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SAE AIR4176

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Cost Versus Benefits of Engine Monitoring Systems

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1. SCOPE:

The purpose of this SAE Aerospace Information Report (AIR) is to provide information that would be useful to potential users/operators and decision makers for evaluating and quantifying the benefits of an Engine Monitoring Systems (EMS) versus its cost of implementation.

This document presents excerpts from reports developed to analyze "actual aircraft cost/benefits results". These are presented as follows:

a. First, to outline the benefits and cost elements pertaining to EMS that may be used in performing a cost versus benefits analysis.

b. Second, to present considerations for use in conducting the analysis.

c. Third, to provide examples of analyses and results as they relate to the user/operator and decision-maker community.

The document encompasses helicopters and fixed wing aircraft and distinguishes between civilian and military considerations.

This document is not intended to be used as a technical guide, nor is it intended to provide methodologies, be a legal document, or be a standard. The findings are informational and are presented in the words of the report authors.

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2. REFERENCES:

There are no referenced publications specified herein.

3. COST/BENEFIT ANALYSIS - THE CONCEPT AS APPLIED TO EMS:

Iterative cost benefit trade-off analysis can be performed for aircraft and engine life cycle costs (LCC) for various EMS configurations, with different benefit savings for specific engine applications. Too much or too little EMS complexity can prevent achievement of LCC savings (see Figure 1). An analysis criterion is to maximize return on investment (ROI) by matching an appropriate EMS to a particular set of projected cost savings. There should be a convergence through the cost benefit trade-off analyses toward a preferred EMS that meets user requirements.

The objective of the cost benefit trade-off analyses is to determine levels and methods of implementation of engine monitoring that are cost effective (see Figure 2). Typically, EMS savings are not realized until after the engine is operational and the design and development are completed (see Figure 3). Cost benefit trade-off analyses require a comparison between two major cost elements:

a. LCC of the aircraft and engine
b. LCC and savings attributable to the implementation of an EMS

3. (Continued):

ROI is an underlying justification for an EMS. Labor and material EMS cost should be identified, projected and tracked to assess ROI benefits. Benefits, such as improved aircraft safety, availability and engine part scheduling, should be included and can be weighted for emphasis.

The main elements of a cost benefit analysis will be the impact of the EMS on engine maintenance (man-hours, aircraft unavailability, etc.) and parts consumption due to variations in the life usage of life limited components. For an established engine, it should be possible to derive the maintenance benefits from historical data and, therefore, the savings can be calculated with reasonable confidence by the LCC model.

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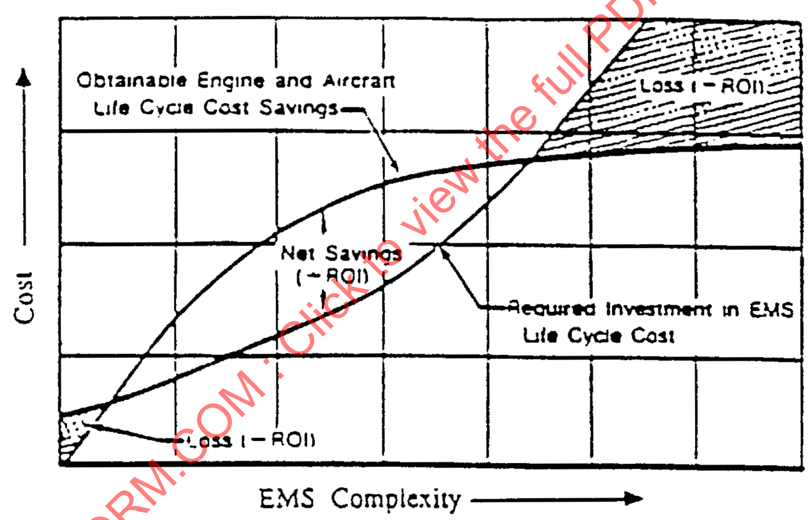

FIGURE 1 - EMS Complexity Impacts Return on Investment (ROI)

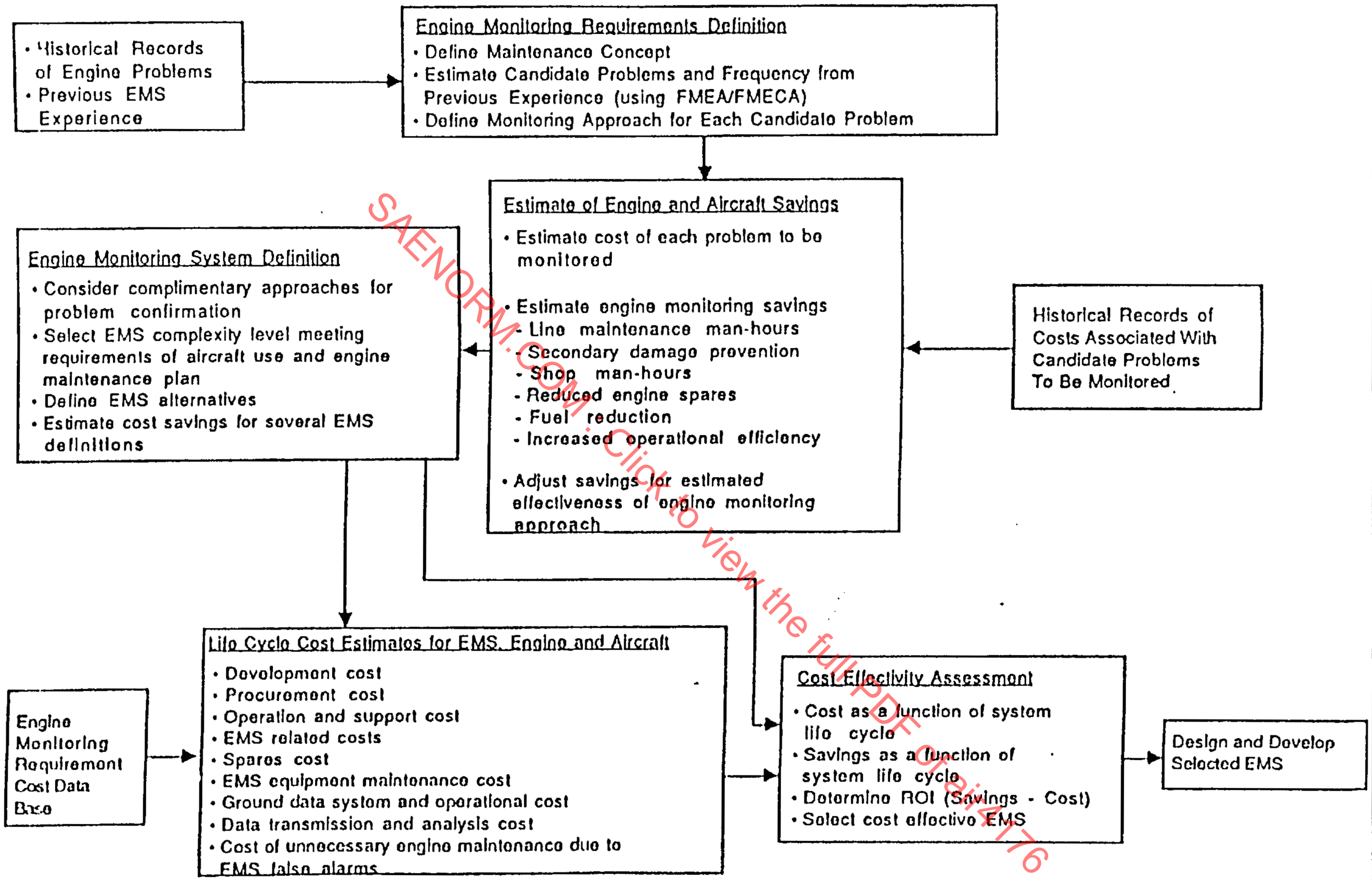

FIGURE 2 - Methodology for Defining an EMS

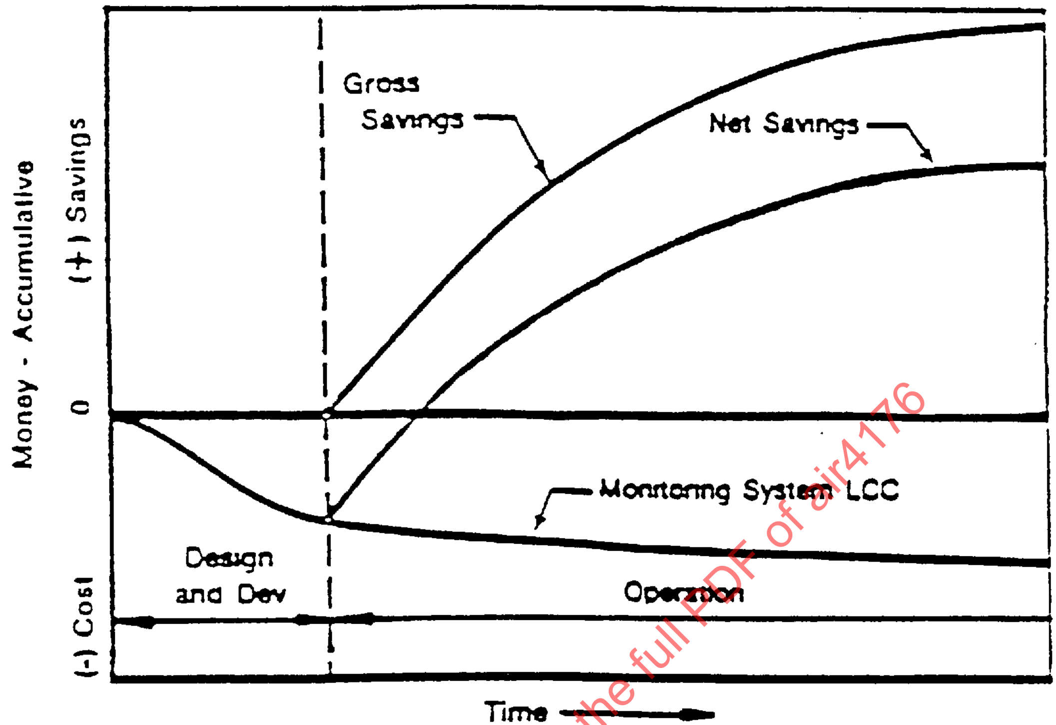

FIGURE 3 - Typical EMS Cost Benefit Analysis Results

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3.1 Costs:

Life cycle elements of an EMS are similar to those of other aircraft or engine systems, and include:

a. Development costs
b. Production costs
c. Operational and support (O&S) costs

(1) Development EMS costs include:

(a) Requirements definition
(b) Design
(c) Development
(d) Qualification

(2) Production EMS costs include:

(a) Aircraft and engine EMS hardware, including spares
(b) EMS ground support and data processing equipment

3.1 (Continued):

(3) Operational and support EMS costs include:

(a) Maintenance labor and material including component replacement or repair
(b) Fuel consumed and lost revenue due to weight of engine monitoring hardware and added fuel
(c) Labor and material for transmission, processing and analysis of EMS data
(d) Projected cost of unnecessary engine maintenance due to EMS false alarms
(e) Software maintenance and enhancements
(f) Training costs

3.2 Benefits:

Knowledge of system benefits is required for EMS cost benefit analyses. These benefits should be quantified to estimate and determine EMS savings. Analyses of EMS benefits should consider:

a. Maintenance cost savings
b. Fuel cost savings
c. Operations and revenue benefits
d. Parts and engine savings

(1) Maintenance Cost Savings

(a) Projected reduction in maintenance labor hours per flight hour
(b) Time saving by fault isolation to specified malfunction
(c) Early identification of unexpected fleet deterioration
(d) Avoidance of engine changes away from a major maintenance base
(e) Ability to predict and schedule future maintenance

(2) Fuel Cost Savings

(a) Fuel savings through reduction of ground test runs
(b) Fuel savings through recognition of inefficient, degraded engines
(c) Fuel savings through identification of malfunctioning components such as bleed systems and control sensors.

(3) Operations and Revenue Benefits

(a) Time savings through confirming pilot reports and maintenance repair actions
(b) Reduction in down time
(c) Reduced maintenance man-hours per flight hour
(d) Fewer canceled and/or delayed flights

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3.2 (Continued):

(4) Parts and Engine Savings

(a) Reduction in required spare parts through elimination of unnecessary repairs
(b) Certification of flight profile assumptions during design and establishment of rotating life-limited parts limits.
(c) Reduction in unnecessary engine and component removals
(d) Engine hardware savings by increased engine and module availability
(e) Reduction in secondary engine damage through removal and replacement of defective parts prior to failure
(f) Life usage monitoring for life critical parts
(g) Reduction in life cycle usage due to reduced operational cycles
(h) Reduction in life cycle damage from operating at high turbine temperatures

4. CASE STUDIES - OVERVIEW (see Figure 4):

What follows are excerpts from actual studies conducted by and for customers who have made the decision to install (EMS). The studies provide real examples of the varied approaches taken to understand the cost and benefit of EMS systems.

