

AEROSPACE INFORMATION REPORT

AIR1828
REV. B

Issued 1984-03
Revised 2005-06
Reaffirmed 2014-05

Superseding AIR1828A

(R) Guide to Engine Lubrication System Monitoring

RATIONALE

AIR1828B has been reaffirmed to comply with the SAE five-year review policy.

FOREWORD

Lubrication system monitoring for gas turbine engines can be classified into three types of activities:

- a. Oil system performance monitoring (monitoring the oil system's performance)
- b. Oil debris monitoring (monitoring the condition of oil-wetted engine components via the oil system)
- c. Oil condition monitoring (monitoring the condition of the oil itself)

Figure 1 shows schematically the techniques and hardware used for these three types of activities.

Further classifications are useful with respect to whether these techniques involve on-aircraft equipment or whether they are based primarily on off-aircraft equipment or facilities. Figure 1 indicates this classification.

Lubrication system monitoring is a part of overall engine monitoring system (EMS), as discussed in ARP1587. Frequently, lubrication system monitoring data are complementary to information obtained from other components of the engine monitoring system, e.g., vibration monitoring.

For on-aircraft debris monitoring methods, proper integration of the sensor(s) into the oil system is essential and can determine their success or failure. Further, both on-aircraft and off-aircraft debris monitoring methods are affected by the degree of oil filtration. This document, therefore, addresses both sensor integration where applicable and interaction of debris monitoring and oil filtration.

SAE Technical Standards Board Rules provide that: "This report is published by SAE to advance the state of technical and engineering sciences. The use of this report is entirely voluntary, and its applicability and suitability for any particular use, including any patent infringement arising therefrom, is the sole responsibility of the user."

SAE reviews each technical report at least every five years at which time it may be revised, reaffirmed, stabilized, or cancelled. SAE invites your written comments and suggestions.

Copyright © 2014 SAE International

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of SAE.

TO PLACE A DOCUMENT ORDER: Tel: 877-606-7323 (inside USA and Canada)
Tel: +1 724-776-4970 (outside USA)
Fax: 724-776-0790
Email: CustomerService@sae.org
http://www.sae.org

**SAE values your input. To provide feedback
on this Technical Report, please visit
<http://www.sae.org/technical/standards/AIR1828B>**

SAE WEB ADDRESS:

