and analyze the tape on the ground station has been reduced from over 30 min to less than 10 minutes.
6. 50 000 flight hours of system operational experience accumulated without an engine-related aircraft loss.
7. Reduction in unsubstantiated component removals (fleet averages three times higher than IECMS-equipped aircraft).
8. Demonstrated capability to monitor life usage data and accumulate for Navy automatic data processing in support of Navy Engine Analytical Maintenance Program (EAMP).
9. Evolutionary design process to optimize parameters monitored (Table 1) and enhance system cost effectiveness.

IV. Lessons Learned: In a program as long as IECMS (over 10 years), many valuable lessons have been learned. These include the following (not prioritized):

1. The complex interrelationships of various design disciplines such as airframe, avionics, ground support equipment and powerplants, as well as the different responsibilities of engineering and product support areas, require a program management focal point to assure success and also a good working relationship with the customer.
2. An EMS cannot be fully tested in a flight test environment. It is essential to "fine tune" the system in the actual operational and maintenance environment in which it will be utilized.

3. A significant data base is required to thoroughly develop diagnostic and data handling techniques. Over 50 000 IECMS flight hours have been accumulated to date, and improvements in data handling and diagnostic accuracy continue to be made.
4. Vibration monitoring has proven to be the most essential element of IECMS from a flight safety point of view. It is essential to have a high degree of signal reliability and adequate software to eliminate false warnings. A change in philosophy was initiated midway through the program when it was decided to concentrate only on engine rotational vibration and not monitor all the gearboxes and accessories. The more sophisticated approach was not economically justifiable due to the amount of additional testing and software development required.
5. Erroneous system outputs cannot be tolerated. While sensor and transducer reliability has been excellent, several software changes have been implemented to recognize bad data and prevent erroneous flag trips, warning lights or diagnostics. This is essential in developing operator trust in the system.
6. Significant problems have been encountered in accurately digitizing the output of the existing A7 fuel flow measurement system. Future systems should take advantage of more modern and accurate fuel flow measurement systems to assure that necessary accuracy can be obtained.
7. Engine operating limits must be re-evaluated upon introduction of an engine monitoring system into a service environment. As an example, TF41 engine turbine operating temperature limits were established taking human factors into account (accuracy of reading the gage, remembering the extent and time above temperature, etc.). When these limits were programmed, data showed many "overtemps" were occurring in normal operation. Limits were subsequently modified to compensate for the difference in human versus machine monitoring. Another factor is "operational" limits versus "design" limits. Early in the IECMS program, some accessory components had no service limits because they had not previously been monitored. When "design limits" were programmed into IECMS, many components were rejectable. Therefore, "operational" limits consistent with IECMS capabilities had to be developed.
8. User skill levels must be an integral factor in the design of an EMS. IECMS has gone through several iterations to tailor system output to the operators' requirements. More complete diagnostic information, less data, simpler operational procedures and reduced analysis time have all been achieved as the program has progressed.
9. Due to the low output levels characteristic of EMS parameters, special care must be taken in harness and connector design to minimize susceptibility to contamination. The next generation TF41/A7E system will utilize special connector booting and harness sleeving to maximize protection from contaminants.

V. Future Recommendations:

1. System cost effectiveness is the single most important design requirement. Utilization of an EMS must result in adequate engine maintenance savings to justify the system cost. The Navy has authorized a multitude of studies throughout the IECMS program to justify the system. Several design refinements have resulted in order to enhance the cost effectiveness of the system.
2. The system must be designed for maximum maintainability, including self-diagnosis and transducer interchangeability without calibration. These features, along with high reliability, are much more important than absolute accuracy. Sophisticated analytical techniques may have to be compromised to assure minimal system maintenance.
3. Computer memory capacity provided should be at least two times that which is anticipated. Both IECMS airborne and ground station computer programs have doubled since the initial prototype system flight test. If adequate capability had not been initially provided, many system improvements and expanded capabilities could not have been considered.
4. The EMS should be software oriented in order to enable flexibility in monitoring engine problems. As an engine evolves through its life cycle, the nature of operational problems encountered changes. The initial IECMS design concept has enabled the system to be programmable to respond to these changing requirements.
5. Adequate resources must be committed to the development of an engine monitoring system. A prolonged development and test cycle due to funding constraints (engine monitoring assigned low priority) reduces the life cycle cost effectiveness of a system retrofit. Unavailability of funding has significantly lengthened the IECMS development cycle.

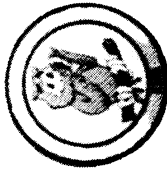
- VI. Summary: The accomplishments and lessons learned as a result of the TF41/A7E IECMS program have established many guidelines for future military engine monitoring programs. This paper provides an overview and some highlights of the more significant of the items. Several reports and papers providing more detail in various aspects of the IECMS program are listed in the references section.

VII. REFERENCES:

1. E. A. Schotta & AEC R. Rosenbrock, USN, "An Assessment of IECMS Cost-Benefit," NAILSC Report No. 200-76-01, February, 1976.
2. L. R. DeMott, "TF41-A-2/A7E Inflight Engine Condition Monitoring System (IECMS)", AIAA paper No. 78-1472.
3. L. R. DeMott, "TF41/A7-E Engine Monitoring System Implementation Experience," SAE Paper No. 801222.

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PROGRAM MILESTONES

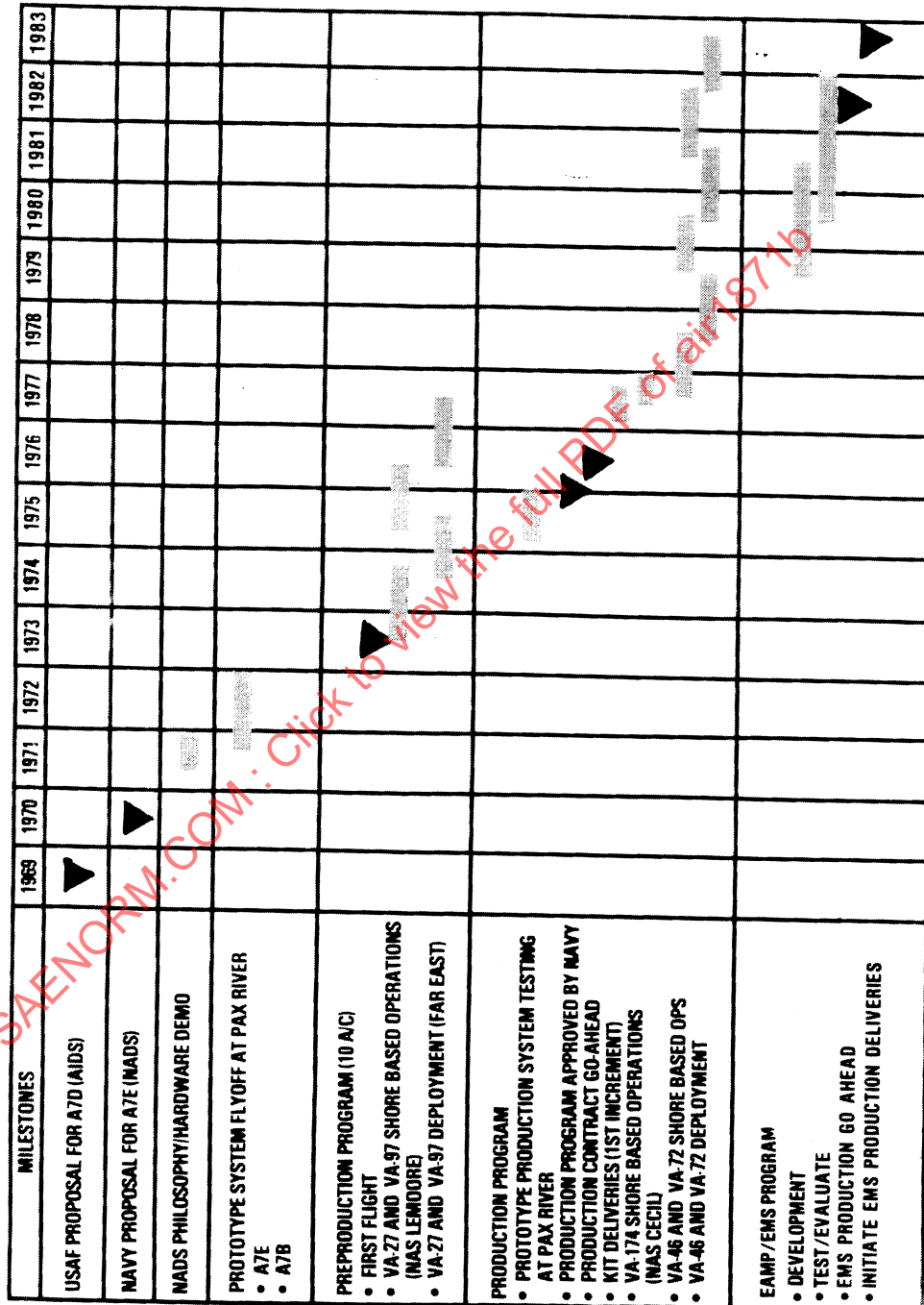
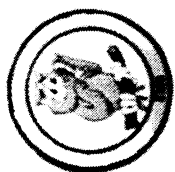


