LEVEL II

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AIRCRAFT TURBINE ENGINE MONITORING SYSTEMS: OVERVIEW AND LESSONS LEARNED FROM SIX CASE STUDIES

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ABSTRACT

The research reported in this paper, conducted for the United States Air Force, reviews the experience gained from several aircraft turbine engine monitoring systems used over the last decade and a half and examines the implications of that experience for recently proposed monitoring systems. Rand report R-2391-AF and a report now in preparation describes in greater detail the supporting research.

Two different approaches to engine monitoring have evolved in attempts to achieve the goals of improved engine operations, maintenance, and management coupled with reduced maintenance costs. The first approach concentrates on day-to-day operations and maintenance concerns and is usually accomplished by recording a few seconds of engine usage data either at predefined performance windows or when certain engine operating limits are exceeded. The second approach focuses on long-term, design-oriented benefits that are gained through improved knowledge of the overall engine operating environment. Generally, this involves continuous recording of engine usage and performance. To achieve the design-oriented benefits, engine usage data must be recorded continuously on at least a few aircraft at each operational location. Our research centers on six examples of engine monitoring applications that indicate the characteristics and implications of both approaches.

Much uncertainty still exists about the benefits and costs attributable to engine monitoring systems. We believe that the estimated maintenance cost savings most often used to justify new monitoring systems are unlikely to materialize over the short term.

But whether new systems pass or fail in the narrow sense of short-term cost savings should not be the sole, nor necessarily the primary basis of justification. The potential benefits of anticipating needed maintenance, helping maintenance crews and engineering support personnel to better understand engine failure cause and effect, and verifying that maintenance has been properly performed have substantial value. These benefits can be especially significant now that the military services are moving toward modular design and an on-condition maintenance posture for new aircraft turbine engines. Unfortunately, none of these potential benefits can be quantified on the basis of experience to date.

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I. INTRODUCTION

Modern military aircraft turbine engines present new and increasingly difficult management and maintenance problems as their level of operating performance, complexity, and cost continue to escalate. As in the past, those responsible for engine maintenance and management have developed increasingly more sophisticated techniques in order to lessen uncertainty and enhance confidence in their decisions. Electronic monitoring of inflight engine performance represents yet another step, albeit a significant step, in this process.

Central to this concept is a growing awareness that traditional maintenance capabilities will not gauge with desired precision the material condition or performance of current or future engines. This is evidenced by the current activity which finds some type of electronic engine monitoring ongoing or under consideration for all recently developed military aircraft engines. But monitoring inflight engine performance isn't a new idea; during the last two decades, at least 20 programs have been attempted. These range from simple time temperature recorders to the complex Engine Diagnostic System (EDS) being developed for the F-100 engine installed on the F-15 and soon to be deployed F-16 tactical fighters. Indeed, while the F100 EDS program will not be treated explicitly in this paper, it is the reason for our reviewing earlier engine monitoring programs.* This paper presents results of our analysis of six earlier monitoring systems and

*See Reference 1.

ongoing engine duty cycle research that are directly applicable to current and future engine monitoring programs.

APPROACH TO THE STUDY

The analytial approach used in this study was to examine the experience of several selected engine monitoring systems, with regard to the information and findings that would be applicable to consideration of new systems. The systems examined included: (1) Time Temperature Recorder (TTR), (2) Engine Health Monitoring System (EHMS), (3) Malfunction Detection Analysis Recoding System (MADARS), (4) Inflight Engine Condition Monitoring System (IECMS), (5) Airborne Integrated Data System (AIDS), and (6) Engine Usage Monitoring System (EUMS).* The EUMS is a British system that has a different focus from that of the U.S. systems. Recent research on engine duty-cycle analysis was also examined.** Engine duty-cycle analysis is of particular interest because it can have a significant effect on engine design and testing. The findings derived from both the monitoring system experience and the duty-cycle analysis will be discussed in terms of their implications for new monitoring systems.

Recent monitoring system proposals have focused mainly on net life-cycle cost savings, to be obtained through reductions in maintenance labor, spare parts, and fuel usage, as justification for developing the system.*** The intent here is not to challenge the

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*The details of these case studies are given in Refs. 1 through 16.

**See Refs. 13, 17, and 18.

***See Ref. 19 for example.

cost-estimating procedure in general, or any particular cost value used in life-cycle cost calculations, but rather to focus on the comprehensiveness of the cost elements considered, the expectation of achieving the net cost savings estimated, and the type of information presented to high-level decisionmakers leading to selection of particular systems.