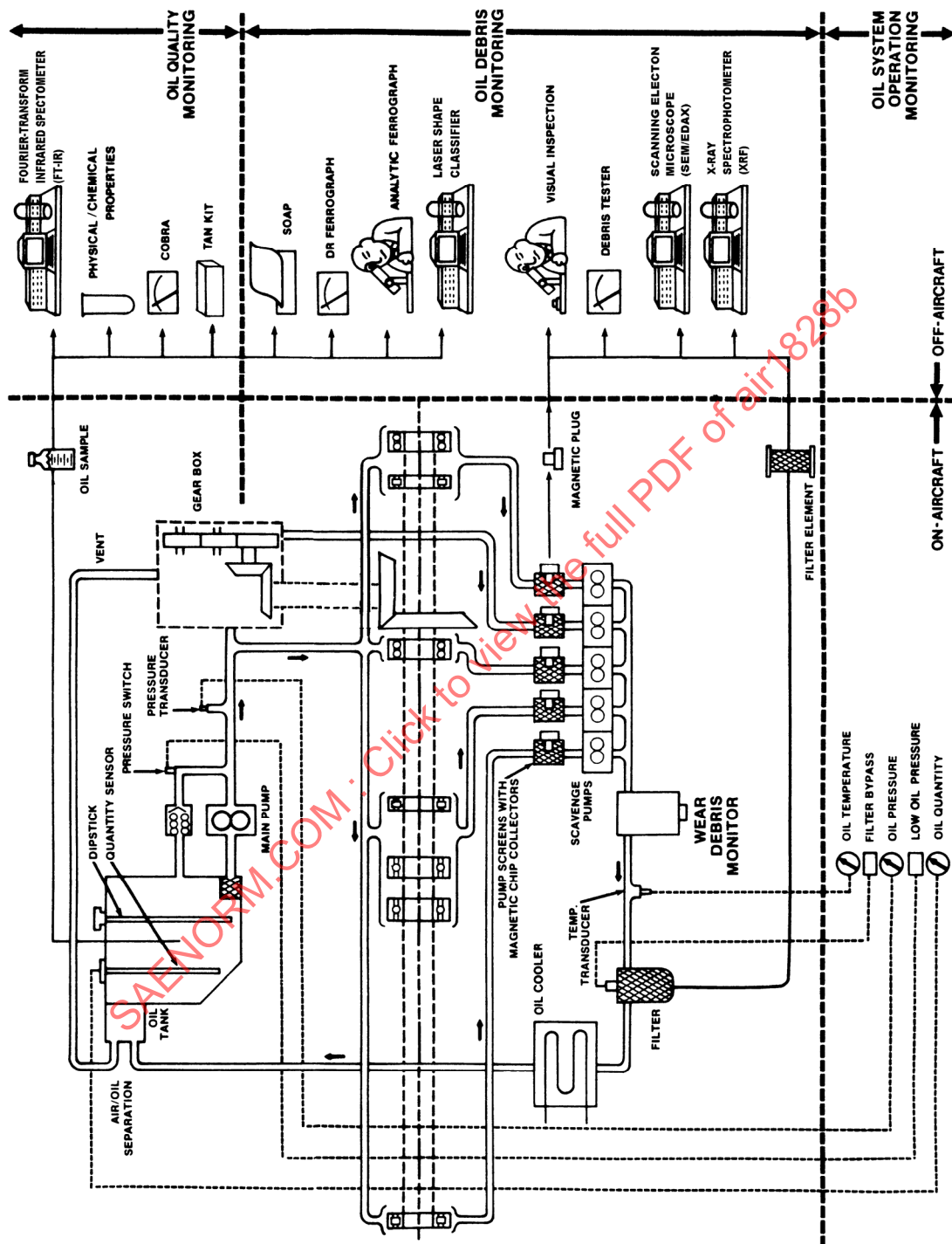


FIGURE 1 - Oil System Monitoring in Aircraft Gas Turbine Engines

Oil system operation monitoring by means of pressure, temperature, and oil quantity constitutes the earliest form of oil system monitoring in aircraft engines. Later, filter bypass indicators were added to alert maintenance crews to clogged filters.

Wear debris monitoring goes back to the periodic checking of filters, pump inlet screens, and magnetic drain plugs in reciprocating engines. By the early 1950s some airlines had developed successful systems for monitoring piston, piston ring, and main journal bearing condition on radial aircraft engines using such methods.

The introduction of gas turbine engines with their high speed ball and roller bearings brought new failure modes with high secondary damage potential. The airlines successfully applied the earlier techniques to these engines. They developed a method consisting of regular removal of the screen-type oil filters, back flushing them and analyzing their content visually in terms of quantity, size, shape, color, and material (see Reference 2.1.1). Experience obtained from previous cases was used to estimate the likelihood and severity of failures and to aid in the decision to remove the engine. Even today, regular filter inspection is used in some applications and is a valuable source of additional information when other methods provide ambiguous indications of incipient failures.

The second generation of gas turbine engines was already equipped with magnetic chip collectors with automatic shutoff valves to retain the oil and simplify routine inspection. Effective oil debris monitoring methods have since been built around this principle. In the early 1960s, electric chip detectors began to replace the magnetic chip collectors in U.S. military engines. In Europe, however, magnetic chip collectors are still in wide use today in military, as well as commercial aircraft.

Filter checks, magnetic chip collectors, and electric chip detectors are effective in detecting debris larger than about 50 μm . For the quantitative assessment of finer debris (smaller than 10 μm), spectrometric oil analysis (SOA) was applied to aircraft gas turbine engines in the early 1960s. The origins of this technique go back to condition monitoring efforts on railroad diesel engines in the 1940s. Today, it is in wide use by most military services and many airlines throughout the world.

The growing emphasis on reduced cost of ownership, increased dispatch reliability, condition-based maintenance, and automated engine monitoring has stimulated the development of new oil debris monitoring and assessment technologies. These include a new generation of electronic on-aircraft debris monitors that are already in service or are being developed. Furthermore, technologies that previously were available only in the laboratory are being investigated for possible development into on-aircraft debris monitors (e.g., optical and X-ray fluorescence technologies) or at least routine oil quality or debris assessment off-aircraft.

At the same time, improved oil filtration with its well-established benefit of longer component life has reduced the effectiveness of some widely used off-aircraft debris monitoring techniques and has stimulated the development of more sensitive instruments and methods for wear debris analysis and characterization.

Besides the hardware to detect the presence of debris in the oil system and the means to verify and diagnose the developing failure, the debris monitoring system also needs to include effective criteria for the initiation of appropriate maintenance actions. These criteria are as important as the hardware in ensuring that secondary damage is kept to a minimum, in-flight shutdowns and engine removals away from base are avoided and serviceable engines are not grounded prematurely.

