



AEROSPACE INFORMATION REPORT

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(R) Lessons Learned from Developing, Implementing, and
Operating a Health Management System for Propulsion and Drive Train Systems

RATIONALE

AIR1871C has been reaffirmed to comply with the SAE five-year review policy.

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1. SCOPE

SAE Aerospace Information Report AIR1871 provides valuable insight into lessons learned in the development, implementation, and operation of various health monitoring systems for propulsion engines and drive train systems. This document provides an overview of the lessons learned for ground-based systems, oil debris monitoring systems, lubrication systems, and Health and Usage Monitoring Systems (HUMS) for military and commercial programs. For each case study, this document presents a brief technical description, the design requirements, accomplishments, lessons learned, and future recommendations.

The lessons learned presented in this document represent a fragment of the knowledge gained through experience when developing and implementing a propulsion health management system. Previous versions of this document contain additional lessons learned during the 1980's and 1990's that may be of additional value to the reader. This document will be maintained as technology progresses so that industry members may benefit from the lessons learned of others.

1.1 Purpose

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

1.2 Approach

Health monitoring systems vary from a simple single system monitor to full propulsion system and drive train HUMS. Health monitoring systems may be fully onboard the aircraft or may include on-ground systems requiring data transmission from the aircraft. This document begins with single system monitoring, oil debris monitoring and fluid system monitoring, and progresses to the more complex, integrated HUMS.

The approach selected in preparing these lessons learned was through the review of available technical presentations and papers covering the development work and through personal interviews conducted with knowledgeable government and industry personnel directly involved with each of the case studies. In most cases, the responsible engineer from the government and/or from industry collaborated in preparing the initial draft for each case study. The SAE E32 Aerospace Propulsion Systems Health Management Committee then worked jointly with these individuals to edit and prepare the final draft. This final draft was then reviewed by the participating organizations prior to release for publication to ensure technical accuracy and clarity of content.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of the other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AIR1828 Guide to Engine Lubrication System Monitoring

ARP1587 Aircraft Gas Turbine Engine Monitoring System Guide

AS5391 Health and Usage Monitoring System, Accelerometer Interface Specification

AS5392 Health and Usage Monitoring System, Rotational System Indexing Sensor Specification



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AS5393	Health and Usage Monitoring System, Blade Tracker Interface Specification
AS5394	Health and Usage Monitoring System, Advanced Multipoint Interface Specification
AS5395	Health and Usage Monitoring System, Data Interchange Specification
SP-478	Aircraft Gas Turbine Monitoring Systems

2.1.2 Civil Aviation Authority Documents

Available from the CAA website: <http://www.caa.co.uk>.

CAP 693	Acceptable Means of Compliance Helicopter Health Monitoring CAA AAD 001-05-99
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2.1.3 U.S. Government Documents

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, <http://assist.daps.dla.mil/quicksearch/>.

AC 29-2C	Certification of Transport Category Rotorcraft (cancelled Feb 2003)
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2.2 List of Acronyms

AC	Advisory Circular
ACARS	Aircraft Communications Addressing and Reporting System
ACMS	Aircraft Condition Monitoring System
AIMS	Aircraft Information Management System
AIR	Aerospace Information Report
AMI	Aircraft Modifiable Information
APU	Auxiliary Power Unit
ARINC	Aeronautical Radio, Inc.
ARP	Aerospace Recommended Practice
AS	Aerospace Standard
ASW	Anti-submarine Warfare
BIT	Built In Test
CA	Calculated
CAA	Civil Aviation Authority
CAP	Civil Aviation Publication
CBM	Condition Based Maintenance
CH	Channel
CMC	Central Maintenance Computer

COND	Conditioner
COTS	Commercial Off The Shelf
DAL	Design Assurance Level
DAPS	Document Automation and Production Service
DELTA P	Delta Pressure
DFDAU	Digital Flight Data Acquisition Unit
DIS	Data Interchange Specification
DMS	Debris Monitoring System
EASA	European Aviation Safety Agency
EGT	Exhaust Gas Temperature
EHM	Engine Health Management
EICAS	Engine Indication and Crew Alerting System
EMI	Electro-magnetic Interference
ETOPS	Extended Range Operation with Two-Engine Airplanes
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Electronic Control
FIM	Fault Isolation Manual
GE	General Electric
HUMS	Health and Usage Monitoring System
IEEE	Institute of Electrical and Electronics Engineers
IFSD	In-flight Shutdown
IHUMS	Integrated Health and Usage Monitoring System
LCF	Low Cycle fatigue
MAT	Maintenance Access Terminal
MMS	Maintenance Management System
NASA	National Aeronautics and Space Administration
NAVAIR	Naval Air Systems Command
Ng, Nr	Speed
NVM	Non-volatile Memory