4.1 SAS Case Study (Section 5):

This analysis covers the use of the Aircraft Condition Monitoring System (ACMS) on the SAS MD-80 fleet of 40 aircraft. The engine concerned is the JT8D-200. Cost benefits accrue from the verified avoidance of engine changes and Fuel Control Unit (FCU) replacements, plus associated costs, as a result of parameter confirmation using ACMS. Total savings identified were $1357K during 1990. Running costs for ACMS during the same period amount to $625K producing a net savings of $750K US. The annual savings per aircraft was $18 274.

4.2 Lufthansa A-310 Case Study (Section 6):

This paper reviews the application of an expanded aircraft integrated data system (AIDS) on A310 and A300-600 aircraft. The system collects data for subsequent ground analysis and storage to allow diagnosis and trending. Savings accrue from:-

(a) Fuel savings derived from optimal adjustment of variable stator vanes (VSV) and bleed valves
(b) Avoidance of dedicated engine runs for MEC optimization and fan trim balancing
(c) Reduction in maintenance costs due to the identification of performance shortfall to module level allowing the recovery of severely deteriorated modules and the return to service of those only slightly deteriorated.

The paper also identifies potential further cost benefits areas not currently capable of quantification. Total savings during the test period (5 years) are projected for the 10 year project life and amount to some $7.9 million. Running and acquisition costs amounted to $4.0 million producing a net saving of $3.7 million US. The annual savings per aircraft was $23 000.

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		COSTS			BENEFITS			
SECT.	STUDY	DEVELOPMENT	PRODUCTION	OPERATIONAL	MAINTENANCE	FUEL COST	OPERATIONS	PARTS/ENGINES
4.0	SAS (ACMS)		■	■	■	■	■	■
5.0	Lufthansa A-310 (ECM)			■	■	■	■	
6.0	US Air (FPM)	■						■
7.0	USAF F-100/PW220 (EMS)				■		■	
8.0	Tri Star (AIDS)				■	■		■
9.0	UH-1 (ODDS)		■	■	■		■	■
10.0	USAF A-10 (TEMS)		■	■	■	■	■	■

FIGURE 4 - Summary Comparison of Actual Studies Versus Cost/Benefit Factors

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4.3 US Air Flight Profile Monitoring (FPM) Study (Section 7):

This study reports on the savings benefit of utilizing an automated FPM to be able to utilize Published Safe Cyclic Life for limited life rotating parts. The system operates with the Rolls Royce Tay engine powering FOKKER 100 aircraft. Total savings for a fleet of 80 aircraft is $3 745 760 of usable disk life, with an annual savings per aircraft of $11 706.

4.4 USAF F100-PW-220 EMS Case Study (Section 8):

This report documents experience gained on the use of a comprehensive Engine Management System (EMS) utilizing high speed data bus communications with aircraft systems and the Digital Engine Electronic Control (DEEC). The system as operated on the F-16 USAF aircraft assisted in the reduction of maintenance man-hours per flying hour by 33% and the improvement of flight ready status by a factor of 5. The DEEC/EMS combination is expected to reduce maintenance manpower requirements to less than 30% of non-EMS engines at maturity. Further benefits from Logistic Support performance and Engineering Data Acquisition for trouble shooting have been identified but not quantified.

4.5 RAF Tristar Case Study (Section 9):

This report outlines the benefits accrued from use of the AIDS and GRAF9 ground station used on the RAF Tristar fleet of aircraft. Benefits occur due to the avoidance of removals and repairs, the avoidance of ground running for the adjustment of VIGV controllers, the avoidance of secondary damage and the avoidance of engine changes away from the main operating base. Other less quantifiable benefits are detailed but not costed. Quantified benefits are assessed very conservatively and do not include manpower savings. Never-the-less savings of £1.43m can be positively identified during the 5 year period of the study. These savings represent two to three times the cost of acquisition and running of the system during the period. Based upon current flying rates expected future savings are assessed at £400K to £500K per annum, which is equivalent to £23.59 per engine operating hour.

4.6 UH1 Helicopter Oil Debris Detection System(ODDS) Case Study (Section 10):

This study concerns the flight test evaluation of the ODDS on a fleet of 50 UH-1 helicopters owned by the US Army. Thirty-eight aircraft were fitted with ODDS systems and the remainder were used as a control group. Benefits accrued from the ability of ODDS to distinguish between benign and abnormal debris thus allowing only equipment with incipient failures to be removed. The system reduced the cockpit chip light alerts by 48% thus avoiding unnecessary precautionary landings. The projected cost savings for the retrofit use of the system on the 400 aircraft fleet have been conservatively estimated at $7.83m per year and potential savings of 65 556 aircraft flight hours were also identified. Payback on the $12m retrofit cost would therefore be less than 2 years.

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4.7 USAF A-10 TEMS Case Study (Section 11):

This paper assesses the benefit accrued from the use of the Turbine Engine Monitoring System (TEMS) on the USAF A10 aircraft. The study is based upon a six month trial period during 1989 but uses operational statistics over longer periods to assess cost benefits. The paper outlines the additional costs of operating the system and conservatively estimates a net savings from reduced maintenance amounting to $5.4m per year for the total A10 fleet of 410 aircraft, or $11 020 per aircraft per year.

4.8 Summary:

Different approaches were taken by the organization performing the actual studies. Very likely each had different requirements that had been established at the outset of the program.

Each study has been compared against the major cost and benefit categories described in 3.1 and 3.2. As can be seen not all the factors were considered in actual studies performed for or by the aircraft operators.

The reader should keep in mind in reading each study that the results vary with the approach taken by the originator of the study. Other studies could produce different results.

5. SCANDINAVIAN AIRLINES - COST BENEFIT ANALYSIS[1]

This analysis covers the use of ACMS on the SAS MD-80 fleet consisted of:

Year: 1990

Fleet Size:	BOEING 767:	8
	DC-10-30:	6
	MD-80:	40
	DC-9:	57

This Cost Benefit Analysis covers the MD-80-fleet with P&W JT8D-200-series engines.

5.1 Current Use of Engine Data for Technical Purposes:

a. Readouts from Quick Access Recorder Tapes for troubleshooting, confirm/deny aircraft log remarks and description of certain events

b. Engine Condition Monitoring program (ECMII) for engine trending

[1] Author Staffan Elmen, SAS, September 9, 1992

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5.2 Verified Cost Reductions:

Fifteen events of engine hot-starts and one event of EPR Overboost happened in 1990. In ten of these cases "engine change was avoided" due to readout of tapes which confirmed that temperatures and/or time over limit were within acceptable limits.

These events avoided the following costs:

a.	10 engine changes:	$ 60 000 USD
b.	10 engine transportation:	$ 35 000 USD
c.	10 shop visits:	$1 000 000 USD
d.	Fuel:	$ 3 000 USD
e.	10 lost revenue flights:	$ 165 000 USD
f.	Total:	$1 263 000 USD

Flashing Fuel Flow and EGT-indications have been a problem that have caused many delays. Due to tape readouts, it has been possible to verify the values and seven replacements of the FCU were avoided.

a.	7 FCU replacements:	$ 7 850 USD
b.	7 FCU shop visits:	$17 500 USD
c.	Fuel:	$68 400 USD
d.	Total:	$93 750 USD

ACMS Cost for the same period: $625 800 USD

Cost Benefit: $1 356 750 - 625 800 = $730 950 USD

6. LUFTHANSA AIRBUS A310 - ENGINE MONITORING SYSTEM[2]:

As an early failure detection tool Engine Condition Monitoring (ECM) has been an integral part of Lufthansa's "On Condition" maintenance concept since the early 1970s and has been paying an essential contribution towards enhancing dispatch reliability and safety.

At the beginning of the 1980s, the development of improved engine diagnosis procedures and the increasing availability of digital electronics in the aircraft led to Lufthansa's decision to introduce a new and more comprehensive engine condition monitoring concept along with the advent of the AIRBUS A310.

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[2] Authors: Heinrich Schlueter, Lufthansa Maintenance Systems & Reliability
Rolf Schoeddert, Lufthansa Engineering Department Propulsion Systems, AGARD Conference Proceeding No. 448

6. (Continued):

The advanced system is aimed at achieving, in addition to the reduction of operational irregularities, a minimization of the engine's total operating cost (fuel, material, maintenance). Also, reduction of ground operation for lower emission has ever increasingly gained in significance in the past years.

This paper reviews the application and economical aspects of this concept based on 5 years of operational experience with the combined A310/A300-600 fleet.

6.1 Conceptual Background:

A modern ECM system is intended to allow comprehensive assessment of each aircraft engine's condition through:

a. Diagnosis of its gas path performance down to the level of each individual module

b. Diagnosis of its mechanical condition in regard to vibration and lubrication system parameters

The objectives in detail are:

a. Verification of engine health
b. Detection of incipient engine problems
c. Optimum adjustment of engine controls (fuel, speed margin, stability);
d. Avoidance of engine run-ups
e. Assistance in engine removal planning
f. Optimization of the engine's overhaul workscope

Aimed at efficient and cost effective application of ECM, major emphasis was put on the establishment of an information system, which is characterized by the following conceptual highlights:

a. Expanded engine instrumentation and propulsion
b. Data multiplexer (PMUX)
c. Automatic on-board data acquisition system
d. Integration of all engine condition relevant information from operations, maintenance, work shop, and test cell
e. Central organization/analysis;
f. High degree of actuality;
g. High degree of user friendliness, versatility and expandability

6.2 System Description (Figure 5):

The Lufthansa A310s and A300-600s are equipped with an expanded AIDS which generates reports for later on ground analysis. Included in this system is an airborne printer which serves as the prime data output device. The layout of the printed reports meets Optical Character Recognition (OCR) Standards which by this permits automated reading.

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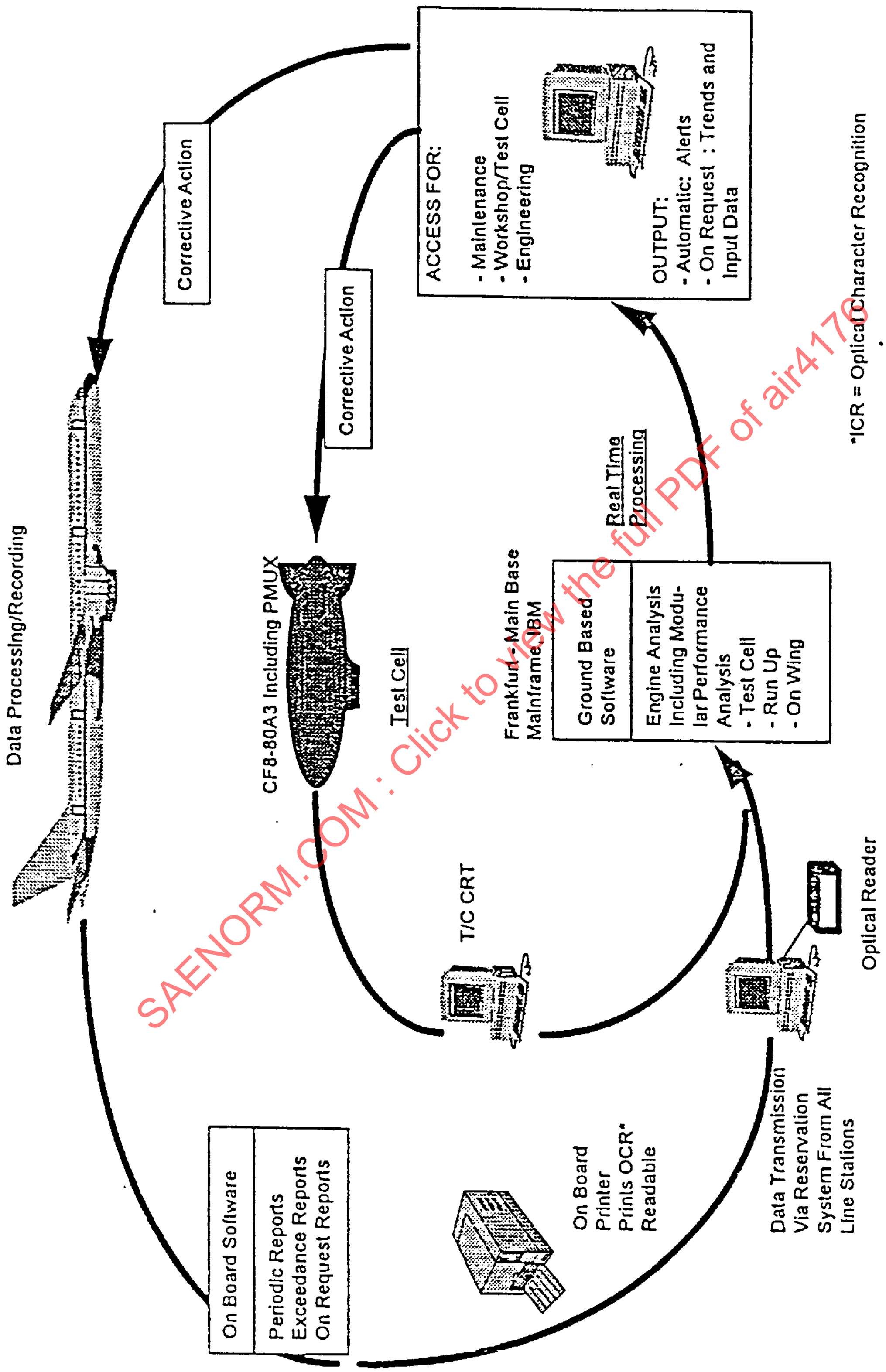

FIGURE 5 - LH 310/A300-600 Engine Condition Monitoring System

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6.2 (Continued):

Since a data link is currently not available at Lufthansa, this inevitably leads to a time lag between data recording and central analysis. For a high degree of actuality, however, a fast data transmittal medium is required. An extended on-board diagnosis capability is not considered a rewarding goal.