Design objectives, development plan, and life-cycle costs problems can arise with new system proposals when the concept formulation does not take advantage of lessons learned from previous monitoring experience. For instance, incomplete and potentially misleading estimates of life-cycle costs can result. Thus a review of past systems histories is a first step in evaluating current expectations.

II. SELECTED CASE STUDIES

The selected case studies, shown in Fig. 1, reflect Air Force, Navy, commercial, and British applications of engine monitoring systems. The systems were applied to engines for U.S. military fighter, attack, trainer, and cargo aircraft, commercial transports, and a spectrum of British aircraft. Applications include both single-pilot and multi-crew aircraft and single-engine and multi-engine designs.

CASE STUDIES

SYSTEM	AIRCRAFT/ENGINE	COMMENT
TIME TEMPERATURE RECORDER (TTR) SEPT 67 - JAN 69	F-100/J57	SINGLE PARAMETER MEASUREMENT; CONUS & VIET NAM EXPERIENCE (CONTROL GROUP)
ENGINE HEALTH MONITORING SYSTEM (EHMS) JULY 76 - MAY 77	T-38/J85	FLEET RETROFIT NOT RECOMMENDED (CONTROL GROUP)
MALFUNCTION DETECTION ANALYSIS RECORDING SYSTEM (MADARS) LATE 60's - PRESENT	C-5A/TF39	CONTINUOUS RECORDINGS USED TO EXTEND TF39 TBO AND FOR CONFIGURATION MANAGEMENT
IN-FLIGHT ENGINE CONDITION MONITORING SYSTEM (IECMS) 1973 - PRESENT	A-7E/TF41	USEFUL FOR OPERATIONS & COMPONENT IMPROVEMENT PROGRAM: STILL IN DEVELOPMENT (NO CONTROL GROUP)
AIRBORNE INTERGRATED DATA SYSTEM (AIDS) LATE 60's - PRESENT	COMMERCIAL WIDEBODIES	LIMITED APPLICATIONS; RETROFIT NOT COST EFFECTIVE
ENGINE USAGE MONITORING SYSTEM (EUMS) EARLY 70's - PRESENT	U.K. AIRCRAFT	INTENDED TO REDUCE FUTURE LCC THROUGH IMPROVING ENGINE DESIGN

Fig. 1--Case Studies.

The monitoring systems themselves run the gamut of parameter measurement--the TTR system measures only a single parameter, whereas IECMS measures in excess of 60 parameters. Most of the systems use snapshot recording; some record data continuously. The operational focus of the monitoring systems is also varied. The U.S. systems orient primarily toward improving day-to-day maintenance, whereas the British system almost exclusively emphasizes the feedback of operational data to the design and test communities. Identified control groups existed for several of these monitoring systems. Unfortunately, the control groups did not control for all the variables of interest, and the time intervals for most tests were too short to stabilize inputs and quantify some of the possible outcomes. Nevertheless, although all the information desired isn't available, much useful information was obtained.

The study described here drew upon the experience from all the case studies, but for this paper we have selected two case studies as illustrative examples: the EHMS on the T-38, because it represents the predominant approach taken by the Air Force, and the British EUMS, because the approach taken for it is entirely different from that of the U.S. systems.

THE T-38 EHMS CASE STUDY

The T-38 EHMS emphasizes improved day-to-day engine maintenance. Engine health data are stored only under the following three conditions: (1) when engine parameters exceed normal limits, (2) on pilot command, and (3) under preprogrammed flight conditions. When any of the three conditions occur, all parameter data as of that moment are recorded (snapshot recording). Program data were obtained for the test that was conducted from July 1976 to May 1977.* Two

*The data for the instrumented and control engines are summarized by engine serial number in Ref. 11. Individual engine malfunction report data were obtained from the Program office.

groups of engines were used in the test: an instrumented group and a control group (see Fig. 2). The two groups contained the same number of engines and were used for approximately the same number of flight hours. Statistical testing detected no significant difference in the time since last overhaul or in flight-hour distibutions among the engines of both groups.

EHMS (T-38 / J85) ACTIVITY OUTCOMES

JULY '76 – MAY '77

	INSTRUMENTED ENGINES	CONTROL ENGINES
NUMBER OF ENGINES	26	26
TOTAL FLIGHT HOURS	6226	6443
MALFUNCTION REPORTS	97	48
GROUND MAINTENANCE		
UNSCHEDULED REMOVALS	53	23
TROUBLESHOOTING (MH)	169	90
REPAIR (MH)	1403	530
ENGINE GROUND RUNS		
TROUBLESHOOTING	52	38
TRIMS	26	14
FUEL USED (GAL)		
TROUBLESHOOTING	4846	1786
TRIMS	5720	4480

Fig. 2--EHMS (T-38/J85) Activity Outcomes.