OAT	Outside Air Temperature
ODM	Oil Debris Monitoring
OEM	Original Equipment Manufacturer
PHM	Prognostics Health Management
PPI	Power Performance Index
PROB	Probability
QAR	Quick Access Recorder
RCF	Rolling Contact Fatigue
RITA	Rotorcraft Industry Technology Association
ROC	Receiver Operating Characteristic
RTB	Rotor Track and Balance
RTCA	Radio Technical Commission for Aeronautics
RUL	Remaining Useful Life
SEM/EDX	Energy-Dispersive Scanning Electron Microscopy
SP	Standard Practice
STC	Supplemental Type Certificate
STOVL	Short Take-off and Vertical Landing
TECH	Technical
TEDS	Transducer Electronic Data Sheets
TEL	Telephone
TRL	Technology Readiness Level
VHF	Very High Frequency

3. LUBRICATION SYSTEM FILTER CONDITION BASED MAINTENANCE

The following section provides a general overview of the lessons learned when developing a lubrication system filter Condition Based Maintenance (CBM) system. The lessons learned are not unique to a specific commercial or military program.

3.1 Technical Description

One method for performing lubrication system filter condition based maintenance is by monitoring the in-system filter element contamination loading in a recirculation system, such as a helicopter main transmission (or turbine engine) lubrication system. Filter element contamination loading is easily determined by monitoring the pressure drop across the filter element. When the differential pressure measured across the filter element approaches a specified level, the filter is scheduled for replacement. An abnormal increase in pressure drop is an indication of potential lubrication system problems. The captured debris within the filter element can also be analyzed to determine the source of the problem.

3.2 Design Requirements

To avoid nuisance alerts, normal differential pressure build-up characteristics across the filter must first be established. Normally, operating recirculation systems are expected to achieve a certain equilibrium level of particulate in the lubrication, based on component selection, filtration performance, and operational duty cycle. For example, in a helicopter main transmission lubrication system, the debris concentration per unit volume of lubrication increases gradually as the oil flows through the various dynamic components in the system, achieving an equilibrium level of particulate prior to passing through the filter element. The system will continue to operate at this equilibrium state until additional, abnormal debris is introduced into the lubrication system from internal or external sources. Internal sources of contamination include wear debris from gears, valves, bearings, pumps, or other dynamic components, seal wear material or oil break down products. External sources of contamination include dirty oil added at servicing or environmental contaminants entering the system through bad seals.

To measure the pressure change across a recirculation system, a differential pressure sensor is essential. Legacy recirculation systems use a differential pressure switch, which opens or closes when the pressure drop across the filter reaches a specified level. However, the differential pressure switch cannot be used to practice CBM due to the inability to monitor the pressure change over time and the inability to validate that it is operational.

A typical recirculation system for a helicopter is shown in Figure 1.