FIGURE 1 - Program Milestones

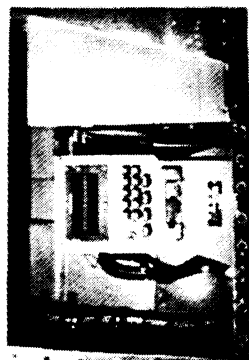


A7E/TF41 ENGINE MONITORING SYSTEM



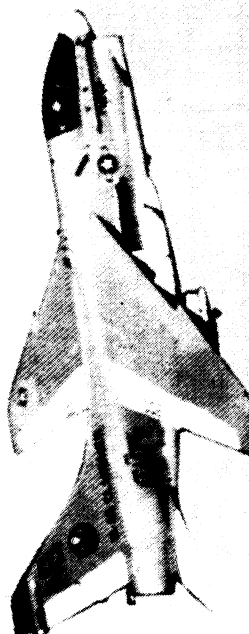
ENGINE KIT

- 35 ENGINE PARAMETERS
- 11 TRANSDUCERS
- EXTERNAL BOLT ON DESIGN



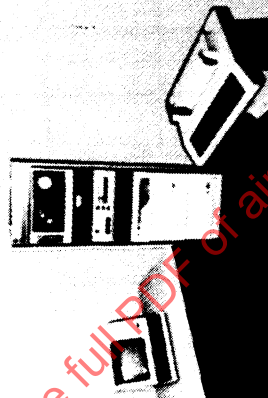
AVIONICS KIT

- CONTINUOUSLY MONITORS ENGINE
- RECORDS REQUIRED DATA
- STORES/DISPLAYS STATUS MESSAGES
- REAL TIME PARAMETER DISPLAY



AIRCRAFT KIT

- 11 OPERATING PARAMETERS
- EDS COMPARTMENT
- COCKPIT DISPLAY & PILOT RECORD SWITCH



DATA PROCESSING STATION

- ANALYZES DATA
- ISSUES MAINTENANCE DIRECTIVES
- PROVIDES MANUSCRIPT DATA
- AUTOMATIC HISTORY STORAGE

FIGURE 2 - A7E/TF41 Engine Monitoring System

1970 - 1983

	PROTOTYPE TECHS	PREPRODUCTION TECHS	PRODUCTION TECHS	PRODUCTION EMS		PROTOTYPE TECHS	PREPRODUCTION TECHS	PRODUCTION TECHS	PRODUCTION EMS		PROTOTYPE TECHS	PREPRODUCTION TECHS	PRODUCTION TECHS	PRODUCTION EMS
MOTOR SPEEDS														
LP Motor (n_L)	X	X	X	X										X
HP Motor (n_H)	X	X	X	X										X
GAS PATH TEMPERATURES														X
LP Compressor Inlet (T_1)	X	X	X	X										X
HP Compressor Discharge (T_3)	X	X	X	X										X
Turbine Out ($T_{5,1}$)	X	X	X	X										X
GAS PATH PRESSURES														X
LP-IP Compressor Static ($P_{S2,1}$)	X	X	X	X										X
LP-IP Compressor Total ($P_{T2,1}$)	X	X	X	X										X
HP Compressor Static (P_{S3})	X	X	X	X										X
Turbine Out ($P_{T5,1}$)	X	X	X	X										X
FUEL SYSTEM PRESSURES														X
LP Governor Differential (ΔP_{PG})	X	X	X	X										X
Hydro-mechanical Governor Differential (ΔP_{HMG})	X	X	X	X										X
Main Manifold (P_{PM})	X	X	X	X										X
Pilot Manifold (P_{PM})	X	X	X	X										X
HP Pump Inlet (P_{PI})	X	X	X	X										X
HP Pump Outlet (P_{PO})	X	X	X	X										X
Main Fuel Control Outlet (P_{FC})	X	X	X	X										X
FUEL HEATER OUTLET TEMPERATURE (FHT)	X	X	X	X										X
IGNITION SYSTEM														X
LH Permanent Magnet Generator AC Output (AC_L)	X	X	X	X										X
BH Permanent Magnet Generator AC Output (AC_B)	X	X	X	X										X
LH Shorting Loop Current (I_{LL})	X	X	X	X										X
BH Shorting Loop Current (I_{LB})	X	X	X	X										X
LH Exciter Output (I_{EL})	X	X	X	X										X
BH Exciter Output (I_{EB})	X	X	X	X										X
LH Igniter Spark Rate (SPR_L)	X	X	X	X										X
BH Igniter Spark Rate (SPR_B)	X	X	X	X										X
ELECTRICAL SYSTEM														X
Permanent Magnet Generator DC Output (PMG_{DC})	X	X	X	X										X
Gold Start Solenoid Voltage (E_{GS})	X	X	X	X										X
LPC Solenoid Current (I_{LPC})	X	X	X	X										X
LPC Solenoid Voltage (E_{LPC})	X	X	X	X										X
Auto Relight Actuator (ARA)	X	X	X	X										X
Double Datum Amplifier Armed (DDA)	X	X	X	X										X
Over Datum Relay (ODR)	X	X	X	X										X
Total Parameters											54	63	52	46

TABLE 1 - Parameter Summary

5.3 Lessons Learned: Advanced Diagnostic Engine Monitoring System - Adems I & II (Report Covers Period 1972 to 1979):

- I. Technical Description: The objectives of the ADEMS program were to evaluate conventional and advanced state-of-the-art turbine engine monitoring techniques on board a large transport aircraft in operational service. The on-board system monitored the No. 3 engine on a C-5A aircraft. A total of 29 parameters were monitored to trend engine performance, track engine usage and isolate engine component faults. Fourteen new sensors were installed to complete the list of parameters to be monitored by the on-board data system. The list of new sensors and existing aircraft (A/C) signals are as follows:

	<u>New Sensors</u>	<u>Existing A/C Signals</u>	
Pressures	2	3	
Temperatures	3	4	
Speeds (NF, NC)	-	2	
Mech. Position	1	1	
Flows	1	1	
Accelerometers	5	-	
Others	<u>2</u>	<u>4</u>	
	14	15	Total 29

- II. Design Requirements: The system will operate unattended in a fully automatic mode and provide the necessary signal conditioning, microprocessor self-check features and indication of system hardware faults. The recorded data will also be processed by the on-board system to detect and display, in real time, any abnormal engine conditions of importance to the flight crew. Data acquired immediately prior to and after detection of an abnormal event will be recorded for in-depth evaluation by the ground based processor. For long term trending, the system will record preselected performance parameters during aircraft takeoff and during appropriate flight conditions for subsequent ground based processing and analysis. After the program was initiated, a separate low cycle fatigue monitoring technique was developed to evaluate the sensitivity of engine life usage to severity of throttle cycles.

- III. Accomplishments: The system accomplishments are as follows:

1. After system installation and checkout, the aircraft entered routine operational service. The system functioned satisfactorily over a ten month period before its removal without causing a flight delay or interference with other aircraft systems. The system accumulated 1121 h total engine operating time of which 700 h were during flight.

2. Approximately 50 h of sea level testing were conducted on the instrumented engine to thoroughly document baseline performance, finalize the ground based gas path analysis algorithm and check out the on-board fault analysis routines. Initial flight recorded data showed good agreement with baseline data permitting the initiation of engine performance trending.
3. Early in the flight test program, the on-board ADEMS hardware indicated that the variable stator vanes (VSV) were operating more closed in the high corrected speed region for optimum compressor efficiency and minimum fuel consumption. After engineering review, it was concluded that the main fuel control schedule was a potential source of the fault. A replacement main fuel control was obtained from supply channels and the unit was bench checked by the manufacturer before installation to verify specified control schedule tolerances. Subsequent flight data indicated that the VSV were back within tolerance. The fuel control removed from the engine was returned to the manufacturer for bench check which confirmed that the control had a schedule error. If the ADEMS hardware had not detected the VSV off-schedule, the engine would have continued to operate at a less efficient condition. This condition would prevail for several hundred flight hours until such time that engine-to-engine fuel flow trend data could be used to indicate a degradation in No. 3 engine performance. If the VSV were detected more open, the engine would have less stall margin than desired and a greater chance for a compressor stall to occur.
4. Once-per-rev rotor imbalance monitoring was successfully demonstrated using high-output piezoelectric accelerometers and bandpass and tracking filters. Since no events of note occurred, the other features of the vibration monitoring system could not be conclusively evaluated. All of the testing conducted under the program reinforced the conclusion that low level accelerometer signal cables and connectors must satisfy stringent design and manufacturing requirements, consistent with the location environment, to provide reliable performance. In addition, the number of connectors in the low level signal wiring should be kept to a minimum to reduce noise and potential signal transmission problems. (See AIR1839, Engine Vibration Monitoring Systems).

5. Flight testing of the ADEMS was concluded when the inner combustion liner failed and the engine was removed and sent for repair. Careful review of flight acquired data indicated that hot section deterioration could be detected by the ground based trend analysis program approximately 200 h prior to the liner failure. Since the ADEMS flight testing was conducted on a non-interference basis, data retrieval and analysis lagged by as much as 30 to 60 days because the aircraft would not always return to home base and the problem of scheduling qualified personnel to remove the data tape when the aircraft was available. The on-board system did indicate a significant reduction in takeoff temperature margin approximately 56 h before the failure. This event was reported but the engine continued in service since the takeoff margin had not reached the critical limit. Due to a series of world wide support flights away from home base coupled with the inherent delay in transporting and processing data tapes, it was impossible for the ground based data system to provide a timely update of the trend in hot section deterioration.

IV. Lessons Learned:

1. Properly acquired takeoff data have been proven effective for performance trending.
 - o During takeoff after the exhaust gas temperature becomes "stable", engine parameters were recorded for ground processing. When the data were averaged, the performance computations provided satisfactory performance trending information that could identify long term engine deterioration. In addition, the on-board computation and display of Exhaust Gas Temperature Margin appears to be a good candidate for flight deck engine monitoring.
2. Automatic recording is of greater accuracy and repeatability than manually recorded data at steady-state conditions.
 - o During the flight evaluation, flight deck instrumentation readings were manually logged and compared with the system acquired data. On numerous occasions, obvious errors were detected in the manually logged data. Approximately 20% of the error in the manually recorded data was due to analog instrument insensitivity and human factors.
 - o Delays must be avoided in data retrieval, trend analysis and "feedback" of engine deterioration information so that "educated" decisions can be made for quick turnaround of the aircraft or opportunistic maintenance scheduling of the engine to avoid extended damage.

3. Proper recording and data reduction of throttle excursions can more accurately predict LCF counts than a major/minor cycle count system.
 - o A refined LCF life count system was developed and evaluated using a computer simulation of different mission profiles and throttle activity. The technique demonstrated more sensitivity to cycle severity and thus more accurate accounting of parts life usage than a major/minor cycle count system. This related the need for adequate tracking of mission usage profiles to more accurately track accumulated damage to life-limited parts.
4. On-board system must validate/filter data prior to recording or "flagging faults."
 - o Comprehensive data validation routines, consistent with diagnostic objectives, are required. Data used for on-board diagnostic processing routines must be validated prior to raising a "flag." If a data system problem is identified, the flight crew and ground maintenance personnel should be advised. Filtering techniques to flag sensor measurement inconsistencies and automatically reinsert the last correct value should be developed.
5. Ground processed data should use algorithms to remove sensor drift, measurement and system bias before meaningful trending can be accomplished.
 - o It is important that the flight acquired data be validated before meaningful trend plots and information can be attained. This will allow differentiation between system and engine problems for meaningful ground based fault isolation. For these purposes, the in-flight processor should incorporate routines to identify sensor drift and to establish median values of compressed data for trend processing over a suitable time frame.
6. Establish performance limits at a level of concern vs. "red-line".
 - o If only "red-line" values are used to identify a fault, then reaching these limits may indicate that a failure has already occurred. With an alarm prior to reaching a red-line condition, flight crew attention can be directed to a potential problem area before extensive damage can occur. This margin can also be used to check for false alarms in the system. In either case, more time is available to address safety of flight and flight planning alternatives.

7. Minimize in-line connectors and length of low-level signal cables to avoid signal-to-noise problems. (See AIR1839, Engine Vibration Monitoring Systems).
 - o Although the accelerometer systems demonstrated responsiveness to fan unbalance, long-length, low-level signal cables with intermediate connectors are not recommended.
 - o It is recommended that vibration signal conditioning be located or incorporated in other electronic conditioners on or as close as practicable to the engine(s).
8. Although durable and maintenance free, the pyrometer turbine blade monitoring system did not prove effective due to unacceptable scatter of data at cruise speeds.
 - o The causes of unacceptable data scatter may be decreased to an acceptable level with a more optimal installation (than utilizing a borescope penetration) and further development of the pyrometer optics and electronics.
9. Further development is required for oil debris monitoring techniques. (See AIR1828, Oil System Monitoring).
 - o Although the capture efficiency of oil debris monitors have shown a 94% capture efficiency, development of an adequate sensing configuration to monitor the rate and identification of collected debris is still needed.
10. Sensor repeatability/sensitivity over specific ranges of concern is more important than full range accuracy.
 - o The requirements for sensor accuracy over ranges that are beyond the expected measurement ranges aggravates validation checks and dilutes the accuracy and repeatability attainable over narrower ranges.
11. Modularize software for ease of update and debugging.
 - o Modularized system software architecture eases the problem of debugging and rapid system changes. It also simplifies the problem of software validation checks, fault isolation routines and maintenance.

12. Until confidence is gained with EMS fault detection capability, costly and time consuming ground test runs will continue to be the primary technique to corroborate engine problems.
 - o Confidence in the fault detection capabilities of an EMS cannot be achieved until the user has become totally confident with the reliability of the system data output and the products of the data analysis are easy to understand and found dependable from experience. Until that point is reached, maintenance personnel will continue to conduct ground test runs to support maintenance decisions.

V. Future Recommendations:

1. Future monitoring system weight and cost can be reduced approximately 50-60% through system integration. This is best accomplished during the initial design and development of the engine and aircraft to provide the necessary interfaces and data sharing via a central data bus and multiplex system. Such methodology should also increase overall system effectiveness and reliability because of less hardware and physical interfaces.
2. EMS design requirements should be based upon the aircraft type and the range of possible mission assignments, and the planned engine maintenance concept which defines in detail the various levels of engine maintenance responsibility and support requirements.
3. The on-board monitoring system should be fully automatic, and contain extensive self-check and fault isolation features. During flight, certain engine parameters should be processed in real time as determined appropriate for detecting and displaying abnormal engine conditions for flight crew operational decisions.
4. Data acquired immediately prior to and after an event should be recorded for ground data processing and analysis in order to adequately assess engine condition and maintenance needs.
5. A signal conditioner/multiplexer (SCM) or Propulsion Signal Multiplexer is recommended to precondition the measured engine parameters before the data is transmitted via a central data bus to the monitoring system processor. The SCM should be mounted on or near the engine to provide the most effective interface between the measured engine parameters and processor. In its most basic configuration, the SCM is designed to precondition and transfer only engine performance data. If engine vibration monitoring is being considered, the SCM should also be designed to charge amplify the low-level signal before transmission, thus, alleviating potential cable and connector noise. If the signal is being fed into a digital data bus, the SCM could digitize the signal prior to transmission. Additional features such as range checks, data validation, averaging, sensor failure identification, self test, etc. can be included in the unit to enhance data quality and reliability and reduce the functional requirements and complexity of the monitoring system processor and data recording unit.