Twice the number of malfunctions were reported for the instrumented engines as for the control engines. This resulted in a larger number of malfunction reports, which, in turn, increased the number of unscheduled engine removals, troublshooting and repair manhours, the number of ground runs, and the amount of fuel used for troubleshooting and trimming the engines. Examination of the malfunction reports revealed, however, that the EHMS flagged only five malfunctions, out of a total of 97, independent of pilot and maintenance crew reports.* From discusions with those involved in the test,** and an analysis of the data, we conclude that the increased number of malfunction reports resulted from increased sensitivity on the part of the pilot and maintenance crew. Both pilot and maintenance crew knew that the system was on the aircraft, and their behavior was affected by that knowledge. Although the EHMS reported few malfunctions independently, it did provide information that significantly improved the cause-and-effect understanding of engine problems encountered, and that was useful in providing maintenance direction to the ground crews.

It is interesting to note that the J85 was a mature engine and that the number of engine problems encountered was not very great. Also, the EHMS was not a new system, having been through a feasibility phase during December 1972 and January 1973. Nevertheless, hardware and software problems in the EHMS caused schedule delays. A 6-month delay was necessary to shake down the installation and software. The shakedown not only lowered the false-alarm rate but also reduced the EHMS maintenance manhours per flight hour below the number deemed necessary for day-to-day operation.

The EHMS Program Office had anticipated that less maintenance, less fuel, and fewer problems would result in all the categories shown

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*More recent data from T-38 experience at Holloman AFB, where the mission profile is more severe, indicate that the EHMS finds more engine problems independently.

** Ref. 2.

in Fig. 2, but more manhours and fuel were actually required, resulting in higher cost. Thus, confusion exists as to the costs and benefits that might reasonably be expected from an engine diagnostic system. Not all of the potentially important system and engine benefits--improved readiness, availability, reliability, and lower intermediate and depot maintenance costs--were demonstrated largely because the controls needed to collect appropriate data for analysis were not maintained over a sufficiently long term period. Current objectives of monitoring systems are oriented to cost-reduction, and the lack of control for certain potentially important variables results from a lack of emphasis on non-cost benefits. In spite of the additional unscheduled engine removals, maintenance manhours, and fuel used, no measurable positive output--i.e., no cost savings and no increase in readiness or availability--was discernible from the EHMS experience. Perhaps the engine's maturity and the shortness of the test explain the lack of positive outputs.

THE BRITISH EUMS CASE STUDY

The British system (see Fig. 3) purposely ignores the short-term maintenance-oriented benefits; instead, the British choose to concentrate on perfecting their engineering understanding of the engine operating environment and to use this understanding to improve present and future engine designs. The system's primary objective is to improve safety and availability and ultimately to reduce life-cycle cost.

U.K. APPROACH – ENGINE USAGE MONITORING SYSTEM (EUMS)

OBJECTIVES:
- IMPROVE UNDERSTANDING OF ENGINE DUTY CYCLE/MISSION

APPROACH:
- INSTRUMENT SMALL SAMPLE OF EACH TYPE AIRCRAFT
- RECORD PARAMETERS CONTINUOUSLY
- UTILIZE DEDICATED ENGINEERING STAFF
- ANALYZE DATA BY MISSION TYPE

EXPECTED BENEFITS:
- ENGINE DESIGN
- CORRELATE TEST/DUTY CYCLES
- MAINTENANCE
- RELIABILITY
- COMPONENT IMPROVEMENT PROGRAM (CIP)

Fig. 3--U.K. Approach: Engine Usage Monitoring System (EUMS).

The focus of the EUMS reflects two conclusions that the British reached in the late 1960s and early 1970s when they experienced a spate of engine problems coupled with rising operating and support costs. Preliminary investigations revealed that the problems occurred because the engine's operational environment was not completely understood.* Subsequent studies concluded that a system that would provide a continuous recording of a few parameters was the simplest, cheapest, most reliable, and most productive solution available, given the prevailing state-of-the-art. This conclusion was also influenced by the fact that despite the investments made by the U.S. in complex

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*The EUMS is also partially a result of the difficulty that the British had in understanding how the Rolls Royce Spey engine could be so successful in the F-4K interceptor, and yet in a modified version (the TF41), this engine could be so troublesome in the A-7E attack aircraft.

monitoring programs, there was not a single one, the British felt, had explored the full potential of engine health monitoring.*