The contents of the reports generated during flight are entered into Lufthansa's ground-based computer network from all flight destination stations. After line station personnel have submitted the data by means of hand held video scanners those are transmitted to the central computer at the Frankfurt maintenance base where extended analysis was specified in a combined GE/airlines effort.

All input data and results are stored in a data base for trending purposes thus making complete ECM histories available. Upon analysis all results are automatically checked for findings and, if significant, are output to the maintenance engineers in the form of an alert message. This concept releases the maintenance personnel from the previous need to inspect all engine data and thus assists in concentrating on problem cases. For in-depth data analysis engine history output is provided on request via computer terminals.

In case an engine removal is due the overhaul engineers make use of engine history information for definition of the optimum shop work scope.

Upon test cell acceptance which the engine has to pass after overhaul PMUX as well as test cell instrumentation data are transmitted to the central computer for modular performance analysis. While the engine is still running the analysis results are made available automatically by return to the test cell personnel indicating the quality of measurement and performance of the engine and its individual modules.

The ECM user family connected to the ground based information system is depicted by Figure 6. Maintenance engineering in charge of the daily monitoring and troubleshooting work is located at the maintenance base in Frankfurt. Engine overhaul, production planning and control, engine test cell, as well as central engineering are located in Hamburg. The engine manufacturer, i.e. General Electric in Cincinnati, is also connected to the ECM system.

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6.3 Review of Application:

In the following the main application areas are discussed focusing on cost and savings.

The financial balance as depicted in Figure 7 is based on the experience gained between 1983 and 1987 and is projected until 1992 to cover the planned aircraft operating time of 10 years.

For the given long haul (LH) A310/A300-600 fleet and the considered time period the resulting net savings through ECM amount to 3.9 m US$.

This is 23 000 US$ per aircraft and year.

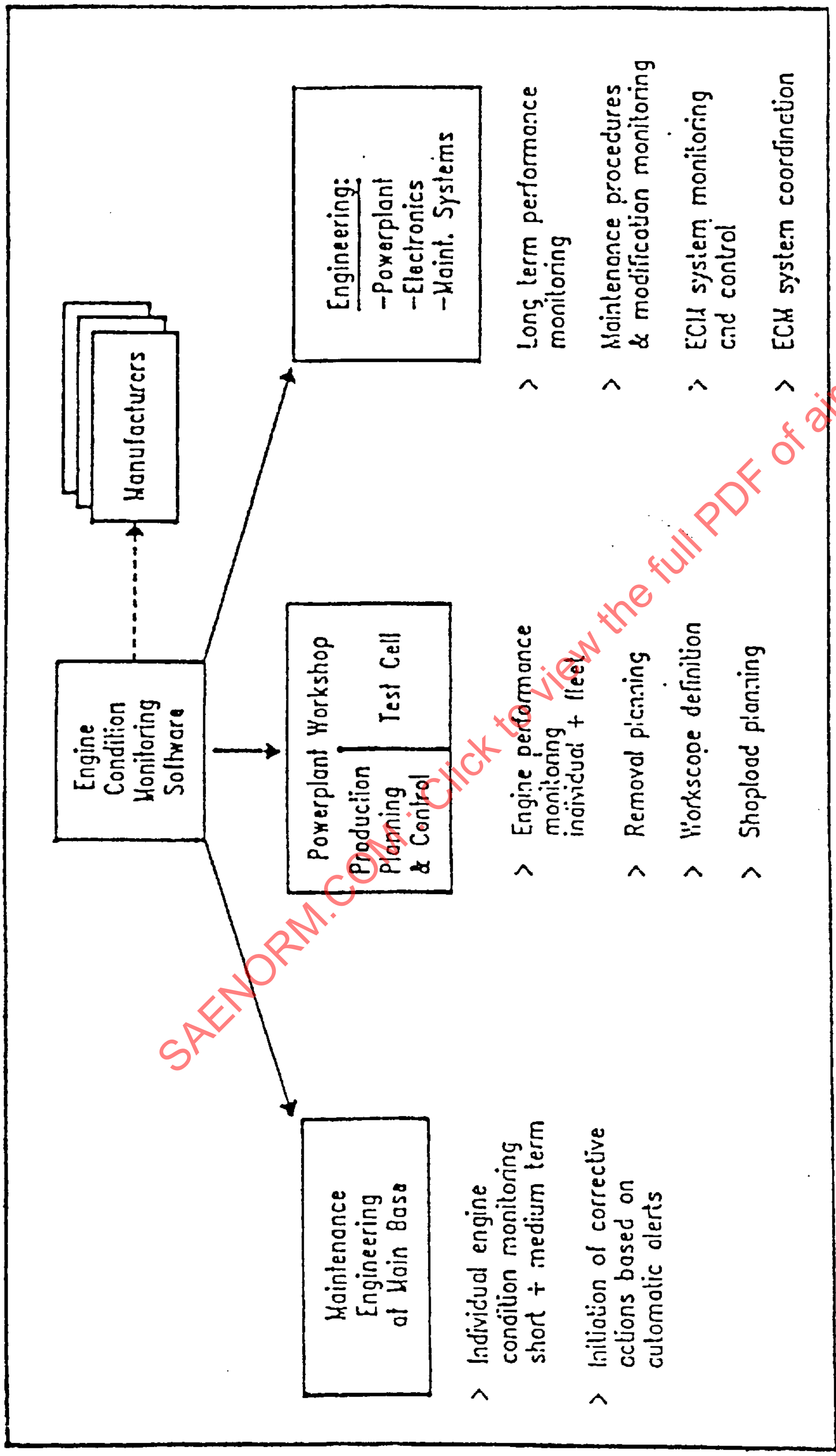

FIGURE 6 - ECM Users Community

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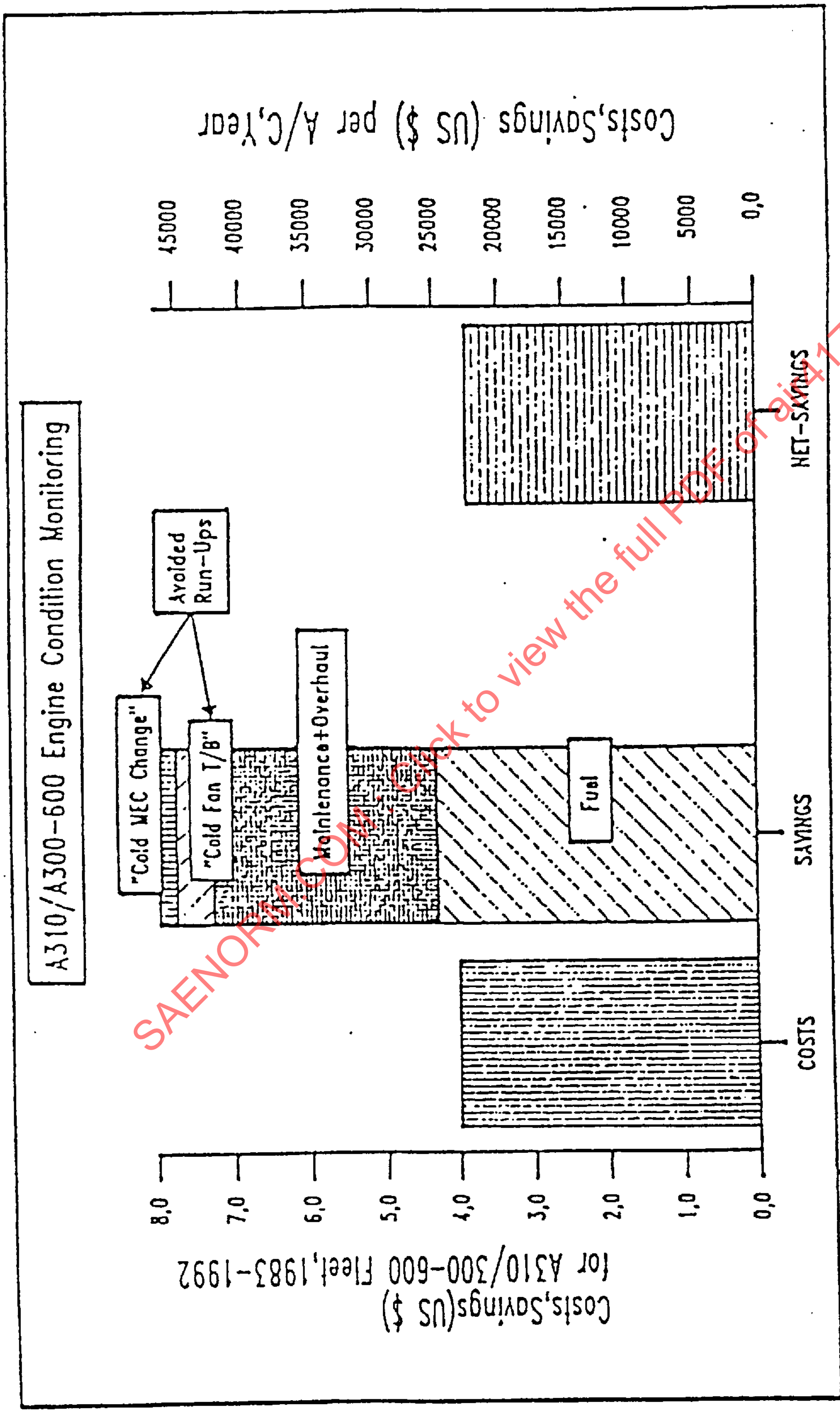

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FIGURE 7 - Costs/Savings

6.3 (Continued):

a. Cost: There are four main factors:

(1) "On-Board Hardware": This factor includes the cost for expanded instrumentation and PMUX as well as a 50% share for the Airplane Integrated Data System attributed to ECM.

(2) "Project Cost": Establishing the basic computer structure required expenditures for:

(a) Creation of the software for data input at line stations
(b) Peripheral hardware investment
(c) Creation of a new real time/on-line data/software structure
(d) Incorporation of manufacturers' programs into LH's computer environment

It has to be emphasized that most of the project costs are one time-investments charging the A310 fleet for the pioneering effort without recurring for the further fleets to come.

(3) "Computer Processing Cost": Currently this amounts to approximately $1000 (US$) per engine a year which is 0.3% of the engine maintenance cost. This is deemed to be favorable. Intended program optimization will further reduce this figure.

(4) "Software Maintenance": To a certain extent, the ECM software is subjected to continual modification for its analytical functionality. This also extends beyond the project period and requires some manpower on a permanent basis.

6.4 Savings:

a. "Fuel" (Optimum Control Adjustment): Currently the largest portion of the savings is achieved by ensuring optimum adjustment of the VSV and variable bleed valves (VBV).

Since the hydromechanical Main Engine Control (MEC) is per design not able to compensate internal deterioration this task has been integrated into ECM:

Maintenance engineering is automatically informed about off-optimum-schedule shifts derived from inflight VSV/VBV data. The corrective action, so triggered, is reduced to a verification of the transducer calibration and the adjustment itself by turning the MEC adjustment screw a defined number of turns.

No ground run is required!

The consequent application of this feature does reduce the fleet fuel consumption by 0.5%!

The associated savings depend on the actual price of fuel. For the time beyond 1987 the price has been assumed to keep the '87 level - for the cost/benefit balance a conservative approach.

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6.4 (Continued):

b. "Avoidance of Engine Run-Ups": Acquisition of operational data by ground runs is no longer required in particular for troubleshooting and verification of maintenance actions due to expanded instrumentation and availability of appropriate inflight data.

Two features are reducing especially the number of high power runs:

After replacing the MEC an optimum rig run/tracking check is normally required. Through ECM, pre-adjusted MECs get this optimum adjustment using inflight data. Only an engine leak check is performed.