6. One of the most significant development needs identified for the future is the availability of an automated maintenance management information system. This system should have the capability to systematically acquire and process the most recent engine data from the field and, in turn, provide updated engine status information to the operational, maintenance and support organizations on a timely basis. The most effective access to the engine data base is through an interactive graphic terminal and printer at the user level.

VI. Problem Areas:

1. For the hardware added to the engine and aircraft, the failures were largely from non-standard components such as a magnetic tape transfer cable, a speed frequency/voltage convertor, two engine run time pulser boards, and two PLA measurement potentiometers which were not manufactured to aviation standards. These problems could have been avoided by more stringent hardware specifications.
2. Through the course of flight evaluation, some aircraft acquired performance parameters evidenced shifts in calibration or provided unusable measurements which had to be dealt with during the trend analysis. These parameters included flight Mach No. and altitude, outside air temperature and engine pressure ratio. This could have been avoided by monitoring the drift of aircraft acquired parameters and/or periodic maintenance to check sensor/signal accuracy.

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5.4 Lessons Learned: F/A-18 Inflight Engine Condition Monitoring System (IECMS) (Report Covers Period 1979 to 1982):

- I. Technical Description: The F/A-18 IECMS is a real-time engine monitoring and life tracking system designed for the GE F404 engine and is 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 5 s before and 35 s 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 shown in Fig. 1. Their locations on the aircraft are shown in Fig. 2. The components highlights are:

Engine Sensors: Thirteen engine sensors, as defined in Fig. 3, 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 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 other systems.

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 2 to 4% of the MC capacity, depending on MC model. The logic, which is summarized in Fig. 4, can be thought of as falling into three categories: continuous engine operation monitoring logic, "as required" monitoring logic, and engine life usage tracking logic. The engine monitoring functions are further defined in Reference 1. The usage monitoring functions are discussed below in Life Usage Indices.

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.

The engine data displayed in the cockpit is shown in Fig. 5. 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 (see Fig. 5). When pressed, 5 s of prior engine/flight data and 35 s of subsequent data are recorded on the MDRM magnetic tape. 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 5 s of data in the computer memory and freezing that data when an exceedance is detected or a data record is requested by the pilot. On F/A-18's delivered before October 1983, only 2 s of pre-event data were recorded because of limited mission computer capacity.

Life Usage Indices (LUI): In addition to the engine monitoring function of IECMS, engine life usage is also monitored during flight. Eight Life Usage Indices (LUIs) 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:

- o Full N2 RPM Cycles: This LUI, sometimes referred to as a "Type I Cycle," is defined as an Off to Intermediate to Off N2 RPM Cycle.
- o Partial N2 RPM Cycle: Also known as a "Type III Cycle," this LUI 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): SRCs are accumulated at a rate dependent on high pressure turbine (HPT) blade metal temperature. The higher the blade metal temperature, the faster SRCs are added.
- o Time at Max 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% of the maximum allowable.
- o Engine Operating Time: This is simply the time the engine operates at or above ground idle.

II. Design Requirements: The design requirements for the system were to:

- (a) Warn the pilot during flight of any detected engine anomaly serious enough to warrant aborting the flight.
- (b) Reduce maintenance costs by recording information during an engine anomaly for fault isolation on the ground.
- (c) Track the engine's remaining life by computing engine life usage parameters during the flight for later analysis in a ground-based Parts Life Tracking (PLT) program.

These requirements can be classified by the timeliness of their impact. The first objective has real-time impact. The second affects the postflight maintenance operations, and the third affects the long-term support costs of the engine.

III. Accomplishments: The system accomplishments are as follows:

- 1. Recording data during engine anomalies has accelerated the development of the engine.
 - o Many times, infrequent 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.
- 2. Reducing engine spare parts costs by tracking engine usage during flight.
 - o The engine usage is tracked using the Life Used Indices previously described. Based on actual usage data, spare parts cost savings were estimated to exceed \$18.10 per engine flight hour, or \$72 400 over the 4000 h life of an engine. Total Life Cycle Cost savings would be even greater if all elements of costs in the LCC accounting system are considered.

3. Successfully alerting the pilot on numerous occasions to engine anomalies during flight.
 - o Many times this feature has alerted the pilot to engine problems, allowing him to reduce engine power or shut the engine down, thus, avoiding costly secondary engine damage.
4. Greatly reducing the impact of a T1 signal failure.
 - o IECMS alerts the pilot to a failed T1 signal, allowing the pilot to retard the throttle to idle, thus preventing secondary damage to the engine. A failed T1 signal results in mis-scheduling of the fan inlet guide vanes and can cause compressor stalls. The new logic was incorporated into all F/A-18 aircraft within six months of encountering the T1 signal problem and has successfully detected faulty T1 signals on seven engines to date.
5. Reducing the engine maintenance costs by improving the post flight trouble shooting process.
 - o The improved troubleshooting is accomplished in two ways. First, after each flight, the ground crew checks the Maintenance Monitor Panel (MMP) in the nose wheel well to determine if an MMP code has been set. Twenty-two MMP codes are defined for each engine. Each code is assigned to a specific engine anomaly. These codes provide a direct entry into the troubleshooting trees, thus, removing much of the guesswork as to the nature of the problem. Second, the pre/post event data is used to further analyze the cause of the problem. Together, these two data sources provide a much improved capability to quickly identify engine problems, thus, greatly reducing engine maintenance costs.

IV. Lessons Learned:

1. To reduce weight and cost, consideration should be given to integration of engine monitoring systems with the other avionics on the aircraft. This is best achieved during initial design of the aircraft.
2. 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.
3. 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.
4. To accelerate development of the monitoring logic, a continuous recording system is desirable during the flight testing stage. Such a recording can be achieved via a separate on-board recorder or through ground telemetry.

5. 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.
6. To avoid setting false cautions and MMP codes due to spurious data, engine exceedances should persist for at least two computer iterations.

V. References:

1. P. M. Doane and W. R. Kinley, "F/A-18 Inflight Engine Condition Monitoring System (IECMS)," AIAA Paper No. 83-1237.

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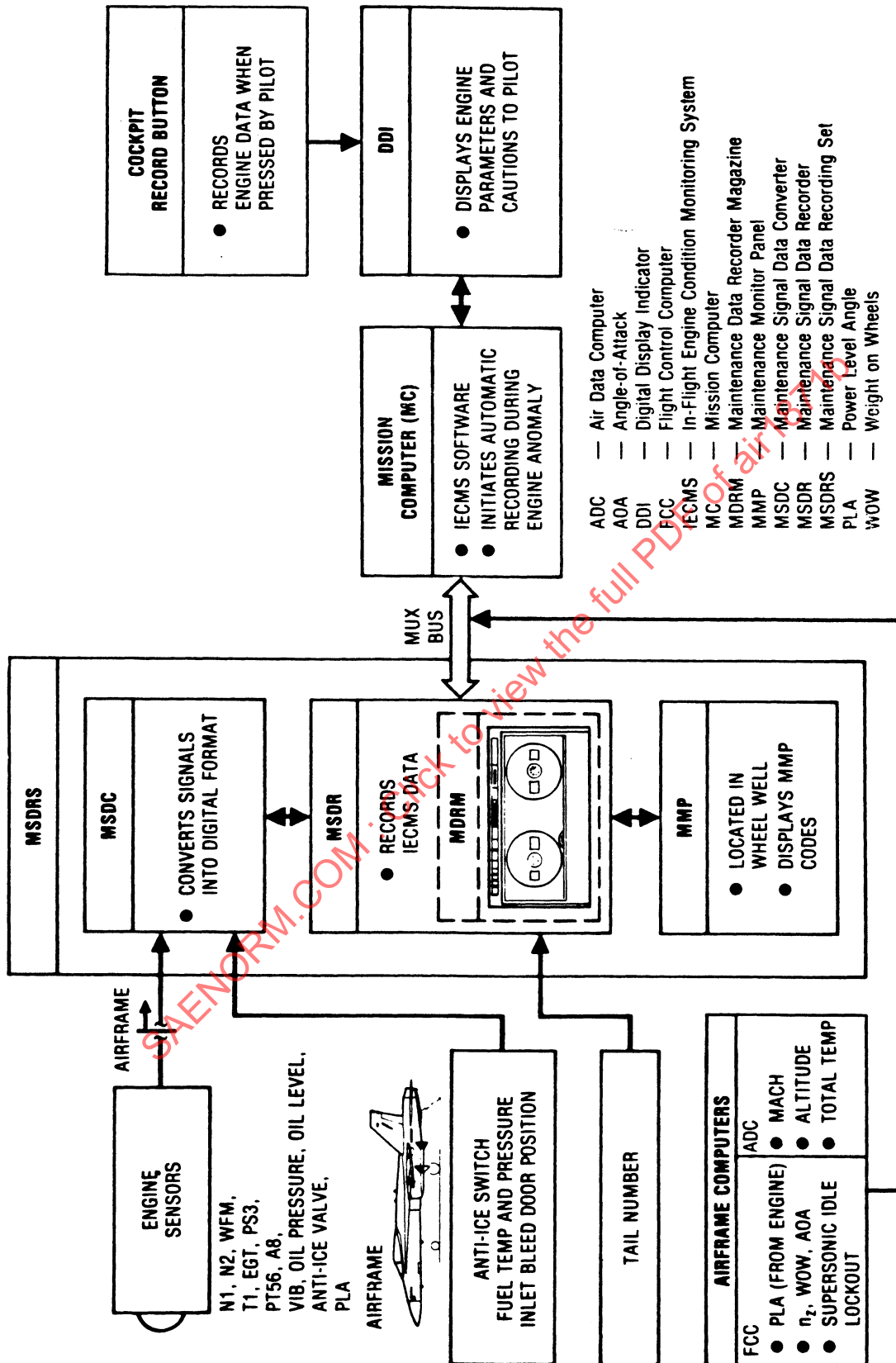