While some oil-wetted component failure modes are common to all engines (e.g., bearing rolling contact fatigue), others are specific to certain engine models, usually because of the design and loading of their bearings, gears, or splines. It is often impossible during engine development to anticipate all failure modes that may occur. As a result, failure modes, detection algorithms, and removal criteria are often established with the aid of the oil debris monitoring system itself. Ideally, this should occur during engine development, but frequently requires in-service experience because of the rarity of oil-wetted component failures.

SAENORM.COM : Click to view the full PDF of air1828B

TABLE OF CONTENTS

1.	SCOPE	7
2.	REFERENCES.....	7
2.1	Applicable Documents	7
2.2	Related Publications	8
2.3	Glossary of Acronyms	9
3.	BENEFITS	10
3.1	Reliability.....	10
3.2	Reduced Cost of Ownership	10
3.3	Product Assurance and Verification	11
3.4	Safety	12
4.	OIL SYSTEM PERFORMANCE MONITORING	12
4.1	Oil Pressure	12
4.2	Oil Temperature	13
4.3	Oil Quantity and Consumption	13
4.4	Filter Bypass Indicator.....	14
4.5	Filter Pressure Drop Monitoring	14
5.	OIL DEBRIS MONITORING.....	15
5.1	General Considerations	15
5.2	Wear Modes, Failure Modes and Debris Particles.....	16
5.3	Filtration Considerations for Oil Debris Monitoring.....	23
5.4	On-Aircraft Debris Monitoring.....	23
5.4.1	Magnetic Chip Collector	27
5.4.2	Electric Chip Detector	29
5.4.3	Pulsed Electric Chip Detector	32
5.4.4	Screen-Type Full-Flow Debris Monitor.....	32
5.4.5	Centrifugal Debris Separator.....	33
5.4.6	Electronic Debris Sensors.....	34
5.4.7	System Performance Verification.....	38
5.5	Off-Aircraft Debris Monitoring.....	39
5.5.1	Spectrometric Oil Analysis (SOA)	40
5.5.2	Quantification and Analysis of Debris from Magnetic Chip Collectors	45
5.5.3	Filter Debris Analysis	46
5.5.4	Ferrography.....	47
5.5.5	Radioactive Tagging	48
5.5.6	X-Ray Spectrophotometer (X-Ray Fluorescence).....	49
5.5.7	Scanning Electron Microscope (SEM/EDX)	49
5.5.8	Laser Particle Shape Classification.....	49

6.	OIL CONDITION MONITORING	50
6.1	Complete Oil Breakdown Analyzer	51
6.2	Total Acid Number (TAN) Kit.....	51
6.3	Remaining-Useful-Life Detection	51
6.4	Fourier-Transform Infrared Spectrometer (FT-IR).....	51
7.	GENERAL REQUIREMENTS	52
7.1	Common.....	52
7.2	On Aircraft.....	52
7.3	Off Aircraft.....	53
FIGURE 1	Oil System Monitoring in Aircraft Gas Turbine Engines	2
FIGURE 2	Life Cycle Cost (LCC) for Oil Monitoring Systems.....	11
FIGURE 3	Thermal Resistance Sensor	13
FIGURE 4	Oil Quantity Sensor	14
FIGURE 5	Oil Debris Classification Chart.....	18
FIGURE 5A	Oil Debris Photographs Type A-D	19
FIGURE 5B	Oil Debris Photographs Type E-L.....	20
FIGURE 5C	Engine Oil Contamination Troubleshooting Chart	21
FIGURE 6	Factors Influencing Debris Detection	24
FIGURE 7	Capture Efficiencies for Debris Particles	26
FIGURE 8	Magnetic Chip Collector with Self-Closing Valve	28
FIGURE 9	Electric Chip Detector.....	30
FIGURE 10	Maintenance Manual Excerpt for Chip Detector Debris Interpretation	31
FIGURE 11	Screen-Type Full-Flow Debris Monitor.....	33
FIGURE 12	Centrifugal Debris Separator with Oil System Deaeration Capability.....	34
FIGURE 13	Quantitative Debris Monitor	36
FIGURE 14	Flow-Through Inductive Debris Monitor	36
FIGURE 15	Airline SOA Sampling Method	42
FIGURE 16	Oil Sampling Valve	42
FIGURE 17	U.S. Military SOA Sampling Method.....	43

1. SCOPE:

The purpose of this SAE Aerospace Information Report (AIR) is to provide information and guidance for the selection and use of lubrication system monitoring methods.