The British proceeded to develop a continuous recorder that would record a small number of engine parameters. For example, on the Harrier engine, only eight parameters are recorded. This equipment is being installed on a few of each type of aircraft now in operation. The field data are sent directly to a central location, where they are analyzed by a dedicated engineering staff consisting of engineers from the Ministry of Defense and from the testing community, as well as by engineers from Rolls Royce.** Analyzed by mission type, these data have yielded interesting and important observations. The British have found, for example, that the amount of engine life consumed depends, to an important extent, on the type of missions flown and how the equipment is used during the mission. They also found that a major contributor to reduced engine life is the cumulative effect of small power transients. They have concluded--and the U.S. military services are also reaching the same conclusion--that engine failure modes, such as low-cycle fatigue, have not been as well understood as they were thought to be. Quantitative engineering data are now being used to improve engine design specifications and to bring both full-scale and component test cycles in line with operational duty cycles. The British are in the process of reorienting their approch to

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*See Refs. 6, 7, and 9 for a complete dicussion of the EUMS objectives and approach.

**The British method of handling data is designed for an engineering study. For day-to-day maintenance purposes data must be used at the squadron level in the field. This is an important distinction.

maintainability and reliability, recognizing that these areas are more a function of engine throttle cycles experienced and the type of mission flown than of flying hours only.

ENGINE MONITORING SYSTEM OUTCOMES

To evaluate the strengths and weaknesses of previous monitoring systems, we divided system objectives into two groups based on a time orientation: (1) short-term operations, maintenance, and management and (2) long-term design. Fig. 4 lists the characteristics that we feel are desirable in a monitoring system. Certain of these characteristics served as design objectives for each of the case studies. For example, as a result of engine monitoring, EHMS expected fewer maintenance manhours, a savings in fuel, fewer parts consumed, and fewer unscheduled engine removals.*

Since the primary design objective of most monitoring systems is to reduce resources, the five outcomes noted by checkmarks in Fig. 4 have received the most attention because it is easier to estimate their costs. Given sufficient information, all characteristics could be assigned values. The first four characteristics have been important in providing justification for previous U.S. selections, but all of them must be considered because, in some cases, the unchecked characteristics may justify the costs of a new monitoring system.

To show the outcome of each monitoring system, we employ the matrix shown in Fig. 5. The coding used in Fig. 5 requires some explanation.

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*The background of EHMS and details of the benefits expected from engine monitoring are discussed in Ref. 11.

SUMMARY OF ENGINE MONITORING SYSTEMS OUTCOMES

MAINTENANCE ORIENTED

- OPERATIONAL
  - AWARE OF ENGINE HEALTH
  - AWARE OF ENGINE OVERTEMPERATURES
- MAINTENANCE
  - ✓ LESS MAINTENANCE MANPOWER
  - ✓ LESS TROUBLESHOOTING & TRIM FUEL
  - ✓ FEWER ENGINE REMOVALS
  - ✓ LESS PARTS CONSUMPTION
  - ANTICIPATE MAINTENANCE (TRENDING)
  - IMPROVE CAUSE & EFFECT UNDERSTANDING
  - VALIDATE MAINTENANCE ACTION
- MANAGEMENT
  - ✓ MODIFY TBO
  - PROVIDE CONFIGURATION CONTROL

DESIGN ORIENTED

- GUIDE CIP
- CORRELATE TEST/DUTY CYCLES
- AID FUTURE ENGINE DESIGN

Fig. 4--Summary of Engine Monitoring Systems Outcomes.

SUMMARY OF ENGINE MONITORING SYSTEMS OUTCOMES

	TTR (F-100)	EHMS (T-38)	MADARS (C-5A)	IECMS (A-7E)	AIDS (COMMERCIAL)	EUMS (U.K.)
MAINTENANCE ORIENTED						
● OPERATIONAL						
– AWARE OF ENGINE HEALTH	R	G	G	G	G	R
– AWARE OF ENGINE OVERTEMPERATURES	G	G	G	G	G	R
● MAINTENANCE						
– LESS MAINTENANCE MANPOWER	R	R	Y	Y	Y	R
– LESS TROUBLESHOOTING & TRIM FUEL	Y	R	Y	Y	Y	R
– FEWER ENGINE REMOVALS	Y	R	Y	Y	Y	R
– LESS PARTS CONSUMPTION	Y	Y	Y	Y	Y	R
– ANTICIPATE MAINTENANCE (TRENDING)	G	G	G	G	G	R
– IMPROVE CAUSE & EFFECT UNDERSTANDING	G	G	G	G	G	R
– VALIDATE MAINTENANCE ACTION	G	G	G	G	G	R
● MANAGEMENT						
– MODIFY TBO	R	R	G	Y	G	G
– PROVIDE CONFIGURATION CONTROL	R	R	G	Y	G	R
DESIGN ORIENTED						
– GUIDE CIP	R	Y	G	G	G	G
– CORRELATE TEST/DUTY CYCLES	R	R	Y	G	Y	G
– AID FUTURE ENGINE DESIGN	R	R	Y	G	Y	G

Fig. 5--Summary of Engine Monitoring Systems Outcomes.