FIGURE 1 - IECMS Components

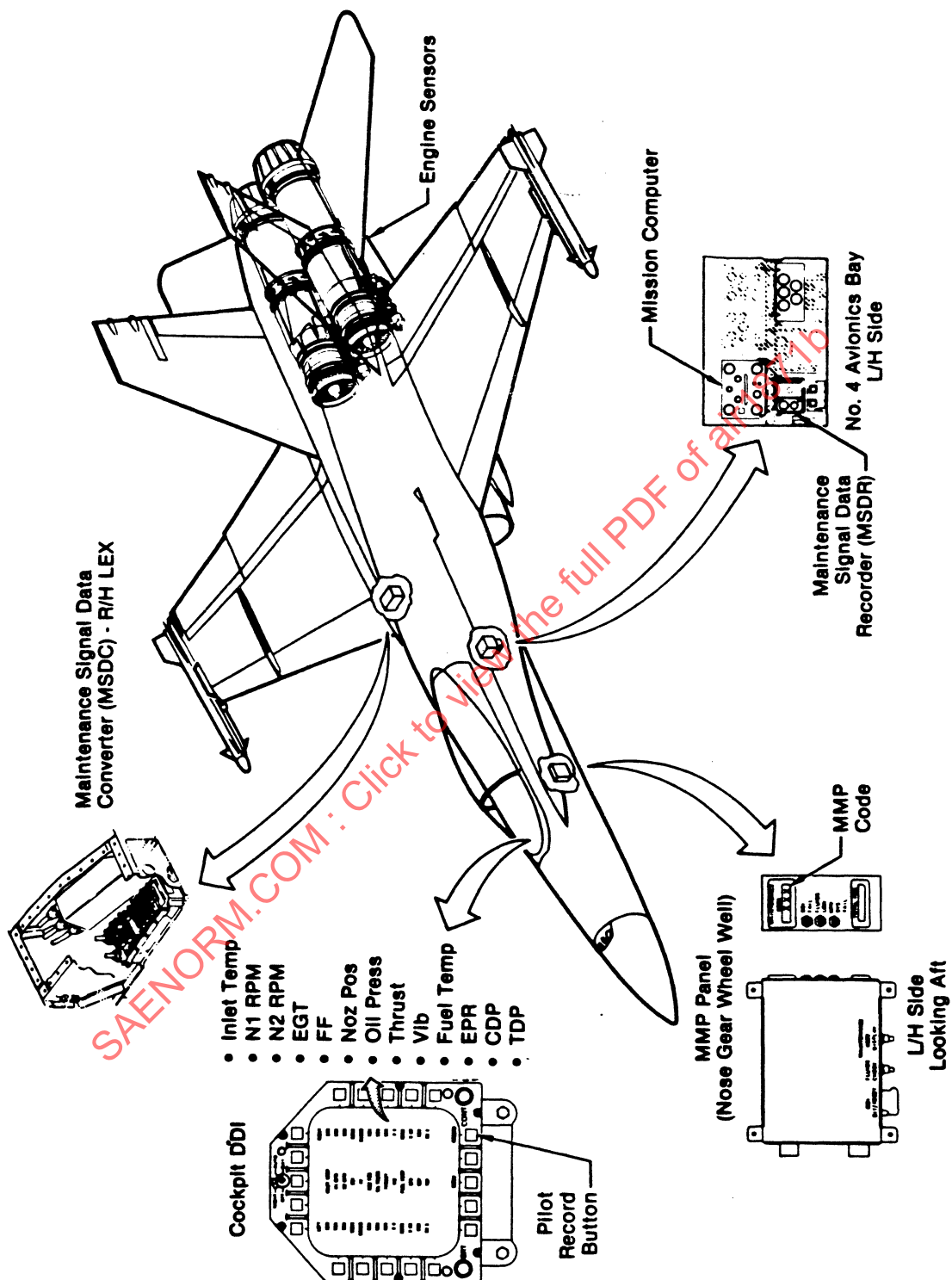
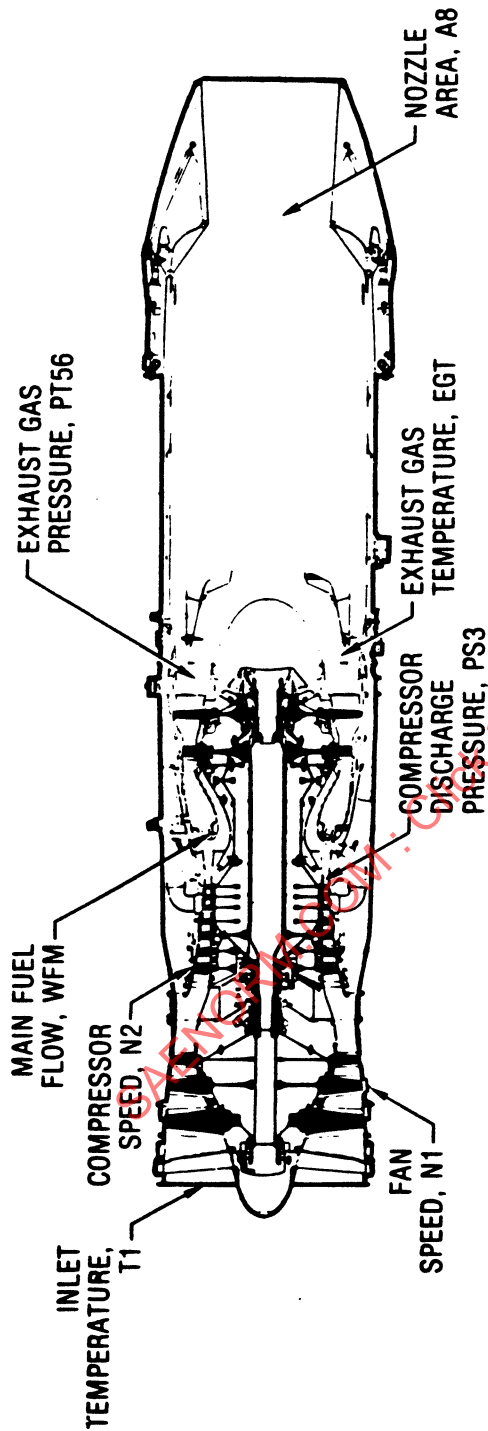


FIGURE 2 - Component Locations



SENSOR	SYMBOL	PRIMARY APPLICATION
● INLET TEMPERATURE ● FAN SPEED ● COMPRESSOR SPEED ● EXHAUST GAS TEMPERATURE ● NOZZLE AREA ● MAIN FUEL FLOW ● LUBE PRESSURE ● POWER LEVER ANGLE ● COMPRESSOR DISCHARGE PRESSURE ● EXHAUST GAS PRESSURE ● LUBE LEVEL ● ANTI-ICE VALVE POSITION ● VIBRATION	T1 N1 N2 EGT A8 WFM PL PLA PS3 PT56 LL AIVP V1	ENGINE CONTROL ENGINE CONTROL COCKPIT INDICATION COCKPIT INDICATION AUTOMATED CARRIER LANDING IECMS IECMS

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FIGURE 3 - Engine Sensors

- **CONTINUOUS MONITORING FUNCTIONS**

- EGT OVERTEMPS
- HIGH/LOW OIL PRESSURE
- ENGINE FLAMEOUTS
- FAN/COMPRESSOR OVERSPEED
- FAILED T1 SIGNAL
- ENGINE VIBRATION

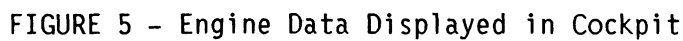
- **“AS REQUIRED” MONITORING FUNCTIONS**

- GROUND HOT STARTS
- TAKEOFF THRUST CHECKS
- POST FLIGHT LUBE LEVEL CHECK

- **LIFE USAGE FUNCTIONS**

- FULL AND PARTIAL N2 RPM CYCLES
- FULL AND PARTIAL BURNER PRESSURE CYCLES
- STRESS RUPTURE COUNTS (WEIGHTED HOT TIME)
- TIME AT HIGH POWER (UNWEIGHTED HOT TIME)
- EQUIVALENT FULL THERMAL CYCLES
- ENGINE OPERATING TIME

FIGURE 4 - IECMS Software Functions



5.5 Lessons Learned: United Kingdom (UK) Military Engine Usage, Condition and Maintenance Systems (EUCAMS) (Report Covers Period 1975 to 1983):

I. Technical Description: Two Engine Monitoring Systems are in use, and a third is under development for UK military aircraft. All three systems are interrelated and are designed for universal application. These systems are:

- (i) Engine Usage Monitoring System (EUMS I & II)
- (ii) Low Cycle Fatigue Counter (LCFC)
- (iii) (Standardized) Engine Monitoring System (EMS)

EUMS and LCFC are both principally aimed at achieving maximum life usage from major engine rotating parts, although they can be used for other engine monitoring functions. EMS is a consolidated development of EUMS and LCFC and is designed to provide a comprehensive engine monitoring capability.

EUMS I: which was developed in 1975, was the first digital Engine Monitoring System to be deployed in UK military aircraft. Essentially, EUMS I is a flight data acquisition and recording system supported by a centralized Ground Data Processing Station (GDPS). An overview of this system is depicted in Fig. 1.

EUMS II: is a microprocessor-based development of EUMS I designed for maximum flexibility as a monitoring system for fleet wide fit. In addition to operating as a flight data recording system, it is capable of executing life usage calculations in real time and displaying results on-board. The incorporation of a microprocessor has introduced flexibility previously unobtainable with EUMS I. Whereas EUMS I was limited to a fixed sampling rate of 32 words per second, EUMS II is programmable in binary steps from 32 to 512 words per second. Improvement to the tape recording system from single track to four track with data blocking has substantially increased the available data storage capacity.

Both EUMS I and II are designed to accept inputs from standard aircraft transducers, utilizing existing sensors and transducers in the majority of installations. Only a small number of any particular aircraft type are equipped with EUMS and, in general, the number of parameters recorded is modest, although some installations are more comprehensive as shown in Fig. 2.

EUMS I: is currently (or has been) used to monitor the majority of UK Royal Air Force (RAF) aircraft types to provide a continuing audit on engine usage in service. EUMS II which provides a more advanced but complementary function to EUMS I has not been adopted on a fleet fit basis, as originally intended. However, it is being used on engine test beds (as well as aircraft) as a low cost general purpose system, ideally suited for the development of engine monitoring algorithms and techniques.

LCFC: is a microprocessor-based unit designed to accept rotor speed inputs from standard aircraft transducers, execute LCF life usage algorithms in real time and display results via electromechanical counters or LED specifically designed for fleetwide application. (See Fig. 3)

EMS: is currently under development as a modular system for universal fleetwide application and consolidates EUMS and LCFC experience. The main functions of EMS are:

- o Life usage calculations (LCF and Hot Section)
- o Exceedance monitoring
- o Vibration frequency analysis
- o Incident recording
- o Bulk data recording
- o Performance monitoring
- o Maintenance advice

For its first application with AV-8B Harrier aircraft, EMS is designed to interface with analogue and digital data systems. Other applications are anticipated and the modular concept will minimize associated development costs.

Fig. 4 depicts the major milestones in the evolution of the three systems.

- II. Design Requirements: The primary objective of EUMS, LCFC and EMS is to maximize engine life and flight safety through accurate measurement of life usage parameters, although the EMS is also designed to have a maintenance capability. All equipment was designed for maximum flexibility, capable of use in any military aircraft. For this basic requirement, the equipment needed to be compact and lightweight as well as easy to operate by aircraft maintenance personnel. Special attention has been paid to the need for adequate facilities to validate the results produced.

EUMS I was designed as a digital system to accept inputs at a standard sampling rate from all types of speed, temperature and pressure transducers without the need to change the configuration of the box. The recording medium needed to be small enough for quick replacement and logistically acceptable for easy transportation through normal postal systems from flying units to the ground facility. The standard audio cassette proved an extremely satisfactory choice. Of particular note was the adoption of an existing in-service voice recorder, suitably modified, to provide the total history recording of all input parameters for processing off-line in a ground based facility.

EUMS II had the same basic requirements as EUMS I with the additional capability of real time engine life and exceedance calculations. Enhanced by the natural progress in electronics technology, it has been adapted for use as an airframe fatigue recording system.

From the results achieved using EUMS on sample aircraft, the RAF were convinced of the value in having a low cost life recorder fitted to whole fleets of aircraft. The LCFC was, therefore, designed to accept only speed inputs from engine transducers which, it was considered, would cater for the vast majority of engines currently in use.

The general availability of EUMS I and II has made them natural choices for more recent engine monitoring development programs. Although EUMS data is used primarily for life usage estimation, the creation of a large data bank has satisfied a general requirement for design feedback to engine parts improvement programs. An allied objective is to collect complete historical engine data records for continual algorithm development by correlation with parts condition. Both EUMS I and II are currently engaged in two unrelated programs with this objective in their terms of reference.

In one of these programs, EUMS I is being used to acquire data from a group of twelve Hawk T Mk 1/Adour MK 151 aircraft specially instrumented as depicted in Fig. 5. This program, with the project name Air Staff Target 603 (AST 603), has two main objectives:

1. To determine the extent of correlations between engine mechanical condition and measurable engine parameters.
2. To examine the impact of flight data recording on the overall maintenance policy of the Royal Air Force, with the ultimate aim of achieving On-Condition Maintenance (OCM).

In the other programs, EUMS II is being used on engine test beds to record the total history of Aircraft Simulated Mission Endurance Testing (ASMET) and Accelerated Mission Tests (AMT) to validate the life criteria to be used in service.

III. Accomplishments:

1. Service life extensions on several engine types providing significant financial benefits through reduction in engine parts consumption and overhauls.
2. The Service User readily accepted the sample EUMS fit as a cost effective means of having a continuous audit of life usage on existing established aircraft types.
3. Realization that notionally similar flying patterns have a wide range of engine usage rates.
 - o This variation in usage was related to many factors which were identifiable from EUMS data analysis. Engine variations, pilot to pilot variations and differing operational base factors provided a sound basis for the case to have dedicated engine monitoring systems as a fleetwide fit.