For fan trim balancing the specific engine characteristic is derived from inflight data subsequent to installing a 'trial' balance weight. From this the optimum balance bolt configuration in the fan spinner is determined. The convenience of this method allows a frequent application to keep fan vibration to a minimum for the entire fleet.

The savings are based on the experience that for both adjustment procedures 2 run-ups per engine a year are avoided with total cost of $1000 (US$) per run-up.

c. "Maintenance Cost": For engine overhaul it is of essential importance to optimize the workscope with respect to both performance recovery and cost. By the availability of performance data down to the individual engine module, this task can be performed.

The information provided includes the modular performance parameter deltas (efficiencies, flow capacities) relative nominal and apparent measurement errors. The contribution of each individual module to the engine's exhaust gas temperature as the most indicative performance quality parameter is derived from this.

The overview of the actual engine health status is completed by:

(1) Initial modular performance information
(2) Overall performance status (T/O EGT margin)
(3) Nongas path related information (Oil Consumption SOAP, Vibration)

The above mentioned information derived prior to engine disassembly provides assistance in defining the workscope. Modules requiring performance recovery in any case are indicated as well as modules with slight degradation to be returned to the engine assembly line without overhaul.

The reduction of maintenance cost currently amounts to 5%.

The realization of these savings is highly dependent on experience, which was gained on deteriorated engines since 2 years. For the financial balance this figure is kept constant beyond 1988 although higher savings can be expected with further practice.

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6.4 (Continued):

d. "Early Failure Detection": This function is primarily aimed at reducing operational irregularities (delays, cancellations) and unscheduled engine removals particularly at line stations.

Within the advanced ECM system this is supported by:

(1) On-line processing and automatic trend recognition reducing the time gap between occurrence of an incipient engine failure and detectability through maintenance personnel

(2) Trending of an extended parameter set including modular performance.

e. "Failure": ECM detectable and inhering the risk for a line station removal - did not occur yet for A310/A300-600. This is due to the engines' high reliability standard, application of other ECM functions and the fleet size. With no occurrence, the cost and benefit balance currently cannot take this factor into account.

Experience from other fleets that such failures are reduced but not avoided. They are still a significant saving potential due to the steady increasing cost for unscheduled removals at line stations.

f. "Unquantified Savings": Beyond the savings described so far, ECM also offers a series of advantages whose quantification, however, is somewhat difficult.

This category includes monitoring hot day EGT margin and the limiting outside air temperature (SLOATL)[3] respectively. Engine overall performance status and engine deterioration characteristics provided by this function enable maintenance to determine the remaining on wing time. Using this information for engine removal planning provides the key to an even shop load rate.

In addition, the application of SLOATL does contribute positively to flight safety; it does prevent unexpected EGT exceedances during takeoff.

Due to the availability of modular performance information it is possible to combine modules with regard to optimum engine efficiency and lowest fuel burn. Since the savings for the attainable fuel burn reduction are currently lower than the cost for additional spare parts, module management is not applied. This scenario will change with an increasing fuel price.

Further benefits are:

[3] SLOATL - Outside Air Temperature Limit at Sea Level

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6.4 (Continued):

(1) Reduced emission due to avoided ground runs (pollution and noise) and lowest inflight fuel consumption
(2) Less unscheduled layovers due to "cold" adjustment methods ("cold fan trim balance", "cold MEC change")
(3) Reduction of secondary damage/high cycle fatigue (e.g. duct ruptures) thanks to engine vibration minimization

It must also not be forgotten that, in many cases, ECM provides information to the effect that no problem is pending. This facilitates or additionally consolidates decision-making processes.

6.5 Conclusion:

The aim of the original ECM approaches was to increase the dispatch reliability by means of early failure detection.

For the advanced ECM introduced with the A310, additional objectives are pursued in order to save fuel and maintenance cost.

The now available A310/A300-600 experience does prove the validity of this approach. Also, the high acceptance by the users has to be emphasized.

The ECM investment had to cover the implementation of the basic computer infrastructure as a major one time effort which therefore cannot be assigned exclusively to the A310; Fleet enlargement and incorporation of new fleets improve economics.

Considering today's high technological standards, it is questionable whether optimum treatment of an engine can be ensured without an extended ECM.

The on-line availability of a large amount of engine operational data will assist the engine manufacturer to better understand and quantify the mechanisms by which engines deteriorate in service. This will contribute to product improvements to the benefit of the airline industry.

6.6 Outlook:

The above described concept will be used as the standard for future aircraft/engine types with some further enhancements.

For AIRBUS A320 and BOEING B747-400, ECM will be extended to a comprehensive "Airplane Condition Monitoring" (ACM) covering engine, APU and airplane performance.

The engines of these aircraft are generally equipped with a Full Authority Digital Engine Control (FADEC). The FACEC per design (Closed Loop Concept) automatically ensures optimum VSV and VBV adjustment. The cost for ECM related on-board hardware is reduced because the FADEC amongst other things replaces the PMUX.

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6.6 (Continued):

As a further "Data Transport Channel" it is planned to establish a direct transfer of digital data from the aircraft via ground stations to the central computer.

The expansion to Aircraft Condition Monitoring (ACM) necessitates software standardization for minimizing the airlines' implementation effort. Standardization endeavors are currently being forced ahead by SAE under strong support by manufacturers and airlines.

ECM is of particular importance for all airlines operating twin engine aircraft under extended range conditions (EROPS). This is supported by the FAA in drafting of an appropriate recommendation for operation under EROPS conditions.

The changing attitude of the manufacturers must also be mentioned. While ECM was still largely left to the initiative of the airlines a few years ago, particularly also the aircraft manufacturers have realized that they have a relevant contribution to make.

A step in the right direction is the approach for integration of an ACMS in the BOEING 737 aircraft. The ACMS requirements are already being taken into account in an early phase of the development. Both the on-board hardware and also the ground-based software will be provided and supported by the aircraft manufacturer. As a matter of course, also in this scenario the challenge of implementation and successful application still remains with the user airlines.

7. USAIR FLIGHT PROFILE MONITORING (FPM) COST/BENEFITS[4]:

USAIR has been able to quantify benefits of using FPM as a requisite for making full use of the Published Safe Cyclic Life (PSCL) for the life limited rotating parts in the Rolls-Royce Tay engine which powers the Fokker 100 aircraft.

Life Cycle Usage is based on equivalent flight cycles in accordance with a datum flight profile envelope that shows the limit of frequency and amplitude of rpm excursions during a flight cycle.

An operator is required to monitor the actual flight profile relative to the datum flight profile. If the operator chooses not to monitor the actual flight profile for whatever reason, the operator may have to forfeit 25% of the PSCL life based on the manufacturer's Life Limited Parts Program.

To USAIR, this means forfeiting $3 745 760.00 (1991 dollars) worth of disk life for a fleet population of 80 engines if one chooses not to monitor actual flight profiles. On an annual basis, at the life usage of 2500 cycles per year, equates to a yearly savings of $468 220.00 of usable disk life that USAIR gains by conducting FPM. One can weigh this against a software charge of $28 000.00 to modify the on-board Digital Flight Data Acquisition Unit (DFDAU) to generate what USAIR call, "LCF Reports" that are down linked to the ground station. These LCF Reports are used to provide the actual flight profile to the engine manufacturer who verifies the datum flight profiles so that USAIR can make full use of the PSCL.

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[4] Summary by David Claar, Senior Propulsion Engineer, USAIR, October, 1994

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8. USAF F100-PW-220 ENGINE MONITORING SYSTEM[5]:

8.1 Introduction:

The F100-PW-220 Engine Monitoring System (EMS) is one of the most advanced logistics support tools in production for the Pratt & Whitney F100 family of gas turbine engines. The highly successful introduction of the PW-220 EMS represents over ten years of diagnostic system and maintenance technology development, utilizing the latest in aerospace electronic component, designs, and digital engine control system implementation. The PW-220 EMS is a comprehensive engine support system that is fully integrated with in-flight aircraft operating systems, as well as, ground-based maintenance and logistics systems.

8.2 System Objectives:

The primary objective of the PW-220 EMS is to provide information to assist in identifying faulty engine control system components, detecting and documenting engine operation beyond acceptable limits, recording normal engine usage, and tracking engine performance. Encompassed in this single objective are redesign goals which include:

a. Fully automatic in-flight operation
b. Electronic data transfer to aircraft and ground systems
c. Use of only off-engine mounted flight components
d. Modular component design for enhanced system maintenance
e. Minimum dedicated flight sensors
f. Field upgradeable software and flight line reprogramability
g. Engine and aircraft interchangeability

For the maintenance/logistics user, achieving the system objectives means fewer maintenance man-hours expended, fewer on-site spares required, increased maintenance effectiveness and increased engine/aircraft availability. For the operational user (pilot), a reliable EMS provides better real-time analysis of propulsion system integrity, higher probability of successful mission completion, and an overall reduced cockpit workload.

For the engineer, the PW-220 EMS provides *in-flight* operational data automatically or on pilot request, without adding extensive instrumentation and specialized recording equipment; however, unlike earlier, less successful attempts, the PW-220 EMS is designed for maintenance support first, and engineering data acquisition is accomplished as a secondary benefit.

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[5] Extract from paper by:

Dennis A. Myers and G. William Hogg
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P.O. Box 109600
West Palm Beach, FL 33410-9600

8.3 System Description:

The PW-220 EMS is comprised of five subsystems. There are two engine mounted units:

a. The DEEC
b. A dedicated engine monitor designated the Engine Diagnostic Unit (EDU)

Two ground support units are used for flight line and uninstalled engine test stand operations:

a. The Data Collection Unit (DCU)
b. The Engine Analyzer Unit (EAU)

The fifth subsystem is the link to the user's engine logistics database system; in the USAF, this interface is called the Ground Station Unit (GSU).

The availability of high-speed databus communications with aircraft systems, offers an excellent, relatively inexpensive data source for engine monitoring purposes, as well as, an opportunity to provide the pilot better indications of the propulsion system health, without the need for analyzing cockpit gauges or stuffing indicator panels with confusing lights. Through interaction with the aircraft cockpit display and data management computer, the PW-220 EMS is capable of supplying real-time engine operating data to augment or replace normal analog data systems. It also provides a continuously updated message identifying every fault detected and each event recorded. In exchange, the EDU acquires aircraft altitude, speed and attitude information to supplement recorded event data.

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8.4 Operational Experience:

The F100-PW-220 engine entered production services in November 1985 with USAF F-15 aircraft. During 1986 and 1987, F-16 aircraft were delivered with F100-PW-220 engines to the USAF, as well as, the air forces of South Korea and Egypt. Approximately 400 units have now accumulated over 20 000 flight hours in worldwide operations, including scenarios ranging from routine training missions to full defense alert. The PW-220 EMS has also supported remote site deployments for extended time periods.

In all applications, the performance of the EMS has met or exceeded its operational objectives.

Since detailed criteria were not strictly defined for the PW-220 EMS prior to initiating the design activity, a general operational goal of less than 10% unconfirmed occurrences at introduction was established. For purposes of operational trending, introduction is baselined around 20 000 engine flight hours (EFH); whereas, system maturity is assumed after 1 000 000 EFH.

Analysis of the system performance factors indicates that even though the introductory confirmation rate has been achieved, the primary negative contributors are FALSE and INDUCED detections. As a result, changes to the diagnostic logic criteria have been identified and incorporated in the production EMS configuration. These changes, along with some related improvements to other engine components, are expected to reduce the system unconfirmed rate to less than 1% at maturity.

8.5 Maintenance Impact:

The direct effect of the EMS on engine maintenance is somewhat difficult to isolate from other factors such as improved component reliability, better component accessibility, and modular component design, which all influence the number, duration and frequency of maintenance actions performed. The F100-PW-220 engine incorporated many changes, including EMS, which were intended to enhance overall maintainability.

Two of the more common maintenance measurement standards are:

a. The number of maintenance man-hours expended for each hour of flight time accumulated
b. The sortie generation rate, or aircraft availability

A comparison of the F100-PW-220 engine with EMS to the remainder of the F100 fleet reveals that the EMS-equipped engines are averaging approximately "33% fewer maintenance man-hours" per flight hour, and are in flight-ready status five times more often. Additional investigation with the EMS users indicates that a significant contributor to this reduced workload is the ability, with EMS, to rapidly isolate a control system anomaly to a faulty component. Coupled with the improved testability of the DEEC system, using the EMS ground support equipment, the fault isolation capability of EMS engines is expected to reduce maintenance manpower requirements to less than 30% of the non-EMS engines at maturity.

8.6 Logistics Support:

Evaluation of the PW-220 EMS logistics support performance is also difficult to accomplish, due to the absence of valid comparison data. Not only are there few, if any, figures-of-merit available for the non-EMS engine support system, but some of the users have not fully implemented the electronic transfer features of the GSU subsystem. However, where the GSU is being used, no data discrepancies have been noted; and the users have submitted new requirements to expand the system functions.