The R (red) coding means that the particular characteristic was not achieved; but we must point out, however, that in many cases it was not a design objective and no attempt was made to achieve it. The Y (yellow) coding signifies that the information necessary to determine if the monitoring system did or did not accomplish the characteristic is lacking. The G (green) coding indicates that the characteristic was achieved or was beginning to be achieved. Several of the green blocks are crosshatched to indicate that the benefits existed but additional explanation is required.

Moving down the EHMS column, for example, we see that both operational characteristics were achieved. Because overtemperature damages the most critical and most expensive engine components, this information is extremely important. Our research on engine overtemperatures in fighter and attack aircraft shows that pilots report only about one-third of the significant engine over-temperatures and are unable to report over-temperature duration. This is to be expected, because these aircraft are mostly single-crew aircraft, and the pilot sits in a small, crowded, vibrating cockpit with a number of small gauges. His attention must be divided among many functions, whereas the monitoring system watches engine parameters full time.

For the EHMS, the first three characteristics under maintenance are coded red because the instrumented engines consumed more maintenance manhours, troubleshooting, and trim fuel, and experienced a higher removal frequency, than the control group engines during the flight test evaluation. The parts consumption block is colored yellow because no data were collected.

The last three characteristics under maintenance are colored green because they were just beginning to be achieved, but achievement requires time to develop fully. Looking at the lower left-hand corner of the matrix, we see that the management and the long-term design-oriented blocks for both the TTR recorder and the EHMS are red. Although the EHMS was not intended to achieve the long-term benefits, we think that the matrix is also telling us that when a diagnostic system is applied to a mature engine, it does not have an opportunity to make a substantial impact in these two areas. This is because the engine is well understood and most of the problems have been corrected, or its service life is considered satisfactory.

In contrast, MADARS, IECMS, and AIDS were all installed either as original equipment or very early in engine life. Each system records internal gas temperatures and pressures. Since all of them provide the operator with an awareness of engine health, these blocks are coded green. Under maintenance, however, the first four characteristics are coded yellow because either all of these engines are instrumented or there never has been an identified control group.

The improved awareness and understanding provided by the monitoring systems has an important effect of the last three maintenance objectives. Three examples are: (1) In the case of hard time maintenance procedures, the data can be used to study engine parameter trends. Some maintenance problems can then be alleviated by using a different maintenance schedule. (2) The data will improve the maintenance crew's understanding of engine malfunction cause and effect, permitting the crew to work smarter rather than harder. (3) The data can be used to avoid a shotgun approach to maintenance in which good parts are needlessly replaced.

Unfortunately, it takes time to fully achieve these benefits. Experiencing engine failures, and reviewing the data leading up to the failures, precedes any attempt to correlate a particular engine parameter's trend with an incipient engine failure. Only when such correlation exists can the operations, maintenance, and management personnel make use of this information to schedule or initiate maintenance.

In the case of modifying the Time Between Overhaul (TBO) evaluation for the MADARS, the crosshatched green block indicates that the monitoring system data provide one of many inputs that constitute the information sets that enables the TBO to be extended. The technical data provided by the monitoring system helps to advance the TBO in three ways: (1) by helping to uncover incipient failure modes that are at present undetected in C-5A fleet engines; (2) by tracking the reliability and durability of new parts and components incorporated into the engines; and (3) more, generally, by providing additional confidence for the decisions affecting TBO intervals.

For the IECMS, the green crosshatching shows that the long-term design-oriented benefits were not part of the original monitoring objectives but result from an engineering need to better understand engine operational use. The IECMS program developed a continuous recoding option to enhance this understanding. The continuously recorded data permitted the operational duty cycle to be correlated with appropriate testing. This is an extremely important contribution, because unless correlation exists, operational fleet failure modes may not be reproduced in the test cell.

The matrix, then, reveals that the U.S. monitoring systems have focused on the short-term maintenance-oriented benefits. In contrast to the U.S. systems, the British EUMS has ignored the short-term maintenance-oriented benefits, choosing instead to focus on the longer-term design, testing, and management benefits. The British system is different in a way that we think is important: it focuses on improving engine design.