4. Some 40 000 h of flight data have been recorded through EUMS to date.
 - o The accumulation and storage of a meaningful data bank of usage information on a comprehensive spectrum of military aircraft has provided the means of compiling realistic engine test schedules. Furthermore, the use of these data to synthesize missions for new aircraft types has proved highly successful.
 5. The continuously recorded data from EUMS on engine behavior in actual service environments has provided important design information for the engine manufacturer, enhancing basic design criteria.
 6. EUMS has been successfully used to evaluate and correlate the results from dedicated life usage monitoring systems (such as the LCFC) under actual service conditions.
 7. Low Cycle Fatigue Counters have been successfully used on a variety of aircraft where engine usage variation is quite marked such as the Red Arrow display team.
 8. The design specification for the Low Cycle Fatigue Counter on performance, weight, and cost was successfully achieved.
 9. AST 603 accomplished the first comprehensive engine health monitoring system operated by RAF personnel. This has enabled the Service to have an in-house capability in engine usage and in-flight performance monitoring complementing its other extensive engine health systems already in operation.
- IV. Lessons Learned: The continuous development of the EUMS program, together with the design and development of a Low Cycle Fatigue Counter, has produced a number of very important lessons for future systems design and operations.
1. Close attention must be given to the overall system design including electrical wiring looms, connectors, etc.
 - o The integrity of the system should parallel that required for engine controls. The effect of poor or sub-standard instrumentation will cause spurious data and erroneous calculations and lead to lack of confidence in the system capabilities.
 2. The importance of validating input parameter values cannot be underestimated.
 - o Where possible, calibration checks should be conducted on a regular basis. For fleetwide applications, suitable automatic data validation methods must be incorporated.

3. Engine Life Cycle Cost benefit analyses should be commissioned as early as possible in the design specification phase in order to estimate cost effectiveness of the system and assist the decision making process of provisioning instrumentation during aircraft manufacture.
4. There is a continuing need to involve Service personnel in the operation and objectives of a sample fit monitoring system such as EUMS.
 - o Without full appreciation, Service personnel are unlikely to maintain interest. Special user appreciation presentations are considered to be an essential element to ensure interest and enthusiasm at base level.
5. Clear User Directives and Procedures are essential for smooth operation of systems.
 - o Where systems are fitted to sample aircraft of a fleet, particular attention must be paid to publishing clearly defined User Operating Instructions to ensure adequate support for the system in the field.
6. The functional requirements for a fleetwide Engine Monitoring System should be confined to those areas which are relevant to the engine type concerned.
 - o The temptation to incorporate a generalized suite of functions can lead to doubts regarding the purpose of the monitoring system. Similarly, the over-specification of functional requirements will lead to the unnecessary over production of maintenance data. This supports the case for a modular design which in itself must be skillfully conceived to ensure optimization for each application's minimum requirement.
7. The requirement for incident data must be carefully considered to ensure adequate on-board data storage capacity and to minimize the over production of data for diagnostic and maintenance purposes.
 - o It should be possible to have flexible recording rates for each parameter depending upon the type of event being monitored. These rates should, however, be kept as small as possible.
8. There is a need to develop automatic data retrieval systems to avoid the inherent problems of manual transcription.
 - o Manual transcription of life data from visual displays can lead to errors. A comprehensive management system was developed for the LCFC to obviate any discrepancies. However, for all future systems, an automatic data retrieval system will be used. Data extracted electronically by the retrieval system will be computer compatible for automatic input into the station computer.

V. Future Recommendations:

1. Systems should include a high degree of self test, having maximum reliability/maintainability and be capable of customizing to suit individual engine/aircraft requirements. Automatic diagnostic routines, simple re-programming facilities and system flexibility are prerequisites for future EMS.
2. Growth potential is essential for a future system to take account of changing User requirement. A minimum factor of two on both processor, computation capability, and memory capacity requirements is recommended. Since the military user requires maintenance information at first line, experience with systems in the field will undoubtedly lead to development of more comprehensive fault diagnostic routines which must be incorporated into the EMS. To assist the operator, it is necessary to have a high level language for ease of use.
3. The capabilities offered by continuous recording systems should be exploited fully during engine flight development to acquire data for defining the eventual requirements of an EMS with respect to:
 - o Validating algorithms.
 - o Minimizing the number of stress features to be monitored by identifying those that are dominant for a given aircraft mission mix.
 - o Determining parameter sampling rates.
 - o Testing data validation methods.
 - o Acquiring actual flight data for bench simulation/validation of proposed monitoring system.
4. Detailed study of the interface aspects of the complete system must be undertaken at an early stage to define in depth the various outputs and inputs. A high degree of interaction is envisaged in the future between the various aircraft systems. Developments in associated areas of accident data recording, airframe fatigue monitoring, transmission/ gearbox fatigue monitoring, and maintenance will, undoubtedly, lead to new approaches for total system(s) integration. Technical feasibility, cost and logistic benefits have yet to be quantified.
5. With the use of qualified in-flight equipment, it should be possible to correlate actual component damage with the life usage for that component. This leads naturally into Retirement For Cause (RFC).