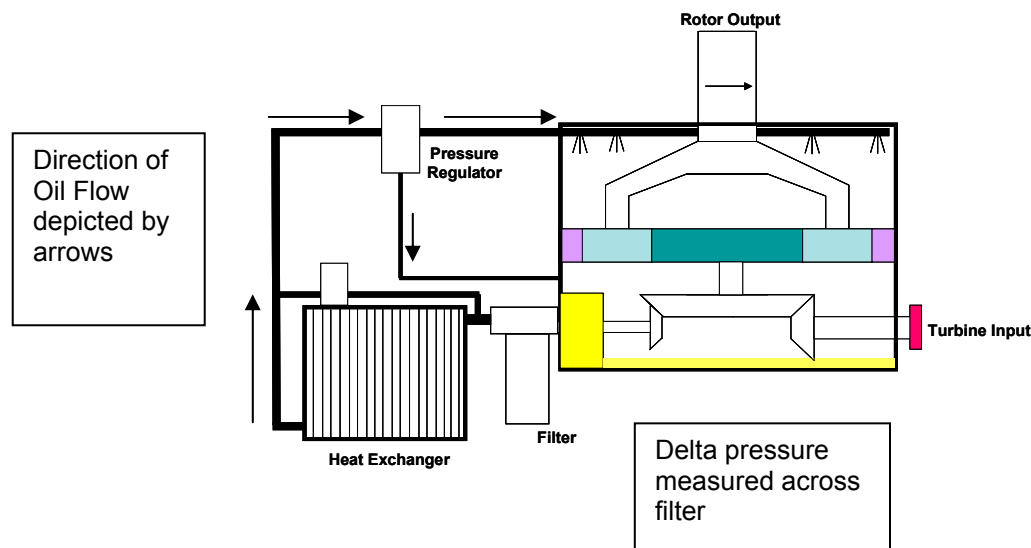


FIGURE 1 – BASIC HELICOPTER TRANSMISSION LUBRICATION SYSTEM

Figure 2 depicts the cleanliness profile of a typical lubrication system as a function of location within the system. The cleanest oil is immediately downstream of the system filter (depicted as a green line at the right of the schematic). As this oil circulates through the system/system components, ingressed/generated particulate contamination is entrained in the oil so that the particle concentration increases, depicted by the increasing blue curve at the left of the figure. The maximum contamination level, referred to as cleanliness equilibrium in the figure, is a balance between filtration efficiency and contamination ingress/generation rate. As the filtration efficiency increases, the equilibrium contamination level decreases, i.e., the line depicting equilibrium cleanliness moves downward, indicating cleaner oil. As the contaminated oil passes through the filter, a large portion of the particulate contamination is removed (vertical red line), resulting in the cleanest oil. The vertical red line depicts particulate contamination removal by the filter (filter loading). The loading will increase downward (indicating cleaner oil from the filter) as filtration efficiency increases. The filtered oil, the cleanest oil in the system, then re-circulates collecting contamination, as described above. The debris captured by the filter element will result in an increase in filter element differential pressure with service time (see below).

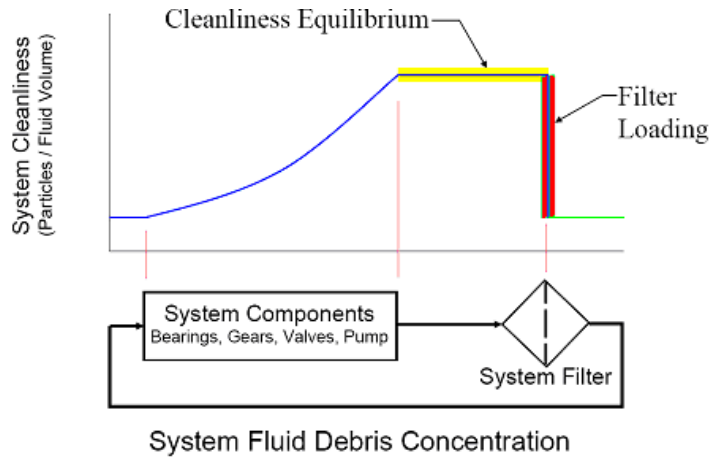


FIGURE 2 – DEPICTION OF THE SYSTEM CLEANLINESS PROFILE AND EQUILIBRIUM CLEANLINESS LEVELS

A new filter element will have a known clean differential pressure and normal system operation service life loading curve. The summation of captured debris over time will increase the differential pressure across the filter element, which can be monitored, as shown in Figure 3.