8.7 Engineering Data Acquisition:

Some features of the F100-PW-220 engine and EMS represent development and design compromises, which, with extended operation experience, have been proven to need refinement or enhancement. The parametric data obtained by the EMS has been a valuable asset in analyzing engine and control system responses to unusual flight and aircraft conditions, and formulating hardware and software changes to tolerate these situations. In several cases, the EMS data revealed operational anomalies totally unknown, and for which no design consideration had been given. Engine system changes have been developed and verified in less than half the normal time, as a result of EMS being available.

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8.8 Conclusions:

The PW-220 EMS experience has not only demonstrated the capabilities of engine diagnostic systems to positively influence engine maintainability and logistics support, but it has also highlighted the potential of EMS to improve overall propulsion system and aircraft integration. Having met system objectives and introductory performance goals, the PW-220 EMS is continuing to provide significant enhancements in failure detection, fault isolation, and repair verification. The PW-220 EMS is confirming the significant payback in reduced maintenance costs and improved logistics support offered by real-time engine monitoring.

9. TRI-STAR AIRCRAFT ANALYSIS (using AIDS and GRAF9)[6]:

9.1 Overview:

This report was sponsored by FS(AIR)42. Its aim has been to quantify where possible the benefits from engine health and usage monitoring on the 'K' series Tristar aircraft operated by 216 Squadron at RAF Brize Norton.

The report concludes that savings of about £75 per aircraft operating hour are being realized, bringing the total saving to date to about £1.5M. These figures are shown to be conservative and areas of unquantified savings are identified, one of which may result in a doubling of these figures.

Although the report was not tasked to establish costs of the monitoring process, it concludes that the quantified benefits alone are a factor of two or three times the cost of implementing and running the Ground Replay and Analysis Facility (GRAF9). The airborne recording system was an integral part of the Tristar at purchase.

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9.2 Engine Health Monitoring Benefits:

9.2.1 Condition-Monitoring Mechanisms: The parts and subsystems of the RB211 which can be monitored for their condition by these analyses are:

a. Performance trends with cruise data

(1) Overall gas path efficiency in terms of Turbine Gas Temperature (TGT) level at an Integrated Engine Pressure Ratio (IEPR)

(2) IEPR indication system calibration, by comparison with fan speed.

(3) Variable Inlet Guide Vane (VIGV) controller calibration - coarse check with IP spool speed at cruise power levels.

(4) SP compressor condition - coarse check with HP spool speed

[6] Author: The Flight Data Co. Ltd., London Heathrow Airport for the UK Ministry of Defense (FS(AIR42, January 8, 1992

9.2.1 (Continued):

b. Vibration trends with takeoff/climb and cruise data

(1) Out-of-balance in all spools, at steady-state operation

(2) Any peaks during takeoff and climb operation

(3) Calibration of each co-located transducer, by comparison with the other

It is noted that, although the AIDS records only the fixed-filter vibration signals from each spool (and from each transducer), the level of the broad band cockpit indication can be monitored, by combining all three filter levels. This allows the progression of the cockpit indication towards the shut-down level to be monitored.

Both performance and vibration trends will show whether the changes are gradual or sudden, or if abnormal levels are present at installation.

c. Variable inlet guide vane controller schedule graphs

(1) Changes in controller schedule at all power levels

d. Exceedances

(1) Approach to, and exceedance of, all limitations

In addition to the above automatic analyses, comprehensive output of the engineering quantities is available from any part of the operation, in video or hard copy form. This is used to investigate any reported problem for which data is not produced by any of the above analyses.

9.2.2 Operational Engine Monitoring: Derate level and IEPR usage analyses do not have a condition-monitoring role. The benefit from these analyses usually comes from knowledge of the power levels used and the application of that knowledge in reduction of operational fatigue.

In the case of derate, there has been no definable benefit, but the evidence that derate is used to a significant degree should assist in reducing the factors which are currently much as x5 for AAR receiving, or display, flying. This situation has hitherto been approached by setting up the LCF cyclic accumulation program described in 2.2(k), but this has not been successful in reducing these heavy factors, for the reasons reported in that paragraph. But there are precedents in civilian operation, of LCF life extensions with derate information only, so this avenue should also be researched. Moreover, Rolls Royce (RR) have recently made a presentation at an Operators Conference which allows later marks of engines to gain life increases if operation to lower levels of usage can be proven. This shows a willingness to allow benefits for operational usage monitoring and the Royal Air Force (RAF) may be able to negotiate the addition of the Tristar engine to this procedure.

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9.2.2 (Continued):

In the case of the IEPR usage analysis, this was set up to monitor the time spent in a particular band of IEPR which was critical to a coupling problem. The benefit therefore accrued largely to RR, who presumably put the information to good use.

9.2.3 Benefit Techniques: The ways in which engine-caused in-service costs are reduced by AIDS/GRAF9 data, fall into a few categories:

a. Improved accuracy and confidence of fault diagnosis. The benefit here accrues before the corrective maintenance action takes place. Because of the better accuracy of the diagnosis, the action can be more effective. Examples of this benefit are an avoidance of the 'shot-gun' changing of many of the components in a system by positive identification of the faulty unit. Or, as another example, the knowledge that a high vibration indication is cased by a long term out-of-balance, rather than a sudden failure, will avoid unnecessary ground runs, boroscopes, etc. In turn, these effects will reduce the number of 'no fault found' LRUs Line-replaceable units) returned for repair, which is a further benefit; also, the time to fix a fault is reduced, saving manpower and increasing operational availability.

   A good example of this benefit is the scheduling of an engine change at base (BZZ), rather than at any other station.

   This has been achieved by monitoring the progression of incipient failures and faults, allowing the removal to be planned. In the one case where this did not happen, the costs of the engine change were considerable, as is brought out in the case study (14751 in 949/1, 16 October 1989, Removal No 14).

b. Detection of incipient failure, allowing avoidance of secondary damage following a primary failure. The benefit here will accrue from avoidance of the damage to downstream gas path components - blades, etc. - by removing an engine as soon as the primary feeler occurs. In some cases, the primary failure occurs without causing much in the way of cockpit indications, and the engine will then run on until the secondary effects cause a major failure, with attendant higher repair costs.

c. Reduction in unscheduled maintenance - costs are avoided by having data available from normal service flying, rather than having to attach test sets and do special engine runs, for example. The prime example here is the adjustment of variable inlet guide vane controllers without the need for engine ground runs.

9.2.4 Quantification: The following Sections list cases where the above benefits accrued, and quantifies them where possible. The Sections are classified under two main headings - removals (including avoided removals and overseas engine changes) and VIGV adjustments. This is because these are the main areas where the benefits have been seen and the means of quantification or other evidence exists.

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9.3 Removals/Repairs:

Of the 24 removals of engines from K series aircraft in the period of this Report - from entry into RAF service until end 1990 - 15 of them were influenced in some way by AIDS/GRAF9 information:

a. Four were removed solely because of this information (indications of incipient failures; faults) (Removals 3, 9, 15, 21)

b. Four were removed mainly/partly because of this information (Removals 1, 2, 17, 18)

c. Three were removed for other reasons, but had a fault which had been identified with this information and which was already being monitored (Removals 4, 13, 22)

d. Four were removed for other reasons, but with diagnostic assistance from this information (Removals 6, 7, 10, 12)

e. Additionally and most importantly, 2 further engines would probably have been removed unnecessarily if AIDS/GRAF9 information had not been available to prove the engines' fitness to stay in service (see discussion on Removal 10).

9.3.2 Success Rate: Of those 15 removals detailed above:

a. Six were found on strip to have failures/wear which positively confirmed the AIDS/GRAF9 symptoms (Removals 3, 9, 15, 17, 21, 22).

b. Three had symptoms which were positively corroborated by crew indications, despite there being no strip condition details available to confirm a mechanical fault (Removals 1, 2, 4).

c. Two were found on strip to be in a condition which may confirm the AIDS/GRAF9 symptoms - i.e., general wear of the type which would produce the symptoms (Removals 13, 18).

d. Four were not relevant to confirmation - AIDS/GRAF9 used only for assistance (Removals 6, 7, 10, 12).

Therefore, of the 11 removals where confirmation of AIDS/GRAF9 symptoms by defects found on strip is relevant, 9 were positively corroborated, and two were probably corroborated by general wear condition.

No removals were based on symptoms which were completely unconfirmed. This gives a 'positive success' rate of 82%, and a 'probable success' rate of 100%, for removal actions.

The two engines which were retained in service (950/1 and /2) when Removal No. 10 (950/3) occurred, after inspection of the AIDS data, continue in service with no effects of the incident which caused the removal of the third engine - in-flight overspeed on flight test. This use of the AIDS can therefore be viewed as totally successful, and a saving accrued from the avoidance of two unnecessary repairs.

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9.3.3 Benefit Quantification: Two removals can be used for quantification of saving due to avoided secondary damage (Numbers 21 and 9), because the strip condition and repair costs are available. These case histories are therefore used to establish a typical saving due to detection of a failure in its incipient stages.

Removal Number 14 is used to establish the typical cost of an unplanned, overseas engine change, when no early failure detection occurred.

The incident which led to Removal 10 is studied to establish the saving of two unnecessary engine removals and repairs.

Other removals are examined to establish benefits of avoided maintenance action and reduced diagnostic effort. A repair cost per flying hour is estimated to quantify the saving due to avoided removals.

9.3.4 Summary of Quantified Savings in The Removal Class: In summary of the above paragraphs, the following savings are aggregated for the period of this report, for removals:

a. Those removals where secondary damage was avoided, due to detection of failures in the incipient stage:

(1) Removals 9 and 21, total estimated savings = £219 000

(2) Note that a major airline operator of similar engines uses a figure of just under £100K per removal as a result of condition monitoring, assuming that all such engines have been subject to this saving.

b. Those removals, planned at BZZ, saving potential overseas costs:

(1) Removals 1, 2, 3, 4, 9, 17 and 21, total estimated savings = 7 X £46 500 = £325 500

c. Those removals which were avoided, due to factual evidence of overspeed and overtemperature:

(1) 950/1 and /2 (Removal 10), £518 000

This gives a total saving o £1 062 500 over the period of the report, for the removals class. This gives a rate of saving of £17.70 per engine operating hour.

For the current rate of flying of 920 h per aircraft per annum, this equates to a saving of £293 000 per year. No quantified savings are claimed here for those removals which avoided further maintenance actions, or where AIDS/GRAF9 data was used to assist in diagnosis, for the reasons given in the relevant paragraphs, although benefits did accrue. Thus, the total saving above is conservative.

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9.4 Variable Inlet Guide Vane Controller Adjustments:

9.4.1 Background: The VIGV controller is probably the most troublesome single sub-system on the RB211 engine. It is a fluidic device, relying on inter-compressor supplies of air, flowing through carefully contoured passages. The balance between these flows provides signals to the ram, to set the schedule between corrected IP speed and IEPR.

Atmospheric and engine-caused contamination of the air changes the contours by deposition, causing a change in schedule. Adjustment is then necessary to restore the schedule, and when the adjustment is used up, the controller must be changed.

The rate of schedule change due to dirtying is usually fairly slow, less than 0.5% N2 per month, but more sudden changes do occur.

The maintenance manual calls for a ground run before and after the VIGV controller adjustment, to assess/confirm the amount of adjustment required/carried out. Thus, 'normal' maintenance practices, without the benefit of recorded data, will entail two ground runs (at least, assuming the adjustment assessment was correct first time), and the work of the adjustment itself. If the first run shows that more adjustment is required than is available, then a change of controller is followed by a run to check its set-up calibration. If not in the required range, a further run will be necessary after its adjustment, making a total of three.

9.4.2 Monitoring Benefits: The effect of having the AIDS/GRAF9 output available is twofold - to monitor the progression of the controller schedule towards the point where operational distress will occur (surge in the case of negative shift or overspeed in the case of positive), and to assess the amount of adjustment needed. The savings from these functions are:

a. The saving in fuel consumption which accrues from having the IP compressor working at its optimum condition. The fuel economy worsens with the controller out of calibration in both positive and negative directions, at a rate of about 0.25% SFC per 1% N2.

b. The avoidance of operational disruption caused by overspeeds, and the subsequent diagnosis and fix.

c. The avoidance of engine ground runs when an adjustment is required, when VIGV graphs are used for assessment/confirmation of the required amount.

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9.4.3 Quantification:

9.4.3.1 Item (a) in 9.4.2 can be quantified by estimation as follows - there is no doubt that 216 Squadron keeps its VIGV controllers very largely within the tramlines set out in the Maintenance Manual; this can easily be ascertained from the GRAF9 output. It is reasonable to assume that an aircraft operator without monitoring output will only know about out-of-calibration when an operational incident occurs, there being no scheduled maintenance item. This will normally happen on takeoff, and, assuming a 'hot' field takeoff ambient temperature of 30 °C, a full rated takeoff (at 1.644 IEPR) will overspeed (exceed 106%) when the out-of-calibration gets to 4% above the upper tramline. Thus, the average improvement in calibration achieved by 216 Squadron can be assumed to be say half this figure - 2%, giving a fuel saving equivalent to 2% N2, or 0.5% SFC. One half percent of the fuel used by the Tristar fleet during the period of this Report is approximately 904 tonnes, which quantifies to a saving of £276 000 for the period.