ENGINE USAGE MONITORING SYSTEM Mk 1

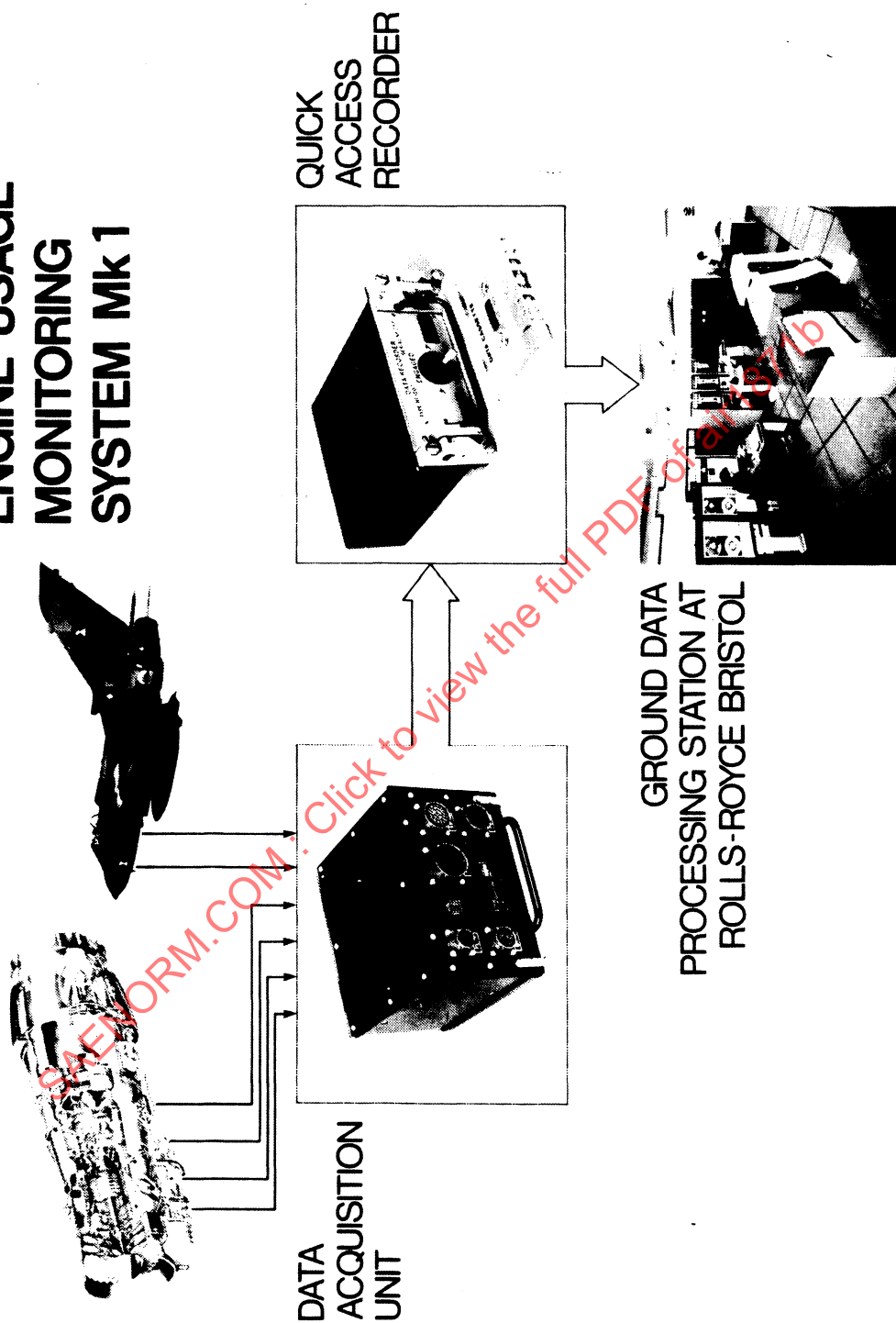


FIGURE 1 - Overview of EUMS System

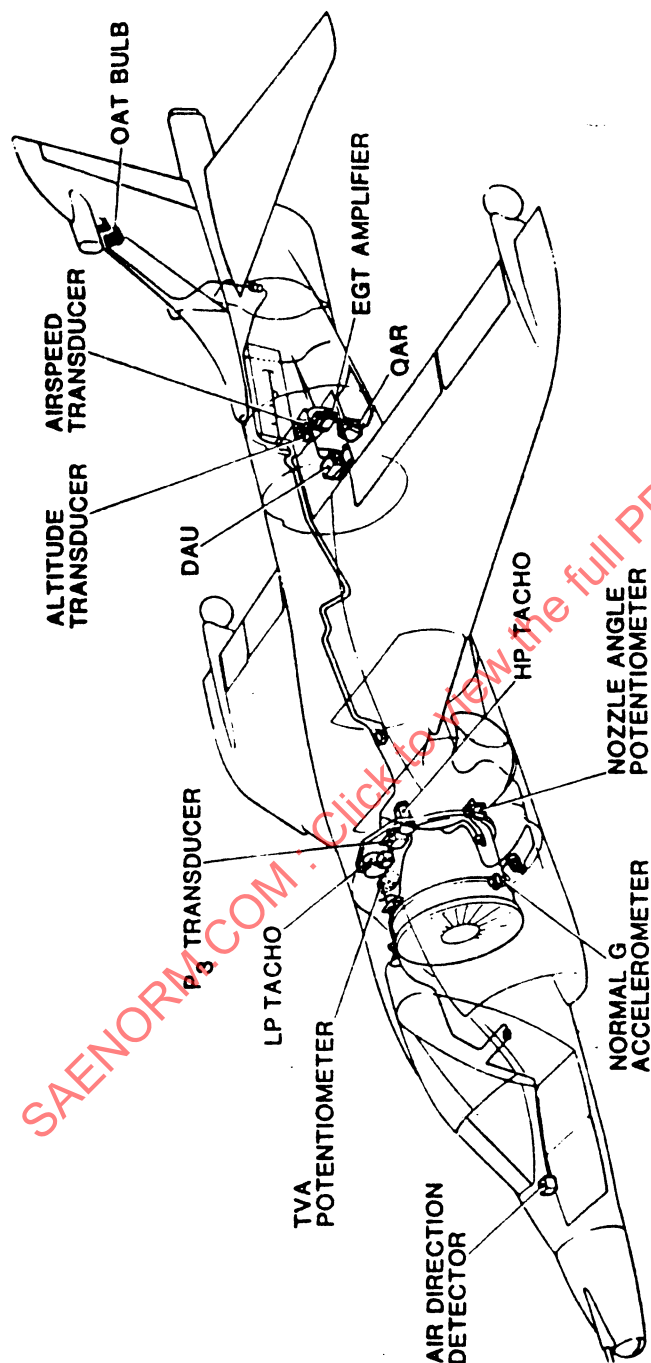


FIGURE 2 - EUMS Aircraft Installation



FIGURE 3 - Low Cycle Fatigue Counter

Development of engine monitoring systems in the UK

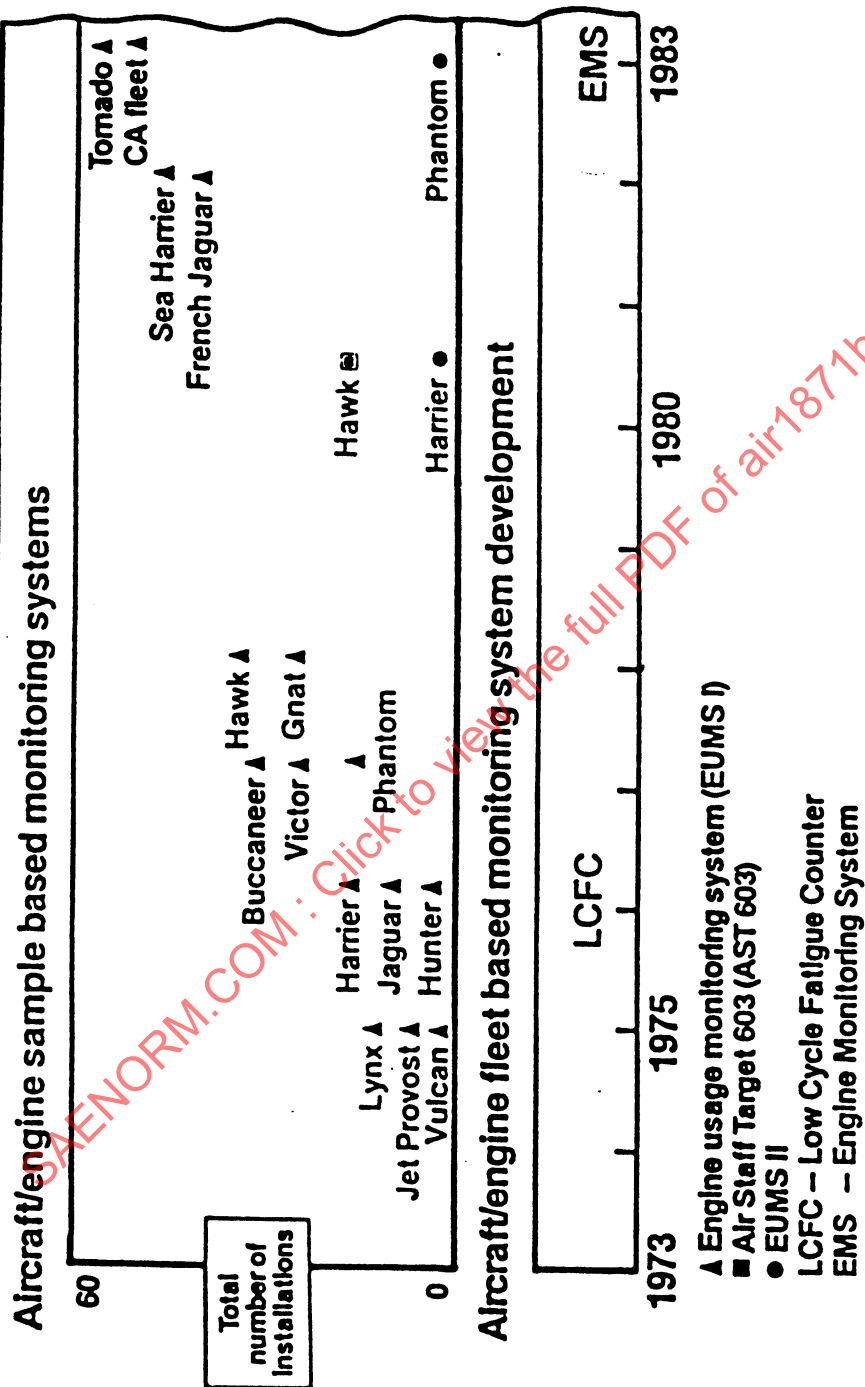


FIGURE 4 - The Major Milestones

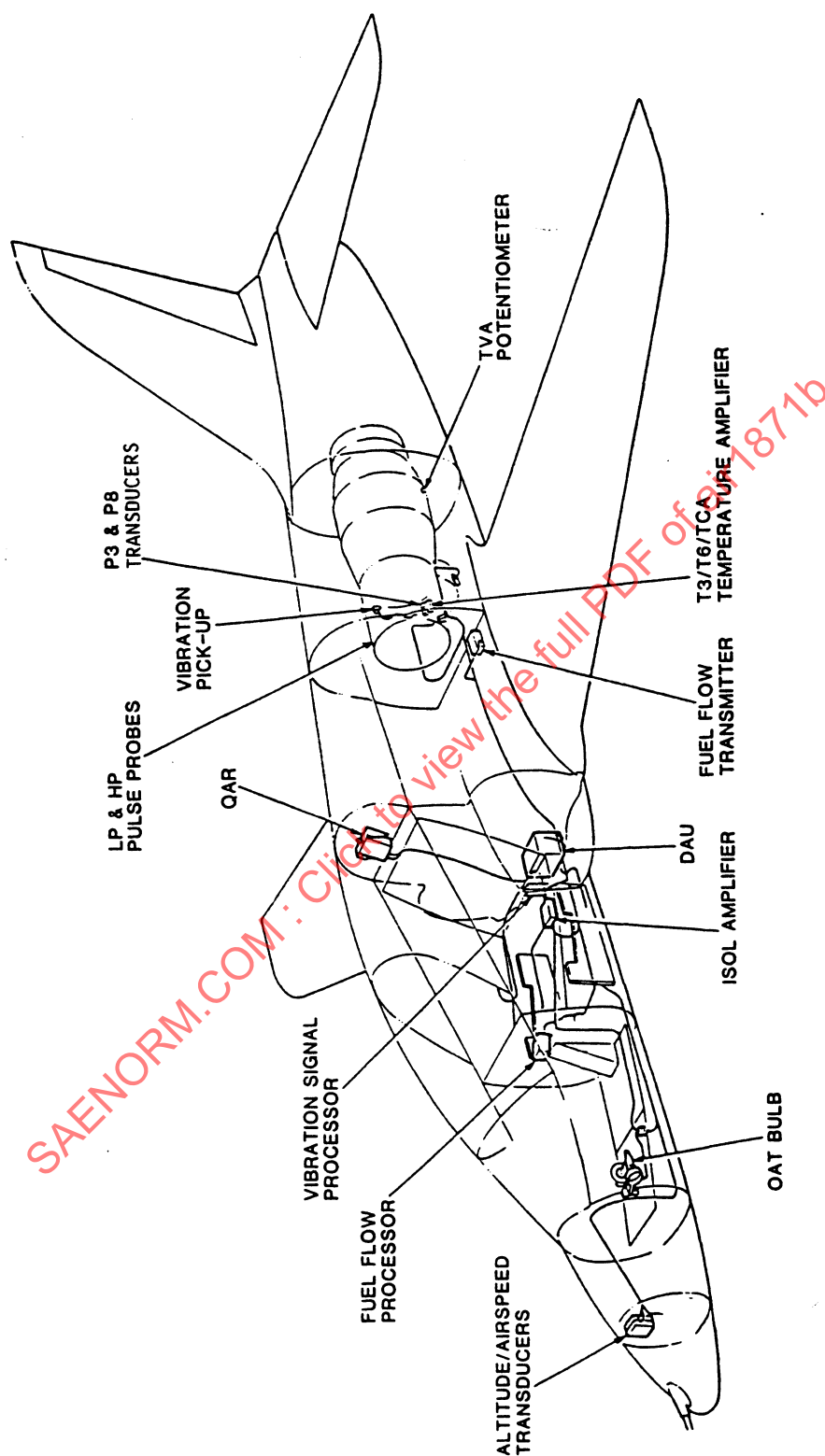


FIGURE 5 - HAWK T MK 1 - Specially Instrumented AST 603 Aircraft

5.6 Lessons Learned: An Operational Engine Monitoring System Applied to an International Airline (Report Covers Period 1979 to 1984):

I. Technical Description: The objective of the South African Airways (SAA) engine monitoring system has evolved over a period of 12 years of development to a main goal of minimizing engine removals away from home base. To accomplish this goal, it is important that the engine monitoring system include all of the following aspects:

- o Physical condition (borescope and vibration)
- o Operation defects
- o Performance (AIDS and manual recorded data)

These activities should be handled within a single group with the monitoring performed on three levels:

- (a) operational - defects and borescope
- (b) trending - problem analysis and forecasting
- (c) strategic - planning shipload and analyzing build trends

The following provides an in-depth description of the types and flow of monitoring information that are shown in Fig. 1:

1.1 Information Sources:

- (a) daily reporting of maintenance and flight defects and maintenance actions performed
- (b) a scheduled borescope program, whose intervals are determined by engine condition
- (c) spectrographic oil analysis on some engine models
- (d) test cell performance information
- (e) flight crew recorded cruise performance and vibration data
- (f) AIDS data gathered automatically during all phases of flight (A typical AIDS system is depicted in Fig. 2.)
- (g) engine build information

1.2 Information Processing:

1.2.1 Operational:

- (a) Although it is the prerogative of line maintenance staff to clear operational defects, Powerplant Monitoring maintains a catalogue of engine related defects, and recommendations for rectification are made after the third repetitive occurrence.

- (b) Borescope information, together with sketches and photographs, are kept with each engine file. A bi-weekly summary of all borescope data is published. Deterioration rates are determined.
- (c) Takeoff EGT margin is processed daily and also kept in the engine file. These data are also published bi-weekly together with borescope data.
- (d) Information is processed on request for various types of incident.
- (e) A small ground-based computer has recently been dedicated to processing engine monitoring information.

1.2.2 Trending:

- (a) A number of proprietary computer programs from engine and control manufacturers are utilized to trend performance and mechanical data.
- (b) Performance data are summarized and provided on a wall chart.
- (c) Module history records are computerized and refurbishment performed is correlated with analyzed performance levels.
- (d) Major operational problems are analyzed by reference mainly to trend information.

1.2.3 Strategic:

- (a) Monitoring information is used to predict shop workload by applying determined deterioration rates to current performance levels.
- (b) Engine workscoping is carried out with special reference to monitoring information. By setting a target for hours to be achieved on wing, workscope is tailored to engine performance level whenever possible.
- (c) Test cell performance levels are analyzed to provide a measure of engine build standard and feedback is provided at workscope committee meetings.
- (d) Aircraft dedicated to long range routes are fitted with more fuel efficient engines as indicated by monitoring data.

Fig. 3 provides a list of software available to analyze AIDS data for engine application.

- 1.3 Information Flow: Of vital importance to any monitoring program is effective communication of monitoring information. For this reason, the main body of monitoring staff is located at the maintenance control centre so that daily interface takes place, particularly with regard to flight defects.

Bi-weekly engine condition meetings are held at which the overall fleet condition as well as individual problem engines are discussed. All technical departments involved attend these meetings.

The workscope meetings are intended to provide another important forum for discussion between the Monitoring Group and other powerplant groups, and the opportunity to discuss the effectiveness of previous worksopes from a performance point of view. The results of this interface are that maintenance, shop and monitoring staff are starting to speak the same language. Each group now understands better the problems which face the other groups.

An important communication channel, often ignored, is contact with flight deck personnel.

- 1.4 Monitoring Philosophy: Monitoring is defined as maintaining constant surveillance. SAA philosophy is that at any time of day or night, easy access should be available to information which provides a full but brief account of all aspects of an engine's condition. This requires vigorous attention to filing systems and becomes at times unwieldy. However, by limiting the information to only the essential parameters it can be manageable.

The following are utilized as prime indicators of engine condition:

1. borescope inspection interval (reduced as distress becomes evident)
2. takeoff EGT margin
3. hours since major shop visit

These normally allow a quick determination of engine condition. Access is freely available to all recent defects and this information is available from an on-line computer system. A sample printout is shown in Fig. 4.

In the medium and long term, access is also available to data regarding fuel flow and module performance but this is seldom used in first line maintenance. Performance data is summarized on a colour bar wall chart system which allows non-performance orientated personnel to easily digest condition information.