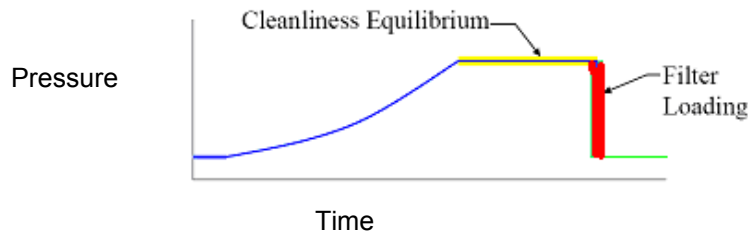


FIGURE 3 - FILTER ELEMENT LOADING CURVE

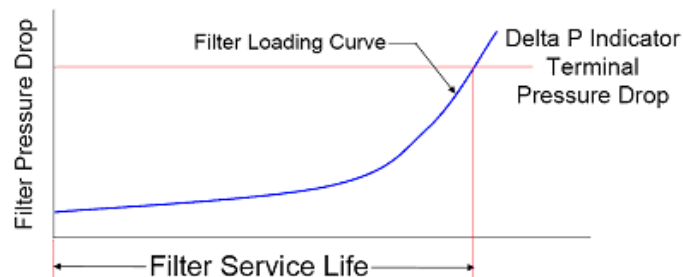


FIGURE 4 - FILTER ELEMENT SERVICE LIFE

For systems using a differential pressure switch, the switch actuates when the pressure drop across the filter element reaches a terminal value (designated as Delta P Indicator Terminal Pressure Drop in Figure 4), indicating that the filter element has reached the end of its useful service life and requires servicing. This condition typically is designed to occur just prior to filter bypass and is often referred to as impending bypass indication. Filter elements in these lubrication systems are typically replaced on hard time intervals ensuring that the filter element is serviced prior to reaching terminal pressure drop, at a time and place of convenience. The safety factor between the hard time and actual differential pressure switch actuation is conservative to minimize unscheduled filter element servicing and operation with uncontrolled oil bypassing the filter element, thus artificially reducing the filter service life. Figure 5 shows the filter service life and safety factor.

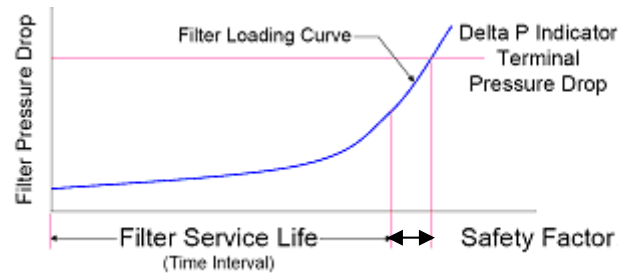


FIGURE 5 - FILTER ELEMENT SERVICE LIFE WITH SAFETY FACTOR

For systems using a differential pressure sensor, the filter element differential pressure build-up can be monitored on a continuous basis and the remaining filter element service life may be estimated based on the rate of filter element differential pressure build-up, thus optimizing filter element service life shown in Figure 6. In addition, temperature compensation of the differential pressure measurement can help to reduce the data scatter, reduce the number of false positives, and provide longer filter life.

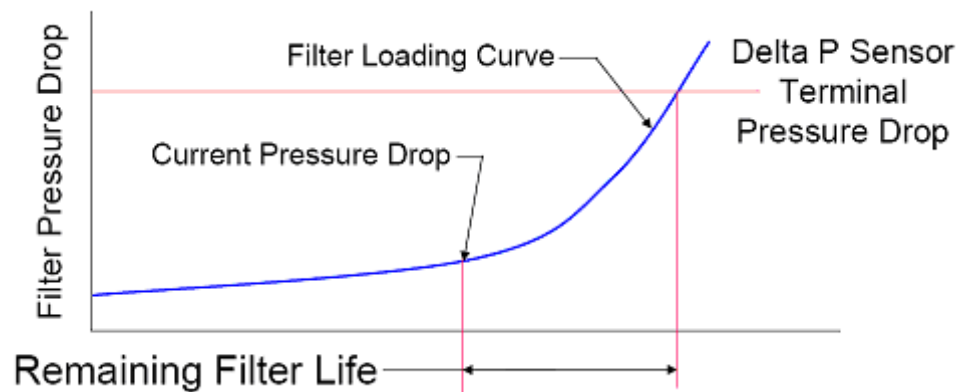


FIGURE 6 - REMAINING FILTER ELEMENT LIFE

Lubrication system filter condition based maintenance also enables early prediction of lubrication system faults. The known filter element loading curve for normal cleanliness equilibrium is used as the baseline. System operation with increased oil contamination levels (abnormal cleanliness level caused by accelerated component wear, impending component failure or oil break down) increases the debris loading of the filter element. This increased filter element loading causes an increased rate of change to the filter element differential pressure build-up curve (operating cleanliness equilibrium and abnormal filter element loading curve in Figures 7 and 8) resulting in a significant loss of filter element service life. The divergence of the filter element's loading characteristics from the baseline loading curve can be easily recognized, before the filter element reaches its terminal pressure drop, thus providing early indication of a system fault. Since the abnormal debris was captured by the filter element (causing the departure from the normal loading curve), characterization of the debris captured by the filter element can then be used to aid in identifying potential root causes.