This AIR is intended to be used as a technical guide. It is not intended to be used as a legal document or standard.

The scope of this document is limited to those inspection and analysis methods and devices that can be considered appropriate for routine maintenance.

2. REFERENCES:

2.1 Applicable Documents:

- 2.1.1 R. C. Hunter: Engine Failure Prediction Techniques, Aircraft Engineering, March 1975
- 2.1.2 P. Cooper: Wear Debris Monitoring of Rolling Bearings, The British Journal of Non-Destructive Testing, Volume 25, Number 2, March 1983
- 2.1.3 T. Tauber: Full-Flow Oil Debris Monitoring In Gas Turbine Engines, ASME Paper No. 81-GT-60, March 1981
- 2.1.4 T. Tauber, S. D'Ambrosia, F. Rudbarg: A Lube System Diagnostic Monitor With Deaeration Capability, ASME Paper No. 82-GT-79, April 1982
- 2.1.5 Proceedings of the 2000 Joint Oil Analysis Program Conference, Mobile, AL, April 2000, JOAP-TSC, Pensacola, FL
- 2.1.6 D. Lotan: Spectrometric Oil Analysis - Use and Interpretation of Data, SAE Publication 720303, 1972
- 2.1.7 Oil System Debris Assessment. Rolls Royce Publication TSD 7001, Derby, U.K
- 2.1.8 J. A. Alcora, L. L. Packer, J. H. Mohn: Bearing Wear Detection Using Radioactive Iron - 55 Tagging, ASLE Preprint 81-AM-GA-3; Presented at the 36th Annual ASLE Meeting, Pittsburgh, PA, May 1981
- 2.1.9 H. A. Smith: Complete Oil Breakdown Rate Analyzer (COBRA) For Identifying Abnormal Operating Turbine Engines; International Oil Analysis Workshop, Pensacola, FL, May 1983
- 2.1.10 S. H. Loewenthal, D. W. Moyer: Filtration Effects on Ball Bearing Life and Condition in a Contaminated Lubricant, ASME Paper No. 78-Lub-34, June 1978

- 2.1.11 S. H. Loewenthal, D. W. Moyer, W. M. Needelman: Effects of Ultra-Clean and Centrifugal Filtration on Rolling-Element Bearing Life, ASME Paper No. 81-Lub-35, March 1981
- 2.1.12 T. P. Sperring, J. Tucker, J. Reintjes, A. Schultz, C. Lu and B. J. Roylance, "Wear Particle Imaging and Analysis – a contribution towards monitoring the health of military ships and aircraft," International Conference on Condition Monitoring, pp. 539-546, University of Wales, Swansea, UK, April 1999
- 2.1.13 B. J. Roylance and S. Raadnui, "The morphological attributes of wear particles - their role in identifying wear mechanisms," Wear 175, 115 (1994)
- 2.1.14 J. E. Tucker, A. Schultz, C. Lu, T. Sebok, C. Holloway, L. L. Tankersley, T. McClelland, P. L. Howard and J. Reintjes, "LaserNet Fines Optical Wear Debris Monitor," International Conference on Condition Monitoring, pp. 445-452, University of Wales, Swansea, UK, April 1999
- 2.1.15 AIR5433, Lubricating Characteristics and Typical Properties of Lubricants Used in Aviation Propulsion and Drive Systems, SAE, May 2001
- 2.2 Related Publications:
- 2.2.1 ARP1587, Aircraft Gas Turbine Engine Monitoring System Guide, SAE, April 1981
- 2.2.2 National Bureau of Standards Publication NBSIR 73-252 (Proceedings of the 18th Meeting of the Mechanical Failures Prevention Group, Gaithersburg, Maryland, 1972)
- 2.2.3 National Bureau of Standards Special Publication 436 (Proceedings of the 22nd Meeting of the Mechanical Failures Prevention Group, Anaheim, California, 1975)
- 2.2.4 National Bureau of Standards Special Publication 494 (Proceedings of the 26th Meeting of the Mechanical Failures Prevention Group, Chicago, Illinois, 1977)
- 2.2.5 National Bureau of Standards Special Publication 547 (Proceedings of the 28th Meeting of the Mechanical Failures Prevention Group, San Antonio, Texas, 1978)
- 2.2.6 National Bureau of Standards Special Publication 622 (Proceedings of the 32nd Meeting of the Mechanical Failures Prevention Group, Santa Monica, California, 1980)
- 2.2.7 Sawyer's Turbomachinery Maintenance Handbook, Volume III: Support Services & Equipment, Turbomachinery International Publications, Norwalk, Connecticut, 1980
- 2.2.8 Tribology 1978-Materials Performance and Conservation. Proceedings University College of Swansea Conference, 3-4 April 1978. Institution of Mechanical Engineers, London, 1978