II. Design Requirements:

2.1 Physical Condition Monitoring:

- o Detect potential engine hardware failures by means of borescope inspection, chip detector inspection, spectrographic oil analysis, and vibration monitoring. Engines with potential problems can then be removed at a convenient time and location.

2.2 Defect Monitoring:

- o Track engine defect reports, establish patterns, and recommend most effective remedial action.
- o Establish troublesome items and recommend modification.

2.3 Performance Monitoring:

- o Track engine gas path performance to identify high EGT and high fuel flow engines, and to assist in determining optimum refurbishment action required when engine visits workshop.
- o Determine cost effectiveness of refurbishment.
- o Provide shop load forecasts.

III. Accomplishments:

- ### 3.1 Operational Reliability: Shop visit rate 15% better than industry average. Inflight shutdown rate 40% better than industry average.

At the time of writing, (10/84), only two engine removals were required away from main base over a period of three years.

- ### 3.2 Correlation between Analyzed and Physical Condition: In order to fine tune performance analysis systems and ensure that actual physical condition corresponds with analyzed condition, it is an essential facet of the monitoring process that good records be kept of engine build and teardown condition. Unfortunately, this nearly always conflicts with production priorities. Once production staff gain confidence in monitoring activity and can observe the benefits, they are more likely to assist with this activity. A trial system on the JT9D-7F seems to have worked quite well and it is anticipated that CF6 build data will shortly be available.

Valuable feedback is also obtained by borescope staff being present at engine teardown.

- 3.3 Cost Benefits: The high level of operational reliability is worth on the order of \$5 million per annum in the form of savings in respect of relief flights, air turnbacks and passenger delay cost. For the SAA fleet of aircraft, this translates into a savings of approximately \$60 per flight hour.

The average fleet fuel flow is within 3% of manufacturers baselines, and approximately 1% lower than before the implementation of monitoring coordination, this being a saving of around \$1 million per year (\$12 per flight hour). Optimized refurbishment packages have saved on material cost, but it is difficult to isolate which savings are due to monitoring.

IV. Lessons Learned:

- 4.1 Information Management: SAA has learned that development of highly sophisticated monitoring systems, if not accompanied by appropriate information management, can be relatively fruitless, and return on investment minimal. Although some useful information was obtained during the formative years of AIDS technology, the system was not being used to anything like its full potential. More recently, attempts have been made to coordinate the flow of monitoring information, so that data can be used most effectively for maintenance management.

All monitoring information should be available to a central coordinating group, who should summarize the total picture, and provide data to maintenance staff in an easily digestible manner. All data should be presented in a form that assists a decision, not such that it raises further questions about the engine status. The amount of printed reports generated by typical systems is far too large.

Maintenance personnel should be trained to interpret monitoring information, and particularly AIDS system output, since this may often be required for flight line troubleshooting.

- 4.2 Experience with Performance Software:

(a) P&WA MAP II (JT9D):

This is a ground-based program to analyze engine test cell data. MAP II has been in use for over two years and has provided consistent results. Back-to-back test runs have exhibited some small unexplained performance shifts but our overall impression is good. In fact, one of the test cell correlation factors has been redefined by P&WA based on MAP II results. A major concern has been that HPT module performance levels are consistently low (-1.5%) and it has not been established whether this is due to HPT build, or a baseline problem.

Concerning test cell rejects due to high EGT, it is usually found that the performance algorithm attributes the high EGT to temperature profile shift, and consequently, lowers the analyzed EGT. Because of this, analysts are often unable to isolate poor module performance, but in a number of cases combustion liner changes can rectify the problem. MAP III has recently been implemented and is achieving excellent results.

(b) Hamilton Standard Airborne GPA (CF6-50):

This is a gas path analysis program resident in the airborne AIDS computer. When steady-state cruise data are available and smooth, consistent results are achieved with the GPA program. Investigation is continuing into causes of the unusually low incidence of steady-state cruise data windows. A program has been developed which is used to trend GPA results which helps to detect anomalies.

The major problem with the GPA program is the inability to modify the baseline coefficients which, through the vendor, takes considerable time. Since the software in the on-board computer has to be modified and reloaded, a ground-based program allows easier modification of baselines, coefficients and so on, and is a more elegant way of handling flight data performance analysis.

The program is fairly well able to contend with transducer inaccuracies as indicated by the steady trends observed in performance data. (Fig. 5)

(c) P&WA Team II (JT9D):

This program, like GPA, is also designed to do module performance analysis. Being ground computer based, it is able to use historical data and module life information. P&WA have recently released the TEAM III version of this program in which most of the TEAM II deficiencies have been cleared up.

Our experience with TEAM II has been good, although it requires a fairly high level of user involvement to obtain best results. The program contains the essential element of sensor error analysis, but it unfortunately tends to attribute most errors to the statistically poor transducers, even when one of the more reliable parameters is obviously in error. This can be attributed to the fact that insufficient in-service data has been fed back into the system to allow "fine tuning" of error probabilities.

Since the program has been in use for approximately 18 months now, the first few engines which have been tracked since their last major shop visit are now coming into the overhaul cycle again. Initial observations indicate that engine physical condition appears to correlate well with analyzed performance level, provided deterioration has been close to average expected rates.

On the operational level, TEAM II provides a valuable ECM output which can be correlated with hand recorded data and be used to highlight and request action on AIDS problems that might otherwise go unnoticed.

The TEAM II program also provides information on the takeoff EGT margin on almost every takeoff which is one of the prime engine condition indicators.

A most useful feature of the TEAM program is the ability to input sensing hardware change information into the program which are indicated on subsequent trend plots at the appropriate date position. From the SAA inventory system (MEMIS), regular printouts are obtained of sensing system component changes and these are then input to TEAM II. Thus, parameter shifts due to equipment changes can be explained and advice can be given to avionics staff of poor sensor performance. (Fig. 6)

By utilizing the TEAM II database in other software programs, monthly fuel flow data and reliability indices for all parameters can be established.

(d) ECM and ADEPT:

These are the mainstays of any airline engine monitoring system and continue to provide reliable cruise trend monitoring. These programs simply reproduce semi-graphical plots of cockpit recorded data corrected and compared to baselines.

- 4.3 Transducers and their Maintenance: The major obstacle to on-wing engine performance monitoring is the quality and maintenance of engine transducers and the associated data acquisition equipment. Since an airline has to meet a fairly demanding flight schedule, use is made of the principle of deferred action. Since the AIDS system is not regarded as necessary for the safety of flight, AIDS systems maintenance is generally very poor.

- Experience indicates that system reliability is best achieved when a dedicated team is responsible for AIDS maintenance.

- The basic quality of civil aircraft engine instrumentation falls short of the repeatability required for very reliable performance monitoring. Fuel flow measurement, one of the main parameters necessary to achieve cost benefit by performance monitoring, is hopelessly inadequate on non-digital aeroplanes, errors of $\pm 5\%$ being commonplace.
- Engine pressure transducers, excepting the latest quartz devices utilized in PMUX (propulsion multiplexor), provide no long term repeatability whatsoever. As a result of this, attempts to perform gas path analysis on wing have been abandoned.
- Engine parameter trend analysis must be accompanied by instrumentation error analysis, and before engine problems are dealt with, instrumentation must be verified. Transducer changes must be tracked so that bias errors can be eliminated from engine analysis.
- Special attention must be paid to wiring. The low-level parameter signals are extremely susceptible to noise, wire chafing and bad connectors, particularly in the hot areas around the engine.
- An operator must be aware that additional transducer maintenance cost may be offset by reduced engine maintenance cost.

4.4 Retrospective Overview: SAA involvement in engine monitoring goes back to 1971 when the Boeing 747 entered service with SAA. Since that time, considerable capital and manpower have been expended on development, particularly in the provision of AIDS.

On the operational level, benefits have been immediately obvious, and our ability to troubleshoot has been considerably enhanced. As various engine problems have arisen, the monitoring systems have been modified or enhanced to cater for these.

On the trending and strategic levels, it is almost impossible at this time to measure whether our program has been successful. The integration of advanced engine monitoring techniques into the overall engine maintenance management process has proved to be an extremely lengthy task. It is evident now that medium/long term monitoring information has been useful to our own Powerplant Group, since information which in the past was provided voluntarily, is now on demand. However, the role which monitoring can play in this area is dependent almost entirely upon the initiative of mainly the monitoring staff. They have to try to recognize the problems facing the Powerplant Maintenance staff and imaginatively develop ways in which monitoring information can be of assistance. This creates the situation of "the tail wagging the dog" and in a lot of cases monitoring techniques are developed for all the wrong reasons. However, by responding to the perceived needs, the monitoring staff creates credibility, which in turn leads to requests for further types of information.

As noted, SAA has not been dramatically successful in the application of medium/long term monitoring. The initial efforts were limited in part by the fact that our development activity was influenced perhaps too strongly by available software packages. By not analyzing needs first, developments were followed which in the final analysis proved not to be worth the effort expended. Recently, we have obtained much more relevant information by developing our own analysis tools, supplementary to the proprietary programs.

V. Future Recommendations:

- 5.1 Essential Planning of Monitoring Systems: Our advice to any airline starting off in the monitoring field is to develop a full definition of information needs, after which the system can be designed to achieve this. Furthermore, all powerplant departments should be committed to their support of monitoring activity. The airline should have a very clear picture of what the monitoring system should achieve. A good starting point would be to pinpoint existing engine problem areas and determine whether monitoring could assist in these cases.

An airline which is heavily involved in monitoring should continually be self-appraising. Perhaps less emphasis should be placed on new system development, and more on cutting down on irrelevant reporting.

It has been found that providing either summarized data or exception reports has enhanced the impact and digestibility of monitoring information.

- 5.2 Look to the Future: Some developments which would enhance a monitoring system are:

- 5.2.1 Data-base system where AIDS data is dumped into the airline engineering computer and users can develop their own application programs. Powerplant staff would then be totally responsible for engine monitoring programs and could respond rapidly to new problems.
- 5.2.2 Transmission of data from out-stations or inflight to allow effective trouble-shooting away from base. Since the sophisticated expertise is at home base, they should have ability to assist route station staff.
- 5.2.3 Integration of AIDS into the total avionics package in such a way that it becomes imperative to maintain the system on top line. AIDS is currently regarded by many line maintenance personnel as a non-essential system and is accorded minimal priority in terms of defect rectification. Should AIDS functions be integrated into units such as the master warning system or the digital engine control, this problem should be alleviated.
- 5.2.4 Engine monitoring data should be presented on display screens, and paper output should be minimized.

VI. Summary of Problem Areas:

1. Inadequate transducer specifications.
2. Low priority for system maintenance.
3. Initial lack of strategy for software definition.
4. Inability to achieve good credibility for on-wing module analysis.
5. Inadequate definition of long term monitoring needs before system implementation.

VII. References:

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VIII. Terminology:

- ADEPT - Proprietary program for cruise data trending.
- AIDS - Aircraft Integrated Data System - on-board computer system for real time parameter recording.
- ECM - Engine condition monitoring.
- EGT Margin - Difference between operating EGT of an engine and the certified EGT limit.
- EVC - Engine Vane Control - varies compressor vane geometry.
- GPA - Proprietary module performance analysis program.
- HPT - High Pressure Turbine.
- MAP - Proprietary module performance analysis program for test cell data.
- MEMIS - Maintenance and Engineering Management Information System.
- PMUX - Propulsion multiplexor - digitizes engine parameters/signals for transfer to AIDS system on digital bus.
- TEAM - Proprietary module performance analysis program for inflight data.
- WORKSCOPE - Process of defining nature of refurbishment to be performed on an engine.