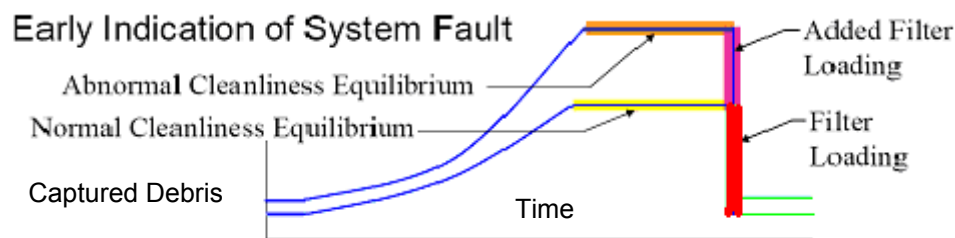


FIGURE 7 – EARLY INDICATION OF A SYSTEM FAULT

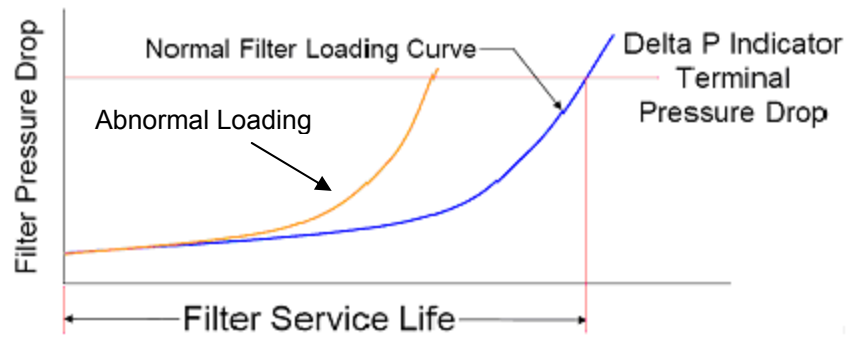


FIGURE 8 - ABNORMAL FILTER ELEMENT LOADING CURVE

3.3 Lessons Learned

- A normal operating recirculation lubrication system achieves a repeatable average cleanliness equilibrium;
- Lubrication system filter condition based maintenance requires the use of a differential pressure sensor across the filter element to enable predictive monitoring of the system;
- Remaining filter element service life can be determined by comparing the current filter element pressure drop and operating time to the baseline loading curve and terminal pressure drop;
- Short filter element service life is caused by increased debris challenge as a result of abnormal system operation. Identifying the departure from the normal filter element loading curve can provide an early indication of a system fault
- Characterization of debris captured in the filter element can provide an indication of the root cause of an early contaminant related lubrication system problem.
- Temperature compensation of the differential pressure measurement should be considered to reduce false indications.

3.4 Future Recommendations

A number of lubrication condition based maintenance systems have been incorporated (retrofitted) into existing applications. The data captured by these systems has proven valuable in predicting abnormal and premature wear of the lubrication system components. However, retrofitting this technology into existing applications does not tend to be ideal as the product envelope and interfaces typically cannot be easily modified. The recommendation is to integrate the lubrication condition based maintenance system early in a platform/program design phase to ensure the most efficient application of this technology for a given application.

4. OIL DEBRIS MONITORING

The following section provides an overview of the lessons learned when developing two different technologies for Oil Debris Monitoring for a propulsion engine.

4.1 Magnetic Debris Monitoring System (DMS)

The following section provides an overview of the lessons learned when developing an inductive Debris Monitoring System (DMS) for a propulsion engine. Some of the lessons learned may be unique to the particular engine, but others may be extrapolated to other commercial or military programs.¹

¹ Tauber, Thomas and Dag Johnsen, "Experience with the Electronic Oil Debris Monitoring System of the General Electric GE90 Gas Turbine Engine on the Boeing 777 Aircraft." 2002 Joint Oil Analysis Program (JOAP) Conference, Mobile, AL, April 2002.

4.1.1 Technical Description

The inductive DMS, as shown in Figure 9, was designed to capture, retain, and electronically count ferromagnetic particles from the lube system larger in mass than 0.13 milligrams. The DMS includes the following components:

- a) the three-phase vortex separator, mounted on top of the oil tank;
- b) the inductive DMS sensor, installed in the vortex separator;
- c) the DMS signal conditioner, which electronically conditions the output signal from the DMS sensor;
- d) the engine controller software;
- e) the engine interconnecting cables.

The three-phase vortex separator separates the air and debris from the oil. The inductive debris sensor generates a signal when a particle is captured. The DMS signal conditioner generates a digital pulse when the debris particle exceeds a preset mass threshold, which may be either on a per flight basis or on a cumulative basis. The digital pulse is detected by the engine controller, which may transmit a maintenance message or an in-flight status message via the data busses.