ENGINE DUTY-CYCLE RESEARCH

The U.S. Navy and Air Force, independent of the British, have also experienced many severe engine problems and, from preliminary investigations, have concluded that their engineering understanding of the engine operational environment has been inadequate. For example, the type of early information supplied to the engine manufacturer for design guidance for a new engine is shown in Fig. 6 for the Navy F-14.* The estimated power required as a function of time for the F-14 intercept mission is shown in view (a). The actual number of engine cycles that occurred on an instrumented F-14 during flight is shown in view (b), together with the resulting change in the predicted design life of certain important engine components.** Low-cycle fatigue is important because cumulative fatigue damage occurs in cyclicly loaded parts as these parts are cycled from low to maximum RPM. Current methods for calculating LCF rely on the usage rates of cycles per hour that are derived from synthetic sortie patterns.

The continuously recorded flight data present a different picture for the frequency of major and minor cycles. Because the increase in the frequency of both cycles is significant and was not originally anticipated, it is contributing to engine problems. The data demonstrates the gross errors in synthetic sortie analysis and indicates that neither the service nor the manufacturer had a clear idea of the probable pattern of engine operational usage.

As a result, engine part life has been overestimated and, hence, life-cycle costs have been underestimated. By analyzing continuously recorded data, the original estimate of engine part life was reduced by an order of magnitude for the first fan disk (see Fig. 6). This

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*Propulsion systems are designed to Request for Proposal (RFP) mission profiles based on a projected combat time with specific weapons load and avionics suite.

**The impact of engine duty cycle on part life and maintenance intervals is discussed in Refs. 17 and 18.

type of information is needed by engine designers and is only available through continuous recording. If, for example, continuously recorded data had been available from previous fighter aircraft mission experience, the F-14 powerplant, an uprated model of the TF30, might have been designed differently.

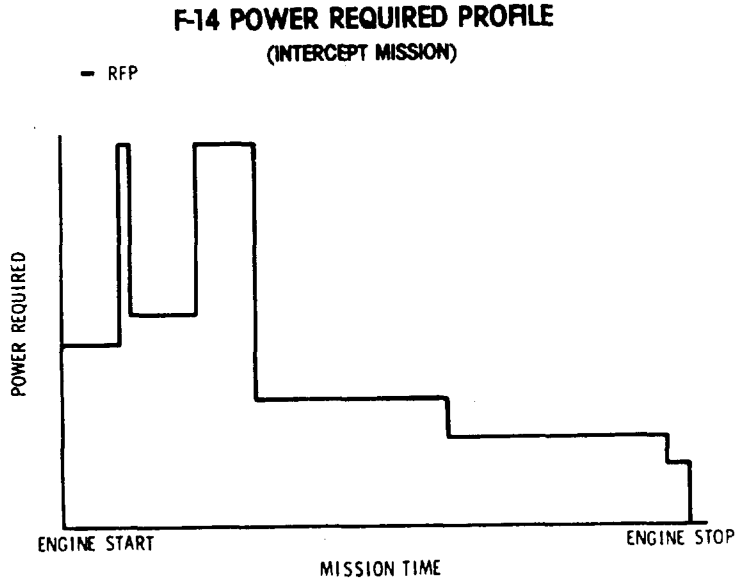

Fig. 6a--F-14 Power Required Profile.

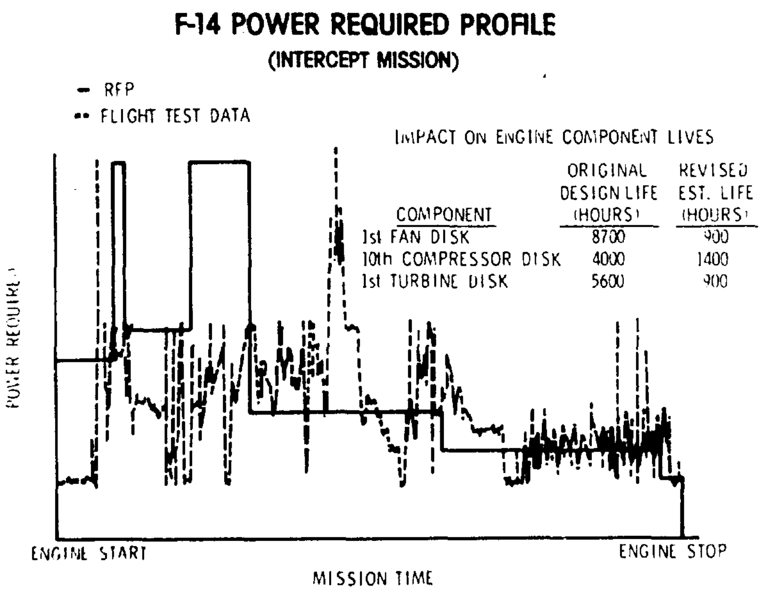

Fig. 6b--F-14 Power Required Profile.