Note that the assumptions used here are an average fuel cost of £0.25 per liter, 10% of time at takeoff power (1.60 IEPR, 7500 kgs/h per engine) and 90% of time at cruise power (30 000 ft, 1.5 IEPR, 2515 kgs/h per engine), 4.4 h average sortie time, 20 000 aircraft operating hours in the period, fuel sg of 0.82.

In order to access savings in the future, then this can be converted to a saving per engine operating hour of 18.77 liters, or £4.69. Assuming the fleet flies an average of 920 h per annum per aircraft, this quantifies as an annual saving of £77 666 for the fleet.

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9.4.3.2 Item (b) in 9.4.2 is more difficult to quantify, because the number of overspeeds which might have happened if the controllers had not been maintained with AIDS/GRAF9 data, cannot be assessed with much confidence.

However, some idea of this number can be obtained from the number of controller adjustments and changes which have been made. There have been 51 adjustments and 19 changes in the period and if it is assumed that they were all required because the schedule was degrading towards a situation where an operational disruption would have occurred, then the maximum number of disruptions would have been 70.

However, it must also be assumed that the flight crews would have noticed the degradation in some cases, thus avoiding the disruption, and that other factors such as routine ground runs for other purposes would have further reduced the likelihood of service disruption. So a figure for operational disruptions of some kind is assumed to be half the maximum = 35 occasions, over the period.

At the current rate of occurrence of adjustments and changes - 92 per year, the number of disruptions would be 46, on the same basis.

9.4.3.2 (Continued):

The cost of each overspeed disruption also cannot be estimated with any accuracy, but a typical case would probably cause an abandoned takeoff, followed by a diagnostic ground run, adjustment or change, and another ground run. The costs for the diagnosis and fix are estimated and included in 9.4.3.3. But the cost of the abandoned takeoff depends very much on circumstances - from virtually no cost in the case of a training sortie at BZZ, to accommodation and subsistence for many people in the case of an AT sortie at an off-shore destination. Assuming that only one third of disruptions caused the maximum cost - 12 occasions, and that 50 people had to have an overnight accommodation, then the total costs would have been in the order of £60 000 (£100 per person per night).

At the current rate of occurrence (92 cases per annum), projected savings would be 15 X 50 X 100 = £75 000 per annum.

Thus the total saving for this aspect is £60,000 for the period and £75 000 per annum in the future.

9.4.3.3 Avoidance of engine ground runs is the most obvious saving by VIGV graphs. Two ground runs are saved, of about 30 min each, giving 1 h's running for one engine at an average of about 4000 kgs usage - average of half power. This gives a cost of £1219 for fuel, based on the pricing assumption in 8.4.3.1. By comparison, a major civilian operator uses a figure of £990 for this saving.

Unless a reduction in the establishment can be made, then the manpower saving does not pertain. However, if this were to be included, then 3 man-hours at the minimum would be saved. Also not included are the knock-on effects of finding a suitable position for high power ground running, which is not always easy.

The number of adjustments which were carried out without ground runs is 29, giving a saving here of £35 000 for fuel only. At the current rate of 58 such adjustments per year, the annual saving is projected to be £70 700. Note that no manpower saving is claimed, as is the case throughout this Report.

9.4.3.4 Thus, the total projected saving in this period of the Report for VIGV analysis is 276 000 + 60 000 + 35 000 = £371 000. The projected savings which will continue to accrue for this analysis, are 77 666 + 75 000 + 70 700 = £223 300 per annum.

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9.5 Avoidance of Secondary Damage

9.5.1 Removal No. 21 (14728, 19th Sept. 1990, 948/1): This removal came about as a result of the detection of the release of a spacer from the IP compressor first stage stators. This primary failure had not caused any crew comments or other operational impact. Being well upstream in gas path of the engine, this failure caused much damage downstream in the IP and HP compressors, as well as some slight damage to the HP turbine. The RR repair report gives the total number of replaced rotor blades as:

a. IPC:

(1) 43 x stage 1
(2) 34 x stage 2
(3) 13 x stage 3
(4) 14 x stage 4
(5) 13 x stage 5
(6) 5 x stage 6
(7) 7 x stage 7

b. HPC:

(1) 31 x stage 1
(2) 42 x stage 2
(3) 40 x stage 3
(4) 30 x stage 4
(5) 40 x stage 5
(6) 38 x stage 6

From the evidence of the vibration trend it would be seen that this failure occurred on 4 September 1990, somewhere between the cruise of Flight 924-1 and takeoff of Flight 971-1 (note that this flight number is made up of F724 sheet number for the first two digits, the F725 line number for the third digit and the sortie code for the last digit), and the removal was on the 18th, some 40 h flying later. From the reported damage, it would be seen that the mechanical integrity of the compressors had been severely reduced, and that there was, therefore, a high likelihood of a further failure, particularly as the primary failure had gone unnoticed by the crew.

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Thus, it is postulated that if the secondary failure had occurred or the compressors had degraded to the point of serious performance loss, there would have been further damage, probably to the extent of half the remainder of the IP and HP compressor rotor blades and half the HP turbine rotor blades. The HP and downstream NGVs are more robust mechanically and may well have been recoverable. This estimation is a simplification of the probable damage, but serves to indicate the likely quantification, as no other components are included. This estimation of secondary damage equates to:

9.5.1 (Continued):

a. IPC rotors:

(1) 2 x stage 1 @ £424 each = 848
(2) 7 x stage 2 @ £261 each = 1827
(3) 20 x stage 3 @ £235 each = 4700
(4) 25 x stage 4 @ £221 each = 5525
(5) 19 x stage 5 @ £126 each = 2394
(6) 22 x stage 6 @ £174 each = 3828
(8) 19 x stage 7 @ £182 each = 3458

b. HPC rotors:

(1) 14 x stage 1 @ £140 each = 1960
(2) 20 x stage 2 @ £116 each = 2320
(3) 27 x stage 3 @ £113 each = 3051
(4) 33 x stage 4 @ £75 each = 2475
(5) 18 x stage 5 @ £102 each = 1836
(6) 18 x stage 6 @ £95 each = 1710

Half a set of HPT rotor blades = 60 x £924 = £55440.

This assumes no further damage to the 05 turbine. However, if damage had occurred as far downstream as the IP or LP turbine, the costs rise quickly, with IPT rotor blades at nearly £800 and LPT stage 1 NGVs at nearly £1500. LPT stage 1 rotor blades are about 1 £730 each and NGV segments are about £1900. With this simplified estimation of secondary damage, the savings due to early warning and removal as postulated above, quantifies as:

£91 372 (The above prices are conversions from 1990 US$ prices, at a rate of 1.65.)

9.5.2 Removals No. 9 (14804, 28 February 1989, 948/2): This removal was caused by the release of a dowel from the LP first stage turbine NGV support plate. This failure was not apparent to the crew, but resulted in a repair cost of over £800K, of which over £500K was in spares. This figure amply demonstrates the high cost of turbine parts. If this failure had not been detected by the AID/GRAF9, it is likely that a secondary failure would have occurred. As the fir-tree fixings of the LP1 blades and the rim of the disc had been badly worn by the rubbing of the released dowel, the secondary failure could well have included a disc failure. Even if this had not happened, the secondary failure would probably have resulted in a loss of most LP blades and NGVs, and this is the assumption here. The actual replacements were:

a. All 92 x LP1 blades
b. 44 x retaining plates

Assuming the further loss of half of each of the remaining stages of rotor and NGVs, the extra costs would have been:

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9.5.2 (Continued):

a. LPT2 NGVs - 33/2 @ £1889 each = £30 224
b. Ditto rotor blades - 68/2 @ £846 each = £28 744
c. LPT3 NGVs - 33/2 @ £2127 each = £34 152
d. Ditto rotor blades - 68/2 @ £998 each = £33 932

Giving an extra parts cost of: £127 052

If the disc had failed, then the extra parts would have been considerably higher, as well as adding the possibility of damage to the aircraft's hull, following noncontainment.

9.6 Avoidance of Engine Changes Away From Base:

9.6.1 Removal No. 14 (14751, 16 October 1989, 949/1): This removal was not influenced by AIDS/GRAF9 information. It occurred at RAF Akrotiri, following an IFSD for high vibration and subsequent investigation. The aircraft was out of service for seven days, because of the combined difficulties of diagnosis without BZZ facilities and the problems of transporting the replacement engine and personnel/tools necessary for the change. An initial working party, dispatched from BZZ to Akrotiri to carry out the diagnosis, was followed by two Hercules aircraft to ferry out the spare engine and working party/tools for the change. The unserviceable engine was brought back to the UK by one of these Hercules aircraft. The size and weight of the RB211 engine has a multiplying effect on the equipment required for changes, and the task of getting all the equipment to any RAF station must not be underestimated. The Hercules will only accommodate this engine with care and specially modified stands. If the failed engine is in the center position, these difficulties would be multiplied again, because of the height of the engine from the ground and the increased amount of staging.

Based on this experience, detailed in 216 Squadron report 216S/810/2/Eng, the cost of a typical overseas engine change, over and above the cost of changing an engine at BZZ, can be estimated thus:

a. Transportation - in the Akrotiri case, an initial diagnosis party and two Hercules with personnel and spare engine were dispatched to Akrotiri, with the unserviceable engine being brought back by one of the Hercules. This was the first such case, and it is expected that in the 'normal' away-from-base engine change case, diagnosis would be done remotely by BZZ. Therefore, it is assumed that only the two Hercules would be required (this also assumes that stationing all the stand and the equipment at all Tristar division airports is not cost-effectively feasible). But it is certain that an engine change away from BZZ will need two Hercules details, of unknown length, if no investment is made in positioning spare engines and stands/tools.

The Akrotiri sortie is a representative distance, but the internal RAF cost of such an operation is not known, if one exists. So the commercial charge for chartering a suitable aircraft is used here, which is about £33 000 for this length of return sortie. This charge is for a CL44 Guppy, which has a payload and internal dimensions that would probably cope with the engine and wing engine stands and personnel in one sortie.

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9.6.1 (Continued):

But if two such sorties were necessary, as would probably be the case for a center engine, then the transportation cost for this aspect would be £66 000. (Note that the Akrotiri report states that, if the failed engine had been in center position, then another Hercules would have been necessary for transportation of the extra staging.) This assumes that the chartered aircraft will operate out of BZZ, avoiding the need for additional transportation of engines and equipment. Given the statistical risk of failure for wing and center engines, a transportation cost of £44 000 is used here.

b. Manpower - again, the initial diagnosis aspect is unlikely to be needed in future cases, but there remains a need for six tradesmen to be used for the engine change. Because these tradesmen would also be needed if the engine change had been planned at BZZ, the additional cost is their traveling time. Again, assuming Akrotiri as a representative location, this entails one day traveling for each man, each way, twelve man-days in all. However, manpower is not taken into account in quantified terms in this report, because of the influence on establishment figures, so no claim is made for this savings.

c. Accommodation and subsistence - assuming that the engine change would be completed in the normal course of events in three to four days, the accommodation and subsistence requirement would be for 18 to 24 man-days. The actual cost of this would depend a great deal on the location, but £100 per man-day is a reasonable expectation, so the extra cost of this aspect is £2200, say. Note that, if the engine had been in center position, then an extra day would have been needed, incurring six extra days' cost -£600. So, assume £2500 for this aspect.

d. The total of these aspects is £46 500, which is a conservative estimate of the extra cost of changing an engine away from BZZ and shows the value of planned engine changes. The true cost may well be substantially higher than this.

Another probable savings must be mentioned, although it cannot be quantified:

Other transport squadrons have specialized away-from-base engine change crews and tool sets, as well as spare engines positioned at strategic points around the world. 216 Squadron has not needed to set up such a network, because of the much-reduced probability of overseas engine changes. If no AIDS/GRAF9 had existed, there is no doubt that these facilities would have been needed. The savings include an increase in establishment levels by six tradesmen at least, a set of staging for wing and center engines, a set of tools including transport stands and, if engine transportation is not acceptable, several spare engines. Taking just the latter need only, the existence of the AIDS/GRAF9 has saved many millions of pounds on spare engines.

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9.7 Avoided Unnecessary Removals:

Repair costs on this engine are reported to vary between £0.35M and £1.20M, with the average at about £0.65M. This latter figure equates to an approximate cost per flying hour of £162 at an average on-wing life of 4000 h (engine MTBR = 0.25/1000 h and because all these removed engines were repaired in some way, the shop visit rate is the same). Therefore, if an engine is kept on the wing by informed diagnosis, and it suffers no more than normal degradation, it is reasonable to assume a savings of this amount for the extra hours operated. In the case of 950/1 and /2 engines, which were kept on in service when all three engines were oversped and overtemperatured, and when the /3 engine was removed due to a cracked turbine blade, the savings can be quantified by factoring the hours operated since the incident by the cost per hour for repairs.