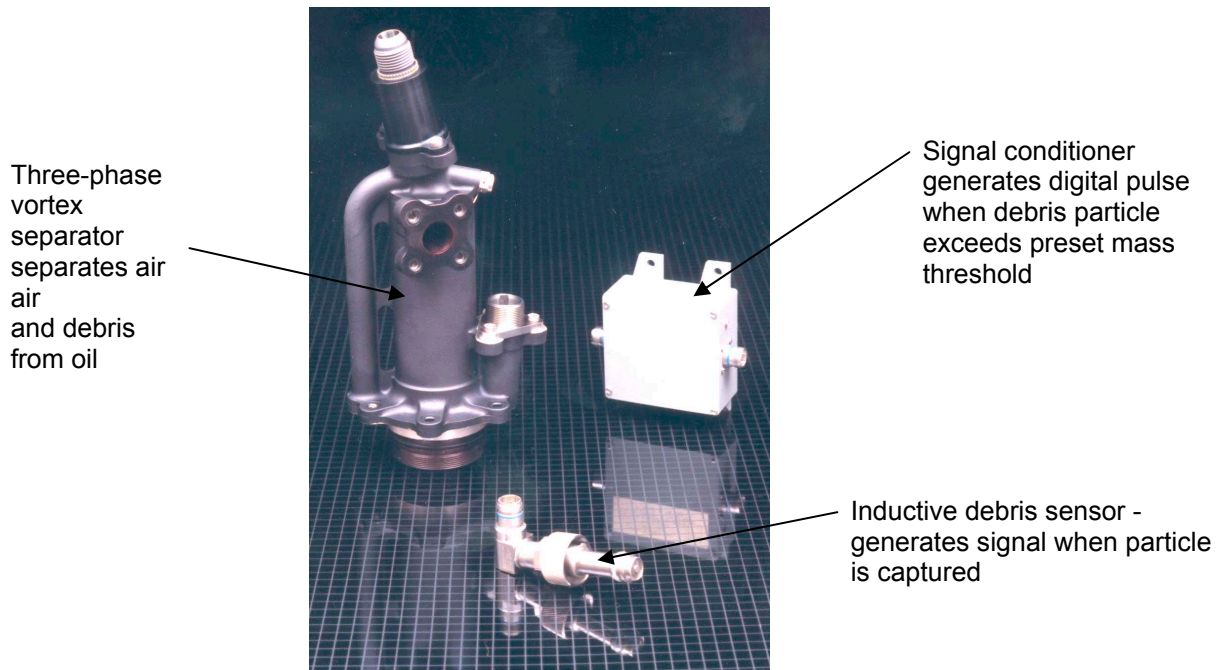


FIGURE 9 – DMS HARDWARE

Debris capture efficiency is a function of particle mass and lubrication system conditions, such as flow, pressure and temperature. The debris capture efficiency can range from 85% to 95% for debris particles characteristic of rolling contact fatigue (RCF). Although the nominal minimal mass of material needed to register a DMS count is 0.13 mg, this threshold may vary depending on magnetic properties and shapes of individual particles. Since the DMS vortex separator is not efficient for the much smaller particles produced by normal wear processes, there is no tendency for “fuzz” to accumulate on the sensor.

Figure 10 illustrates examples of Rolling Contact Fatigue (RCF) particles taken from an engine. The sensitivity of the DMS is not a function of particle size, but of the mass and the magnetic properties of the debris material and, secondarily, the shape. The DMS is calibrated using precision test platelets that are more representative of the RCF produced by engine components undergoing distress. The test platelets are square, having a thickness 1/10th of the edge dimension, commonly referred to as a 10:1 aspect ratio. Spherical calibration material having a diameter equivalent to the platelet edge dimension is more than 5 times as massive. It is important to consider the form factor and not just the particle size when designing a DMS.