PREPARED BY
SAE E-32 COMMITTEE
AIRCRAFT GAS TURBINE ENGINE MONITORING

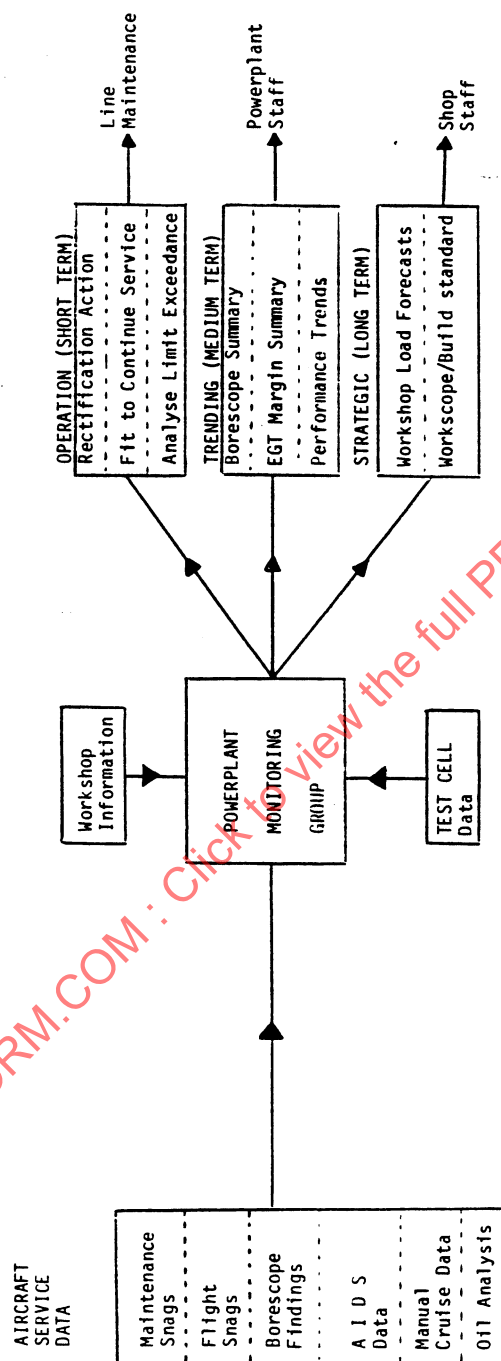


FIGURE 1 - SAA Powerplant Monitoring Information Flow

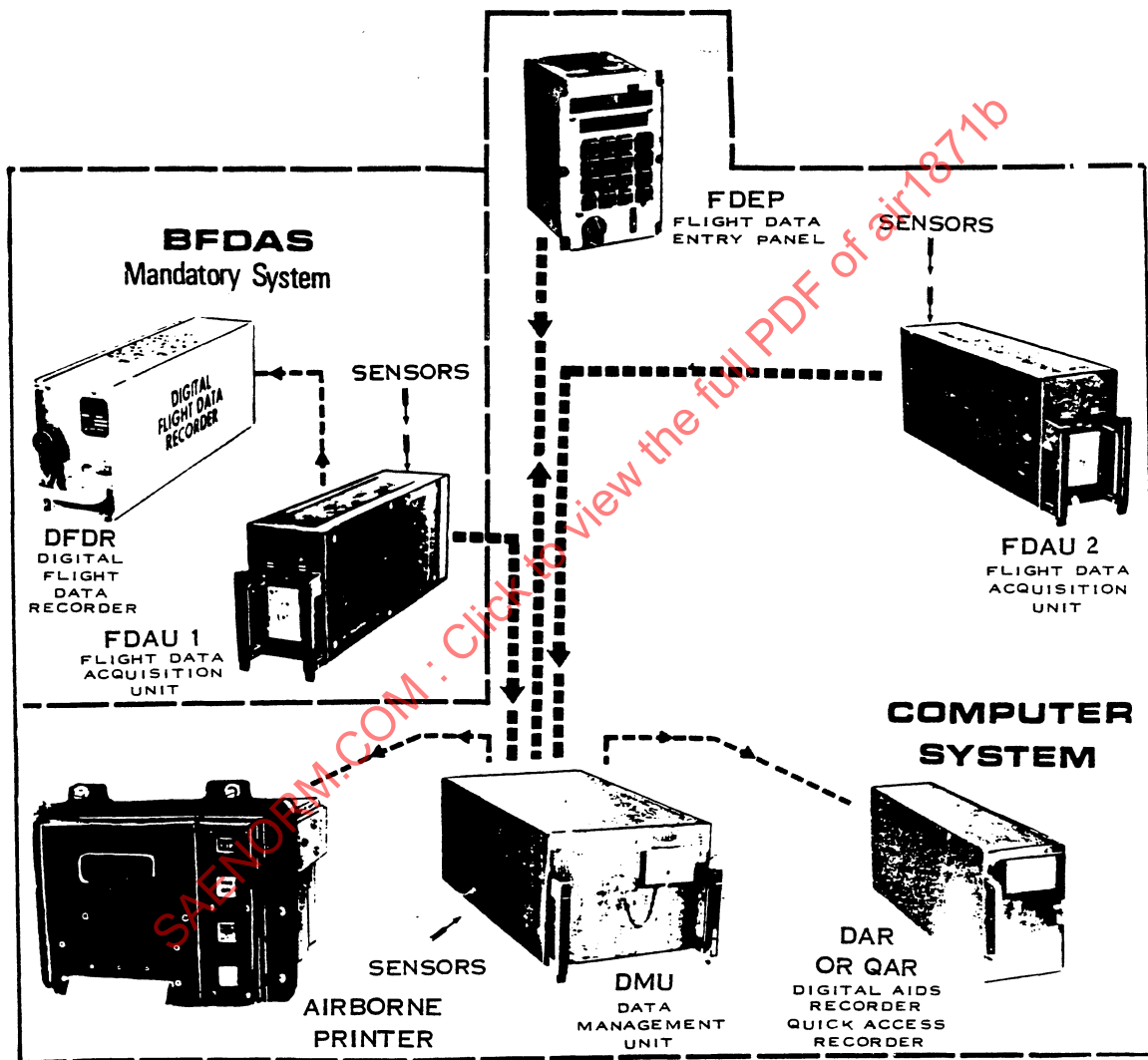


FIGURE 2 - Typical A.I.D.S. System Components

SAA GROUND BASED ENGINE MONITORING SOFTWARE

- | | |
|-------------------------------|--|
| 1. PMR QUICK LOOK | - Dumps PMR data in engineering units |
| 2. DFDR QUICK LOOK | - Dumps DFDR data in engineering units |
| 3. EGT EXCEEDANCE CHECK | - All A/C |
| 4. EGT MARGIN CHECK | - B747/A300 - Hot day margin |
| 5. EGT PROFILE CHECK | - B747 - individual probes |
| 6. STABLE FRAMES | - Capture stable cruise data |
| 7. PARAMETER PLOTS | - Short term trending |
| 8. TANDEM BLEED CHECK | - B747 |
| 9. THROTTLE STAGGER | - B747 |
| 10. VSV/EVC DATA FOR PLOTTING | - A300/B747 |
| 11. VIBRATION CHECK | - A300 |
| 12. N1/N2 EXCEEDANCES | - All A/C |
| 13. ECM MANUAL DATA | - All A/C |
| 14. ECM AIDS DATA | - All A/C |
| 15. GPA TREND PLOT | - Plot onboard printout trends A300 |
| 16. TEAM/MPA | - 747 cruise performance analysis |
| 17. MONTHLY AVERAGES | - 747 monthly performance summary |
| 18. ENGINE START ANALYSIS | - All A/C check FCU and nozzles |
| 19. REMOVAL PROJECTIONS | - B747 |
| 20. TAKEOFF SEVERITY | - B747 Analyze EPR and EGT levels |
| 21. THROTTLE CUSHION CHECK | - B747 |

FIGURE 3

TYPICAL ENGINE STATUS PAGESREMOVALS RECORDED
*****ENGINE 702436

<u>DATE</u>	<u>REMOVAL REASON</u>	<u>FINDINGS</u>
84/07/12	TURBINE DISTRESS	1ST STG HPT BLD BROKEN OFF AT MIDSPA
84/09/27	FUEL LEAK BETWEEN PUMP AND FCU	LEAK AT FCU THRU SHAFT

<u>LAST SHOP VISIT:</u> *****	<u>DATE</u>	<u>FAN</u>	<u>LPC</u>	<u>HPC</u>	<u>C/C</u>	<u>HPT</u>	<u>LPT</u>	<u>MGN</u>
	82/06/01	0	0	0	0	0	0	0
	84/09/02	0	0	N	0	0	R	8

CURRENT POSITION: SAS4 DATE IN: 84/09/27 HOURS ON-WING: 1897 EGT MGN: -3
*****BORESCOPE CONDITION: CLEANDELAYS & COMMENTS: REMOVED EX SAS3 84/09/27 DUE TO FUEL LEAK

<u>REPETITIVE DEFECTS</u>
EPR IND FLUCTUATES
85/02/02

REMOVALS RECORDED
*****ENGINE 715044

<u>DATE</u>	<u>REMOVAL REASON</u>	<u>FINDINGS</u>
84/09/26	TO INSTALL B2 PACKAGE ENGINE	

<u>LAST SHOP VISIT:</u> *****	<u>DATE</u>	<u>FAN</u>	<u>LPC</u>	<u>HPC</u>	<u>C/C</u>	<u>HPT</u>	<u>LPT</u>	<u>MGN</u>
	83/05/25	0	0	0	0	0	0	35
	84/10/11	N	N	N	N	N	N	12

CURRENT POSITION: SAL2 DATE IN: 84/10/22 HOURS ON-WING: 5522 EGT MGN: 33
*****BORESCOPE CONDITION: CLEAN, interval = 760DELAYS & COMMENTS:

<u>REPETITIVE DEFECTS</u>
TCCS INOPERATIVE
840501

FIGURE 4

SOUTH AFRICAN AIRWAYS ** ENGINEERING AND MAINTENANCE ** CE6-50 PERFORMANCE TREND DATA ** A300B

ENGINE SERIAL NO. 528268

CORR N2-RPM										CORR FUEL-FLOW										CORR VSV											
DATE	AC	POS	-4	-3	-2	-1	0	+1	+2	+3	+4	*	-4	-3	-2	-1	0	+1	+2	+3	+4	*	-4	-3	-2	-1	0	+1	+2	+3	+4
830607	SSDE	1				G						*				G						*									.B
830613	SSDE	1				G						*				G						*									.B
830613	SSDE	1				G						*				G						*									.B
830616	SSDE	1				G						*				G						*									.B
830620	SSDE	1				G						*				G						*									.B
830624	SSDE	1				G						*				G						*									.B
830624	SSDE	1				G						*				G						*									.B
830625	SSDE	1				G						*				G						*									.B
830628	SSDE	1				G						*				G						*									.B
830628	SSDE	1				G						*				G						*									.B
830628	SSDE	1				G						*				G						*									.B
830629	SSDE	1				G						*				G						*									.B
830630	SSDE	1				G						*				G						*									.B
830701	SSDE	1				G						*				G						*									.B
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830701	SSDE	1				G						*				G						*									.B
830702	SSDE	1				G						*				G						*									.B
830703	SSDE	1				G						*				G						*									.B
830705	SSDE	1				G						*				G						*									.B
830707	SSDE	1				G						*				G						*									.B
830711	SSDE	1				G						*				G						*									.B
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830716	SSDE	1				G						*				G						*									.B
830717	SSDE	1				G						*				G						*									.B
830717	SSDE	1				G						*				G						*									.B
830717	SSDE	1				G						*				G						*									.B
830719	SSDE	1				G						*				G						*									.B
830725	SSDE	1				G						*				G						*									.B
830730	SSDE	1				G						*				G						*									.B
830801	SSDE	1				G						*				G						*									.B
830802	SSDE	1				G						*				G						*									.B
830802	SSDE	1				G						*				G						*									.B
830805	SSDE	1				G						*				G						*									.B
830808	SSDE	1				G						*				G						*									.B
830808	SSDE	1				G						*				G						*									.B
830810	SSDE	1				G						*				G						*									.B
830812	SSDE	1				G						*				G						*									.B
830814	SSDE	1				G						*				G						*									.B
830815	SSDE	1				G						*				G						*									.B
830816	SSDE	1				G						*				G						*									.B
830817	SSDE	1				G						*				G						*									.B
830817	SSDE	1				G						*				G						*									.B

FIGURE 5 - Trend Plot of G.P.A Data Illustrating Smoothing