Hours operated since 28 February 1989 for both engines:

a. Both engines ran 168 h before the aircraft went to MCE for maintenance.

b. /1 is still in the same position, having been removed and reinstalled while at MCE, and has run 1473 h since.

c. /2 was installed in 948/1 without repair, having been also removed by MCE during maintenance, and has accumulated 1723 h since.

Therefore, total saving = 3196 x 162 = £518 000 approximately in saved repair costs. It should be noted that the engine which was removed after this incident - 950/3, did not have the reason for removal confirmed on strip. This is further corroboration of the correctness of the decision, based on the AIDS/GRAF9 data, to keep the other two engines in service.

Another way of quantifying this benefit is to consider the reduction in hourly repair costs due to the 'extension' in the on-wing lives of these two engines. As reported above, the average hourly cost over the whole period and fleet has been £162. If these two engines had been removed at the time of the incident, when their total hours under MoD ownership had been about 100 each (ZD950 was at Boscombe Down for trails the first 3 years of MoD ownership), and a minimum repair cost had resulted (£350K), then the hourly repair rate would have been about £350), then the hourly repair rate pertains, then a savings of £188 per hour will have accrued = £664 000.

Yet another approach to this quantification is that, whatever the reason for removal, the repair workscope will always contain a minimum list of items, because of the requirements of the Reliability and Maintenance Program (RMP). This program calls for fixed work packages, and, therefore, prices, on each module, and the effect of this and the 'soft' lives that apply to each module is that any engine repair, even if the reason for removal is not corroborated, will result in an irreducible minimum cost. This is the figure of about £350 000, giving a savings on these two engines of £700 000, by this method of quantification.

In any of the above methods of quantification, it is very clear that avoidance of unnecessary removals is a powerful cost saver.

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9.8 Avoided Maintenance Actions:

Removals 3, 15 and 18 - high oil consumption, fan out of balance and HP compressor deterioration respectively, were all cases where early detection and planned removal of engines with incipient faults, avoided maintenance action which would have been called up to cope with operational reports, if the engines had remained in service. In all cases, crew reports were being generated because of the symptoms of the fault, and maintenance time was being spent on diagnosis - for high oil consumption in the first case, high vibration in the second case and high TGT in the third. However, if no AIDS data had been available, the actual cause would have been much more difficult to assess and the likelihood is that many more maintenance actions would have occurred before ultimate removal. However, these are marginal cases for quantification, because of the trade-off between savings for maintenance actions due to early removal, and the increase in hourly repair rate which results. See earlier discussion above. Therefore, although it is clear that there will have been a savings of maintenance actions here, no quantified savings is claimed.

Removal 13 - HP spool out of balance, was a special case because of the intervention of the LP1 turbine blade life threshold. But the decision not to apply for an extension of this life because of the high vibration trend, means that benefits did accrue due to avoided maintenance actions. But because of the trade-off discussed above, no quantified benefits are claimed.

Removal 22 - high LP vibration, was another case where a trend on the GRAF9 output was being monitored, and was indicating a real fault, when a removal was carried out for another reason. In this case, the other reason was also showing up the same fault. Because of these circumstances, no claim for quantified benefits is made, although the decision to remove was substantiated by the GRAF9 trend.

9.9 Diagnostic Assistance:

Removals 6, 7, 10, and 12 were all cases where operational incidents caused engine limits to be exceeded, which were reported by the crew. AIDS/GRAF9 data was used to assist the diagnosis, and in all cases confirmed definite exceedances. In two cases (Removals 7 and 10), borescope inspections indicated cracked blades, as well. Despite there being no faults found on strip in three cases (Removals 7, 10 and 12) and there being no strip information available that firm evidence of exceedances of RR limits is valuable. But this value is impossible to quantify, and none is claimed.

9.10 Other Engine Benefits:

9.10.1 As mentioned in 9.2.3(a), there is a general benefit which accrues from maintaining the serviceability of the various systems associated with the powerplant, to a higher level of availability and affectivity than would otherwise be the case. This use of AIDS/GRAF9 data is often called incident investigation, and it entails the free-thinking use of any data which can be gleaned from the GRAF9, whether from fixed analysis or by detailed inspection of the raw flight data.

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9.10.2 An example of this use is the monitoring and troubleshooting of the Integrated Engine Pressure Ratio (IEPR) system, which is the prime operating parameter for the engine.

It is a relatively complex system, with pressure tappings from rakes in the hot and cold exhaust gas streams, and a splitter block to combine these two pressures according to the ratio of nozzle areas, and to divide the resultant integrated pressure with inlet pressure. A signal conditioner box converts the resulting ratio pressure into an electrical signal and allows the matching of the ratio signal to thrust with a ballast resistor. Because the AIDS gets its signal from the IEPR cockpit gauge, the recorded IEPR parameter level can be used as a monitor on the serviceability of the whole system (and this is true for most engine parameters).

The IEPR system has many failure modes - leaking/broken pipes, malfunctioning splitter block or signal conditioner, blocked or broken rakes, etc., and the symptoms of a monitored or reported fault can be studied in depth and with a much reduced need to carry out investigations on the aircraft itself.

Typically, this system suffers from under/over-reading, causing exceedances in other parameters due to, over-powering in the first case, and loss of takeoff thrust and performance in the latter.

9.10.3 The benefits from the above circumstances apply to many other systems - vibration indication is another good example, and there are virtually impossible to quantify. This is because they are such an integral part of the normal everyday maintenance activities, that there is no attempt to record any individual case histories on which quantification could be based, by comparison with the 'what if?' situation.

Quantification on a collective basis would need a control group of similar aircraft, or by using some statistic such as unplanned maintenance man-hours or parts cost. No such statistics exist for RAF.

So, no quantified amount is excluded in this Report for this type of benefit.

9.11 Quantified Benefits:

The savings which have been identified positively for the period of the Report are quantified as: £1 433 500.

This saving equates to a rate per aircraft operation hour of £71.68, or £23.89 per engine operation hour.

The savings per annum is quoted on the basis of arisings during the trial period only. Projected savings outlined in the above paragraphs are higher. To be consistent with the body of the report, the annual projected saving should be £516 300.

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9.12 Additional Estimated Benefits:

The above savings are based only on engine monitoring and then only on positively-identifiable costs, mainly parts and fuel. They are very conservative because of the following exclusions and minimized estimations:

a. There is no element of reduced expenditure on investigation and troubleshooting of system faults or engine removal decisions - e.g., avoided no-fault-found LRU repairs.

b. There is no RAF man-power in any benefit quantification, due to the influence of establishment numbers.

c. Minimum estimations used in several cases - only one sortie for transportation of a spare engine and equipment for an overseas engine change, for example.

d. The lowest of three methods of estimating the savings of avoided removals has been used.

e. A conservative estimate of secondary damage following a turbine failure has been used.

f. There has been no inclusion for the avoidance of the need for an overseas engine change team, tools, procedure and spare engine investment, see 9.3.3.2 and removal 14.

Because of the influence on quantification estimates of the items mentioned above and elsewhere in the Report, the savings at 5.1 must be taken as conservative. An estimate of the savings due to these excluded items, except item (f), is that they will be a low fraction of the identified value, probably between 10 and 40%. Even at the low end of this estimation, this brings the total saving over the period to: £1 576 850 in the Report period, or £78.84 per aircraft flying hour, and a current saving of: £435 210 per annum.

But Item (f) is a much larger effect. No quantification is possible without a set of procedures, to determine whether spare engines would be necessary, for instance. But even if only one extra spare engine had been required to support a positioning policy, then the savings above would have increased to the order of: £3M to £4M.

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9.13 Conclusions:

9.13.1 The use of the AIDS/GRAF9 has been highly successful in detecting incipient failures in engines in service. If the two 'probables' are included, the rate of successful detection is 100%. Furthermore, this ability has allowed all but two K series aircraft engine removals to be done at BZZ, avoiding the costs and disruption of many other away-from-base engine changes.

9.13.2 The GRAF9 operation at BZZ has demonstrated very clearly that the use of monitoring as a 'pro-active' maintenance tool works well.

This means the close monitoring of engines and their sub-systems, to the level where incipient faults of all kinds are detected and monitored, so that pre-emptive action can be taken to avoid the painful consequences. The prime example of this is variable inlet guide vane system monitoring.

This principle has not only been shown to work, but has been quantified in the case of removals and avoided VIGV maintenance costs, influenced by the AIDS/GRAF9.

The identified and quantified savings are not particularly great, when compared with the significant number of aspects which have been ignored, or considered entirely unquantifiable. There is no doubt that, if any engine which has been removed in the incipient stages of failure, had gone on to cause a catastrophic failure with the attendant risk of aircraft hull damage, the bill for repair to the aircraft would exceed all the aggregated savings identified herein. This may well have ensued with the turbine dowel failure.

9.13.3 It must be remembered, when judging the cost-effectivity of the Tristar recording and analysis activities, that the RAF bought a ready-made airborne system, which had been fully developed by BA. The wisdom of putting this system to work virtually unchanged, by reconstituting the BA ground analysis facilities, shows in the fact that the primary analysis - engine health monitoring and flight operational monitoring, are basically the same now as when first introduced to 216 Squadron in 1985, and have been working well since then.

It was not part of the brief for this report to comment on the cost-affectivity of the system overall, but there is no doubt that just the savings quantified herein have far outweighed the direct costs of acquiring and running the ground facilities, probably by a factor of 3 or more.

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10. UH-1 HELICOPTER OIL DEBRIS DETECTION SYSTEM (ODDS) (Edited)[7]:

10.1 Summary:

A flight test evaluation was conducted which involved a fleet of 50 UH-1 helicopters at the US Army Aviation Development Test Activity (USAADTA), Fort Rucker, Alabama. Of these, 38 were equipped with the ODDS, incorporating ultrafine oil filters. The remaining 12 unmodified aircraft were used as a control fleet in order to monitor the oil condition in the absence of regular oil changes. Approximately 80 000 flight test hours were accomplished. The objectives of the evaluation were to attain 30% reduction in unscheduled removals brought about by poor diagnostics; to reduce the rate of false indications in current chip detectors; and to extend the oil change intervals from 100 to 1000 h on the engine and from 300 to 1000 h on the transmission.

[7] Author: Wayne A. Hudgins, May 1984; Report to U.S. Army Research & Technology Laboratories (AVSCOM)

10.1 (Continued):

The ODDS was designed and tested on the UH-1 aircraft; however, the results of this program have shown that it is a highly effective diagnostic system for monitoring the condition of gears and bearings in all Army helicopters. It has demonstrated reliable detection of failures while eliminating no-fault removals.

The ODDS requires no scheduled activity on the part of maintenance or operator personnel; it is passive until a symptom of impending component failure is manifested, at which time a chip light is illuminated. Due to its operating principle of fuzz discrimination, about 50% of the chip-light-caused precautionary landings/mission aborts are eliminated. Maintenance and operator personnel workloads are reduced significantly, with an overall increase in safety of operation.

The 3-µm filtration used in the ODDS is extremely beneficial in producing a "long-life" environment for gears and bearings. Components subjected to 3-µm filtration for many operating hours have proven to be far less distressed than similar components in standard filtered systems. Of particular interest is the great beneficial effect of 3-µm filtration on the wear rate of seals the test fleet experienced a significantly reduced seal removal rate.

The results have also shown that the oil change intervals currently used are much too short and oil use can safely be extended to 2000 h, which for all practical purposes puts the oil change on an on-condition basis. Filtration level has no effect on oil life.

Projected benefits expected from the ODDS are improvements in safety, mission reliability, and availability; an increase in engine, transmission, and gearbox mean time between oil change intervals; and an increase in bearing, seal, and gear life. These benefits combine to produce a substantial cost benefit, with payback calculated at less than two years on the UH-1 fleet as well as other aircraft.

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10.2 Problems:

Problems that have existed with the Army Oil Analysis Program (AOAP) and the splash-type chip detectors which have stimulated the continued research efforts in the improvement of diagnostic techniques include the following:

a. The UH-1 helicopter experiences a chip light indication every 130 flight hours, with 86% of these indications being false or not related to actual failures in process. The resulting mission aborts and precautionary landings have obvious safety and economic impacts. The current AOAP, in addition to being a maintenance/administrative burden, is not effective in detecting debris related to gear and bearing failures.

b. The ineffectiveness of the diagnostic schemes has produces 20 to 40% no-defect replacement rates on engines, transmissions, and gearboxes.

c. Army helicopter oil change intervals have been approximately 10% of those of other Services. Oil changes have been made on Army aircraft engines and transmissions at a much too frequent rate, with the oil removed being essentially new.