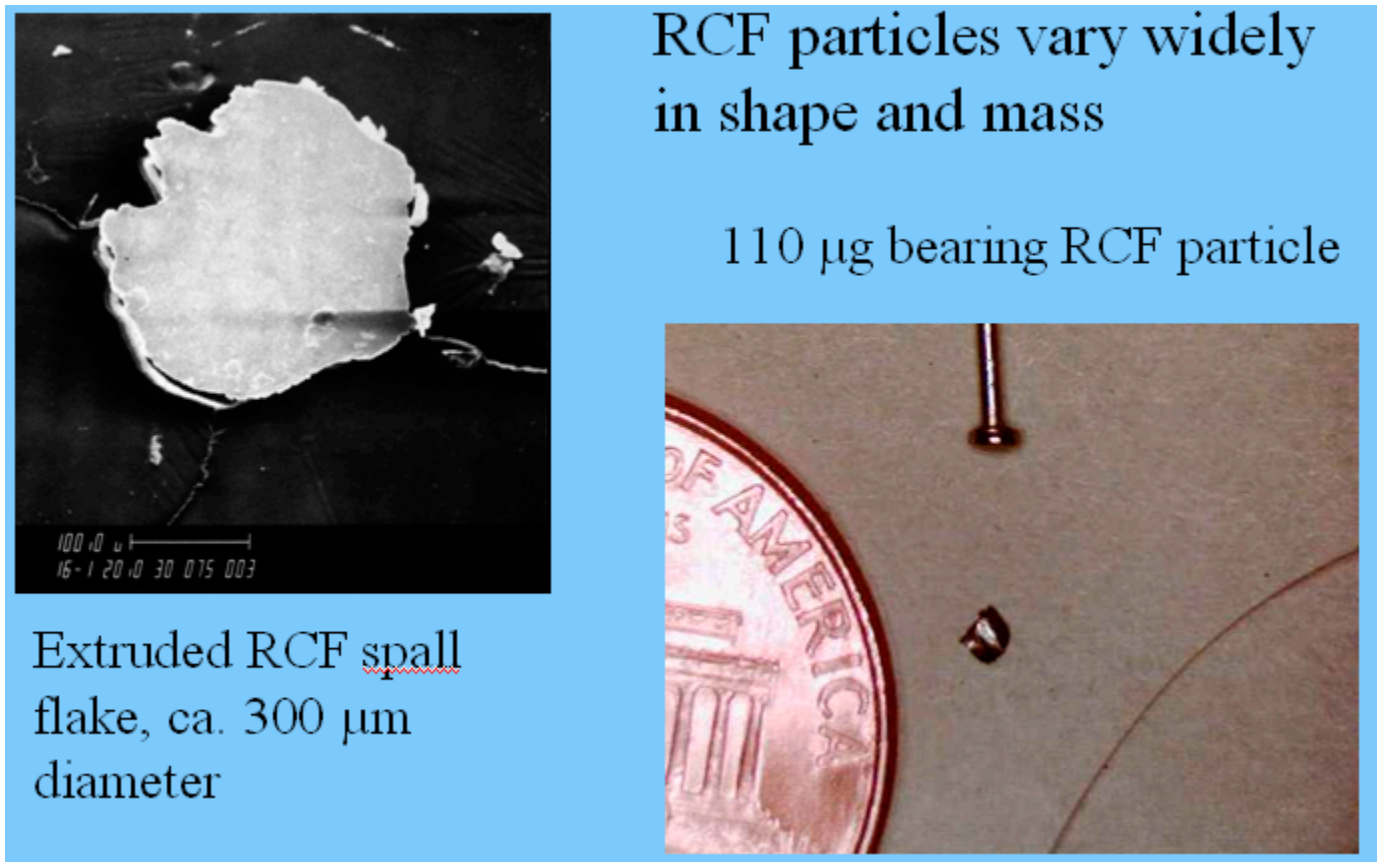
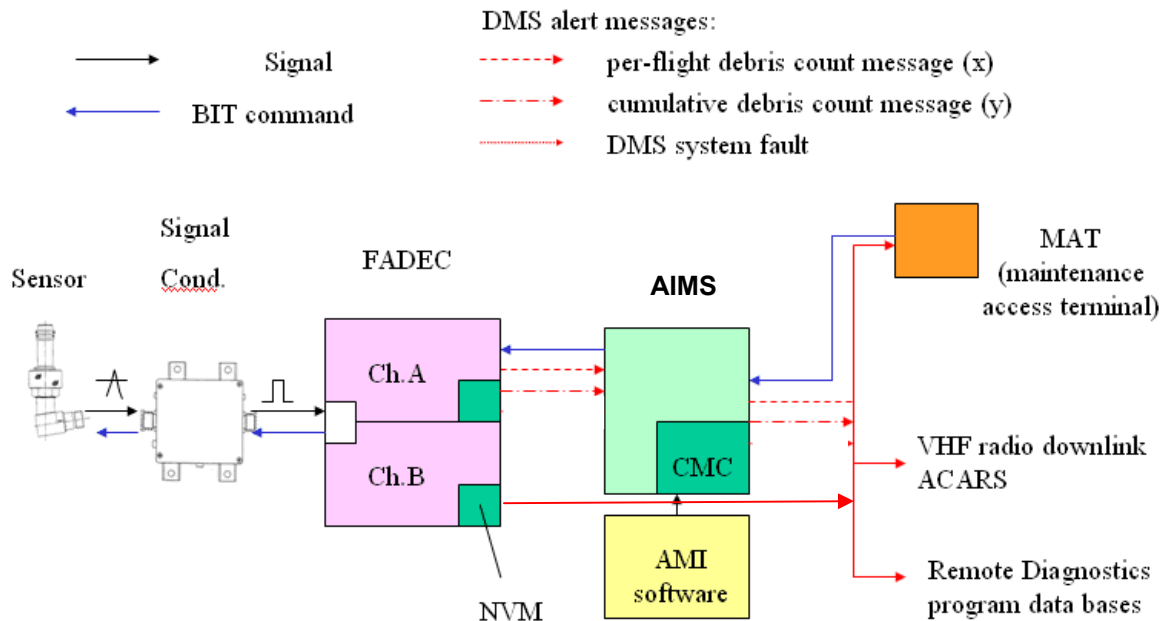