III. FINDINGS OF CASE STUDIES AND DUTY-CYCLE EXPERIENCE

We now summarize the findings of our case study reviews and the engine operational duty-cycle work. These findings, shown in Fig. 7, are as follows:

FINDINGS – ENGINE MONITORING EXPERIENCE

- OUTCOMES FROM PREVIOUS ENGINE MONITORING APPLICATIONS ARE NOT CONCLUSIVE
- CONTINUOUS RECORDING PROVIDES IMPORTANT DESIGN INFORMATION
- MODIFICATION AFTER SOME OPERATIONAL USE ALMOST ALWAYS DESIRABLE
- MONITORING SYSTEMS DO PROVIDE AWARENESS OF ENGINE HEALTH
- MONITORING TENDS TO INCREASE EARLY SUPPORT COSTS
- SEVERAL DEVELOPMENT PROGRAMS DOMINATED BY HARDWARE AND SOFTWARE PROBLEMS

Fig. 7--Findings: Engine Monitoring Experience.

(1) The benefits and costs of engine monitoring are still very uncertain. Many quantitative benefits have not been realized, and costs have been higher than expected. Nonetheless, because the control groups did not control all the variables of interest, and because the time interval for the tests was so short, we can't be definitive about the outcomes.

(2) A continuous recording system provides important design information that can be of substantial value to the Air Force, although many of the important benefits cannot now be treated

quantitatively. Time is required to assimilate this information and to develop and to fully utilize the data derived from the monitoring procedure. Specific action will be necessary if we are to obtain certain long-term benefits. The maximum utility of the monitoring process occurs early in an engine's life when an opportunity still exists to affect engine component redesign and to give direction to the component improvement program.

(3) Improvements in the monitoring system design should evolve as we gain experience with the system.

(4) Monitoring systems provide the engine design and test community and maintenance crew with an understanding of problem causes and effects and, through corrective actions, ultimately improve the material condition of the engine. Engine over-temperatures are especially important, particularly in the case of a single-pilot and a single-engine aircraft.

(5) The increased sensitivity of pilots and ground crews to engine condition does result in more malfunction reports and consequently increase costs initially. Problems are identified and resources must be allocated to correct them. Another source of increased costs is the low reliability and high false-alarm rates experienced by most of the monitoring systems during initial operations. Together these two factors can initially result in a low system credibility, a handicap difficult to overcome.

(6) Several of the programs have been dominated by early monitoring-system hardware and software problems such as latent design deficiencies, manufacturing defects, nonavailability of key software subroutines, and logic errors in software. These problems continue to

exist even after the monitoring systems have reached the field. It takes a long time to work out all the bugs, and this drives up initial support costs, especially when systems are prematurely fielded. These early problems are difficult to overcome but, again, for both short-term maintenance and longer-term design and testing, the benefits appear significant if they can be resolved.

IV. IMPLICATIONS FOR NEW MONITORING SYSTEMS

DESIGN OBJECTIVES

What does all this mean for new monitoring systems in terms of design objectives, completeness of analysis, cost estimates, and development?

Let's return to Fig. 5. For new designs, such as the F100 EDS, we would expect good coverage in the operational areas. For the first three objectives under maintenance, we would expect, initially, to require more maintenance and fuel, not less. Over the long term, the cost outcome is still uncertain.

We would expect to realize benefits that are difficult to quantify, but, as we have seen from all the case studies, they will take time to develop. In the management area, for example, it is not clear how the hard-time limit on the life of critical parts will be affected. As presently designed, new U.S. monitoring systems are snapshot recording systems and, like previous U.S. monitoring systems, will not capture the information needed for long-term design-oriented benefits. Those benefits can be achieved by developing a continuous recording option.

ESTIMATED COSTS AND SAVINGS

Previous monitoring studies have focused on the net life-cycle cost savings. In life-cycle cost analyses, the first three cost elements--RDT&E, procurement, operating and support--shown in Fig. 8 are usually addressed. However, these elements, data management, monitoring system improvements, and modification costs associated with a specific system must be added. The first two additional elements are generic to all life-cycle cost analyses and should be considered. This problem is typical in life-cycle analysis because, frequently, only some of the costs and some of the benefits are analyzed.

ESTIMATED COSTS AND SAVINGS

LIFE CYCLE COSTS

- RDT&E
- PROCUREMENT
- OPERATING AND SUPPORT
- DATA MANAGEMENT
- MONITORING SYSTEM IMPROVEMENTS
- UNIQUE MODIFICATION COSTS

SOURCES OF LIFE CYCLE COST SAVINGS

- FEWER UNSCHEDULED ENGINE REMOVALS
- LESS FUEL USAGE
- LESS SECONDARY ENGINE DAMAGE
- EXTENDED DEPOT OVERHAUL

Fig. 8--Estimated Costs and Savings.