10.2 (Continued):

d. Filtration levels used in Army helicopters have generally been in the 25- to 60-µm range.

10.3 Objectives:

The objectives of this program were to attain 30% reduction in unscheduled removals brought about by poor diagnostics; to reduce the rate of false indications in current chip detectors; and to extend the oil change intervals from 100 to 1000 h on the engine and from 300 to 1000 h on the transmission.

10.4 Concept Description - Standard/ODDS:

10.4.1 Standard: The characteristics of the standard oil monitoring systems include splash-type chip detectors; a 25-µm filter in the transmission; a 60-µm filter on the engine; and condition monitoring capability through AOAP, chip detectors, and screen/filter inspections. The power train of the UH-1 aircraft includes four components with oil systems: engine, transmission, 42° gearbox, and 90° gearbox.

10.4.2 Concept Principles:

10.4.3 Flow-Thru Detectors/Debris Discrimination: It is recognized that as failures progress, debris is generated in increasing quantity and size. This relationship is fundamental in the diagnosis of failure progression as the failure progresses, more and larger chips are generated and chip lights become more frequent.

In order for a detection system to reliably detect and identify failure debris as failures progress and to be useful as a monitoring tool, three basic parameters must be addressed:

a. The detection system must capture particles of a size that indicates a real impending failure.
b. It must have a high capture efficiency for these articles.
c. The quantity and frequency of particles being generated must be known.

One of the major features of the ODDS installed in the UH-1 test aircraft which addresses the above three parameters is referred to as "flow-thru". This means that all of the oil flow passes through the detector and, therefore, almost all ferrous debris will be captured and will provide an early warning of a potential problem with the oil-wetted components. (Due to the high capture efficiency resulting from the flow-thru feature, this system is the most effective detection system in operation today.)

Although a high capture efficiency is necessary for accurate, reliable diagnosis, that capability has the potential of producing operational problems in the form of chip light indications resulting from the capture of meaningless debris in the lube system. There are numerous sources of such benign debris. Often, spurious debris will result from maintenance actions involving the lube system, including the replacement of a component with one which has been newly overhauled. Residual overhaul debris is not infrequent and may be detected at any time in the component's life as it is dislodged.

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10.4.3 (Continued):

Each engine and transmission will produce particles of ware and other debris which are not considered to be of concern and will develop different signatures with regard to debris classified as normal wear versus debris indicating true failure progression. In the case of the T-53 engine, the torque cylinder produces very fine wire- or hair-like debris on the detector. This debris can occur at any time during the life of this engine and does not indicate engine problems. Other systems, especially transmissions, have drastically different debris-generating characteristics. A larger, higher power transmission would generate more debris than a UH-1 transmission due to the component size. However, sensitivity of the detector would be the same as that for the smaller size transmission, since the sizes of the particles which must be detected for failure progression analysis are the same. Therefore, the larger system design must be tuned to capture the same size particles, but would allow for larger accumulation prior to illumination of the chip light. Techniques and/or procedures are required which will reduce/eliminate chip light incitations that result in mission aborts or precautionary landings, but at the same time will provide that result in mission aborts or precautionary landings, but at the same time will provide a reliable and timely indication of impending failure.

It is apparent that identification of debris being generated by an incipient failure and the differentiation between that debris and unimportant debris must be accomplished in order to develop a meaningful and reliable failure-indicating system.

10.5 Program Description:

Using the UH-1 aircraft as a test bed, a diagnostic oil monitoring system was designed, incorporating high-efficiency, 3-µm filters and full-flow burn-off chip detectors in the engine and transmission, and with burn-off detectors in the 42- and 90° gearboxes. The test program was structured to establish the feasibility and utility of the improved ODDS for use in Army helicopter engines, transmissions, and gearboxes. The ODDS was designed to reliably detect failures, to reduce the high rate of false and nuisance chip indications, and to reduce no-fault removals of oil-wetted components while improving component life and extending oil change intervals. It was expected that the effectiveness of the chip detector, coupled with the cleaning capability of the 3 µm filters, would substantially reduce the precautionary landings/mission aborts as well as relieve the maintenance and operational personnel of the heavy maintenance burden placed on them by the current AOAP process.

10.6 Test Results:

Study of debris generated during this program, in conjunction with good disassembly inspection reports, provided a much clearer understanding of UH-1 engine and transmission wear/failure mechanisms. As a result, debris could be grouped into abnormal (failure) and benign categories. Particles resulting from progressing failures became easily distinguishable from benign debris, i.e., debris generated by the engine torque meter assembly or induced by maintenance. In cases of benign debris indications, maintenance action was not required.

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10.6 (Continued):

The debris discrimination system tested on the UH-1 helicopter has demonstrated high accuracy and reliability in detecting incipient failures of the oil-wetted components well in advance of catastrophic failures. The failed components included the transmission mast bearing, input quill bearing, and gears, as well as the engine shaft bearings and accessory drive bearings. In all cases, the full flow-thru clip detectors provided early and repeated warnings. The important factor is that the chip lights experienced with the flow-thru detector were significant and were true indications that metal particles were present. AOAP samples were taken on a regular basis; however, none of the impending failures could be detected by AOAP since the 3-µm filters remove particles normally detectable with AOAP.

10.7 Cost Analysis:

An assessment of the projected cost savings for retrofitting the current UH-1 fleet with the ODDS is shown in Appendix A. This analysis has indicated that retrofitting the fleet would result in a 10-year return on investment of 5 and that the installation break-even point would be less than 2 years.

10.8 Conclusions:

a. The ODDS is an on-line, real-time system which reliably and accurately detects impending failures of oil-wetted components well before their presence is of concern. It requires no scheduled activity on the part of operator or maintenance personnel and remains passive until symptoms of impending component failures are manifested. Further, as a result of its operating principle, it will prevent no-fault removals.

b. Due to its reliable and accurate early detection of incipient failures, the ODDS on the UH-1 main transmission will allow on-condition maintenance to replace the current time-based change interval.

c. Based on the results of the large number of test aircraft oil samples subjected to AOAP analysis, the use of the 3-µm filter renders the current AOAP useless.

d. Analysis of the oil taken from the test and control aircraft fleet has indicated that the oil change intervals of the main transmission, the T-53 engine, and the gearboxes in the UH-1 helicopters can be safely extended to 2000 h. Further, it has been shown that filtration level does not control oil condition or changes intervals. The current procedure of changing oil on a time basis can be terminated and oil changes can be made on the basis of oil condition.

e. Assembly and maintenance-induced debris contributes significantly to the number of false or nuisance chip light occurrences.

f. The system as tested, with chip lights in the cockpit, caused a 48% reduction in chip light indications and the resultant precautionary landings.

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10.8 (Continued):

g. Failure progression of any component occurs over a considerably longer period of time (at least 100 h) than any one particular flight. It has been found that no single chip light is of importance, since components produce many chip lights during the progression of a failure. Hence, the cockpit indicating light can be placed in the maintenance bay of the helicopter and included as a post-flight inspection item with no decrease in diagnostic effectiveness. In so doing, precautionary landings due to chip light indications would be eliminated and an increase in safety would result.

h. The wear rate of seals is significantly reduced with the use of 3-µm filters in the lubrication system.

i. Component inspection results that secondary damage and sludge buildup is significantly reduced with the 3-µm filtration system installed, and it is expected that component life will be significantly increased.

j. Based on the analysis found in Appendix A, a significant cost avoidance can be realized when the system developed under this program is incorporated in the Army fleet.

k. Through incorporation of ODDS, coupled with the techniques and methodologies developed, realistic component removal decisions can be made at the unit level.

10.9 See Appendix A for the Oil Debris Detection System Cost Savings Summary.

11. USAF A-10 COST BENEFITS ANALYSIS OF TEMS (See Figure 8) BASED ON DATA GATHERED AT MYRTLE BEACH AFB)[8]:

The investigation reported in this document was requested by the Engineering and Reliability Branch, System Management Division, Directorate of Material Management, of San Antonio Air Logistics Center, Kelly AFB, Texas 78241-5000, under contract no. F41608-87-C-0582. It is published as a technical progress report only, and does not necessarily represent recommendations or conclusions of the requesting agency, either at the time of publication or at the end of contract.

11.1 Introduction:

In early August, 1989 two personnel from Support Systems Associates, Inc. traveled to Myrtle Beach AFB (MBAFB), South Carolina to investigate the “cost savings/benefits” of the TEMS on the A10A aircraft. Their mission was to find out if TEMS is in fact, saving the Air Force money and to attempt to determine the dollar value associated with these savings.

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[8] Author: Douglas S. Murray, Senior Engineer, SAIC, September 15, 1989; Report Antonio ALC, Kelly AFB

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ANNUAL COSTS:	
Man-Hour Cost Expended Maintaining TEMS Equipment	$207 131.81
Cost to Collect and Process TEMS Data Daily:	$1 166 971.81
Extra Cost at Test Cell Due to TEMS:	$178 841.19
Total Costs:	$1 552 944.81
ANNUAL SAVINGS:	
MMH Savings Due to ETTR [1]Elimination:	$470 933.64
Savings on ETTR [1]Repair:	$90 415.20
Savings on ETTR [1]Data Collection:	$1 314 822.30
Savings on Water Washes:	$199 987.73
Savings of Trim Runs:	$334 653.60
Savings Due to Reduced Engine RR: (Removal Rate)	$4 573 987.50
Total Savings:	$6 984 7910.97
NET ANNUAL SAVINGS:	$5 431 846.17

[1]"Engine Time and Temperature Recorder"

FIGURE 8 - Summary of TEMS Costs/Benefits (excludes acquisition cost)

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11.1 (Continued):

For this study, Myrtle Beach AFB (MBAFB) is assumed to be typical of the fleet and the costs/savings are calculated based upon this assumption. A certain amount of error is inherent in this assumption; however, it was decided to proceed this way in order to keep the amount of time and resources dedicated to the effort to a minimum. Although the majority of the data used in the report were collected at MBAFB, other sources have been utilized when they provide a more reliable or direct source of the information.

The majority of the data collected comes from a 6 month period from 1 January thru 30 June, 1989. This period was thought to be of manageable size and would provide a large enough sample to indicate the existing trends. In extending the data from MBAFB to the rest of the A10A fleet, the ratio of the cost/savings to the hours to the hours flown at MBAFB was determined and multiplied by the programmed total flight hours for the fleet in 1989. The resulting figure is the estimated cost/savings per year for the entire fleet in 1989 dollars.

Myrtle Beach currently flies both TEMS modified and unmodified aircraft. At the time of this writing, just 7 of the 72 aircraft in the wing have not been modified. All aircraft that are modified with TEMS have the Hot Section Life Improvement (HSLI) modification as well. Because of this, it is not always possible to isolate the impact of TEMS from HSLI. This is especially true when examining the removal rate of the TEMS/HSLI engine (-00A) verses the unmodified engine (-100). In this case an attempt has been made to adjust the data in order to make the comparison more valid.

11.2 TEMS Costs:

The following areas added costs that did not exist before TEMs implementation.

a. Man-Hours Expended Maintaining TEMS Equipment: Maintenance Man-Hour (MMH) data for Work Unit Codes (WUCs) was gathered at MBAFB. These WUCs represent all of the major subassemblies of TEMS.

(1) MMHs January - June 1989

Aircraft, on and off eqt.:	255.4 MMH
Engine, on and off eqt.:	40.2 MMH
Total:	295.6 MMH

Flight Hours (FH) January - June 1989
TEMS equipped aircraft: 14 296.8 FH
Non-TEMS aircraft: 2 298.0 FH
Combined: 16 594.8 FH
Projected Fleet FH for 89: 226 038 FH

Cost per MMH (from AFLC Pamphlet 173-10): $44.32/MMH
Ratio MMH to FH: 295.6 MMH / 14 296.8 FH = 0.0207
Cost / Year: 0.0207 * $44.32 = $207 131.81

(2) Cost to Collect and Process TEMS Data Daily

The MMH and FH used in the following calculation were taken from observations and/or interviews with the maintenance personnel involved at MBAFB at 353rd AMU.

Time to download EPU data from aircraft: 0.25 MMH
Time to upload, print and troubleshoot TEMS data: 3.0 MMH
FHs on observation day: 27.9 FH

Ration of MMH to FH: 3.25 MMH / 27.9 FH = 0.1165
Estimated Fleet MMH: 226 038.0 • 0.1165 = 26 330.6

Cost / Year: $44.32 • 26 330.6 = $1 166 971.81

b. Extra Cost at Test Cell Due to TEMS

Test cell personnel estimated that a TEMS equipped engine requires approximately 1.25 h more to process than a non-TEMS engine. The increased time is spent removing TEMS sensors that interfere with placement of the test cell vibration sensors. Also, the left rear pylon panel must be removed before the hoist adapter can be placed on the mount ring.

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