FIGURE 10 – RCF PARTICLES

4.1.2 Design Requirements

Figure 11 illustrates the inductive DMS installation on a propulsion engine in service today. This example illustrates how a DMS system has been successfully implemented and it is not meant to imply that other system architectures could not be developed to function equally as well. In this application, the DMS communicates with the aircraft, via the engine controller, through the aircraft's data buses, as part of the Aircraft Information Management System (AIMS). The AIMS relay distributes the DMS signal to the Central Maintenance Computer (CMC) which provides for the collection, storage, data management and display of all maintenance messages. The CMC communicates with the Maintenance Access Terminal (MAT) on the flight deck, which displays maintenance messages when interrogated by the maintenance personnel. The CMC can also be accessed from additional MAT ports located in other areas on the aircraft.

The DMS may be active or inactive, depending on the cockpit selection. A test of the DMS may be initiated from an onboard maintenance computer. The DMS Test checks for maintenance messages that indicate detection of debris and allows the operator to reset the debris counters stored in engine controller Non-Volatile Memory (NVM). Typically, this test is run and the chip counts are set to zero whenever the inductive DMS sensor is removed and cleaned. During engine start up, an automatic Built-in-Test (BIT) check is initiated by the engine controller to the DMS Signal Conditioner. The DMS Sensor has two wire coils: one being the sense coil and the other the BIT coil. When the engine controller issues a BIT test command to the DMS Signal Conditioner, an analog pulse is sent to the BIT coil which inductively couples the signal into the DMS sense coil simulating the arrival of a debris particle. In this way, the entire DMS, including electrical harness, is tested end-to-end before each flight.



GE90 DMS/Engine/777 Data Communication at Service Introduction

FIGURE 11 – DMS/ENGINE DATA COMMUNICATION

4.1.3 Lessons Learned

- During early service in the late 1990s and prior to a new engine controller software upgrade which included an in-flight DMS status message on the Engine Indication and Crew Alerting System (EICAS), the recommended maintenance action included a once-weekly check of DMS messages onboard the aircraft. A subsequent in-flight shutdown caused by an advanced main shaft bearing failure showed fault messages three flights prior to the IFSD, and additional counts further back. This event indicated that checking for DMS messages once a week was insufficient since failures of this type can progress more rapidly.
- Subsequently, the aircraft manufacturer recommended to all operators:
 - activate the DMS, if not already active;
 - check for DMS messages daily; or
 - if the DMS is not available, perform daily visual sensor check.
- One major airline started checking for DMS messages prior to every outbound Extended Operation for Two-Engine Airplanes (ETOPS) departure. The airline further introduced “soft” alert thresholds to avoid cancellations caused by DMS messages. These thresholds were set below those that require mandatory DMS sensor inspection and aircraft grounding if debris was found. In this way, the airline was able to put a particular engine under closer observation and obtained greater flexibility with respect to subsequent maintenance actions.
- Figure 12 illustrates the changes made to the DMS system as a result of lessons learned. The primary changes were to provide for fleet wide debris data trending, and to send a status message to the EICAS in addition to the MAT message.