We find that with large, complex systems, resources required for data management can be extensive. We also find that it will be necessary to make monitoring system improvements to increase the initial low reliability, improve sensor durability, and increase system capability.

The users anticipate that the acquisition cost of the monitoring system will be more than offset by outyear engine support cost savings. The first three items shown on the lower portion of Fig. 8--fewer unscheduled engine removals, less fuel usage, less engine secondary damage--reflect the sources of these life-cycle cost savings. Previous monitoring system experience, as shown by our case study reviews, strongly indicates that the first two items may not be realized, at least initially. Some data are just beginning to appear for the third item (engine secondary damage), and we have been unable to address it. To these three expected sources of life-cycle cost savings, a fourth, not usually considered, should be added. The engine monitoring system should help to extend the interval between depot overhauls. Even a small change in this interval, affecting a large number of engines, could result in significant cost savings.

In addition to those benefits that can be easily converted to costs, full consideration must be given to the unquantifiable benefits--the unchecked characteristics in Fig. 4. For example, if we can improve our understanding of failure cause and effect--and thus extend the depot overhaul interval sooner than would be possible without engine monitoring--reduced outyear costs can be achieved and the system may be cost effective over the long term. There is no current evidence either way. The important point is that if cost savings constitute the only criterion for monitoring, is is doubtful that the monitoring systems can be justified on the basis of current information.

DEVELOPMENT PLAN CONSIDERATIONS

Three important lessons learned from the earlier monitoring system development plans are:

(1) A major complaint of the earlier monitoring systems programs were that not enough engine problems were experienced to wring out the

system.

(2) To really be effective, more time is needed in schedule. A new monitoring system must operate as a system. Consideration must be given to operational software as well as to hardware, i.e., to how the data are to be used and by whom. For maintenance purposes, the data must be used at the squadron and wing level, whereas the engineering data can be processed at a central site. If data utilization for maintenance is not taken into account, the time required to become fully operational will increase.

(3) In the process of trying to model an advanced engine's mechanical and thermodynamic behavior, many things will be learned that may cause a change in the parameters monitored and thereby result in modifications to the software and hardware. Thus, in all likelihood, several iterations of the design will probably be necessary until the system functions as intended.

CONCLUSIONS

There has never been a controlled experiment of a maturing engine over a long enough time period to allow monitoring system outcomes to be quantified. However, several conclusions can be drawn based on our case studies. These are outlined in Fig. 9.

We conclude that the maintenance cost savings used to justify new monitory system selection are unlikely to materialize over the short term. But whether a new system passes or fails in the narrow sense of cost savings over the short term should not be the sole criterion on which it is judged. Substantial value lies in the potential benefits of (a) anticipating needed maintenance, (b) helping maintenance crews and engineering support personnel to better understand cause and effect of engine failure, and (c) verifying that maintenance has been properly performed. These benefits are especially significant now that the services are moving to an on-condition maintenance posture. They can also be important in helping to achieve the original design objectives. Unfortunately, none of these benefits can be quantified on the basis of experience to date.

CONCLUSIONS

- EXPERIENCE DOES NOT WARRANT OPTIMISTIC NEAR TERM EXPECTATIONS
  - COSTS ARE LIKELY TO BE HIGHER
  - SUCCESSFUL NEW SYSTEM TAKES TIME TO MATURE
- TEST PLAN NEEDS TO YIELD CONCLUSIVE EVIDENCE ON VALUE
  - ADEQUATE AIRCRAFT SAMPLE
  - SUFFICIENT ENGINE FLIGHT HOURS
  - APPROPRIATE FOCUS
- SCOPE OF NEW SYSTEM SHOULD PROVIDE FOR VALUABLE LONG TERM BENEFITS
  - DESIGN FEEDBACK
  - CORRELATION BETWEEN TESTING/OPERATIONAL USAGE

Fig. 9--Conclusions.

The development plan for a new engine diagnostic system should be designed to yield conclusive evidence regarding its value. The test aircraft sample and programmed flight hours must be sufficient for selection decisions. The program focus must not be too narrow. Software and data processing should be considered within the overall system, and the long-term design-oriented benefits given proper consideration.* It is especially important to have a balanced program now that those who decide on monitoring system utility must consider reliability, durability, and cost issues almost on an equal footing with performance objectives.

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*To achieve the design-oriented benefits, data for a few carefully selected engine parameters must be recorded continuously on a few aircraft at each operational location.

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