- 2.2.9 R. A. Collacott: Mechanical Fault-Diagnosis and Condition Monitoring. Chapman & Hall, London; John Wiley & Sons, New York
- 2.2.10 Ferrography. Proceedings - Symposium Organized by the Condition Monitoring R&D Group of The British Institute of Non-Destructive Testing, October 1979
- 2.2.11 Wear Particle Atlas. Naval Air Engineering Center Report NAEC-92-163, June 1982
- 2.2.12 Proceedings of the 1998 Joint Oil Analysis Program Conference, Mobile, AL, April 1998, JOAP-TSC, Pensacola, FL
- 2.2.13 B. J. Roylance, T. M. Hunt, "Wear Debris Analysis", Coxmoor Publishing, 1999
- 2.2.14 Proceedings of the 2002 JOAP International Condition Monitoring Conference, Mobile, AL, April 7-11, 2002

2.3 Glossary of Acronyms:

ANN	Artificial Neural Net
AIR	Aerospace Information Report
BIT(E)	Built In Test (Equipment)
COBRA	Complete Oil Breakdown Analysis
DRF	Direct Reader Ferrograph
EDAX	Energy-Dispersive X-ray Analysis
EHL	Elastohydrodynamic Lubrication
EMI	Electromagnetic Interference
EMS	Engine Monitoring System
FAR	Federal Airworthiness Regulation
ICP	Inductively Coupled Plasma
JOAP	Joint Oil Analysis Program
LCC	Life Cycle Cost
LVDT	Linear Variable Displacement Transducer

2.3 (Continued):

RCF	Rolling Contact Fatigue
RDE	Rotating Disc Electrode
ROI	Return on Investment
SEM	Scanning Electron Microscope
SOA(P)	Spectrographic Oil Analysis (Program)
TAN	Total Acid Number
XRF	X-ray Fluorescence

NOTE: In agreement with industry usage, wear particle size ranges are given in micrometers ($1\text{ }\mu\text{m} = 10^{-3}\text{ mm} = 10^{-6}\text{ m}$) and (0.001 in = 25.4 μm).

3. BENEFITS:

The benefits that can result from oil system monitoring include increased reliability, reduced cost of ownership, improved product assurance, and enhanced safety of the equipment.

3.1 Reliability:

Lubrication system monitoring methods with good diagnostic/prognostic capability can improve operational readiness, removal scheduling and engine management, and enhance mission reliability.

3.2 Reduced Cost of Ownership:

Reliable lubrication system monitoring methods can reduce occurrence of in-flight shutdowns, engine change-outs or repairs away from main overhaul facilities, unnecessary removals, and secondary damage of progressive failure modes by identifying appropriate maintenance action.

An implemented lubrication monitoring system with fault isolation and identification capability can often give an indication of the location and type of defect that might otherwise lead to engine removal.

A cost/benefit evaluation criterion for oil system monitoring is life cycle cost (LCC). An objective of LCC trade-off analyses is to maximize return on investment (ROI) by addressing projected cost benefit (Reference 2.2.1).

3.2 (Continued):

The acquisition costs of many oil system monitoring devices are relatively low compared to the engine components they are intended to protect. The cost/benefit ratio is, therefore, generally favorable. However, maintenance, added weight, inspection, logistics, training and support personnel requirements can be dominant contributors to LCC and must be taken into account (see Figure 2).

LCC = RDT & E + Acquisition + Operational and		
Costs	Costs	Support Costs
Development	Procurement	Maintenance
	Spares	Inspection
	Laboratory	Logistics
	Facilities	Support Personnel

FIGURE 2 - Life Cycle Cost (LCC) for Oil Monitoring Systems

The cost/benefit ratio of oil debris monitoring methods can vary greatly from engine to engine, even within the same performance class. This is due to the fact that the mean time between oil wetted component failures depends on loads, speeds, lubrication conditions, and number of components, all of which can vary from design to design. In a given engine, oil wetted component defects may be a relatively frequent occurrence and an effective debris monitoring system can contribute significant cost savings. This may be especially true in the early years after service introduction. In engines where this is not the case, an expensive oil debris monitoring system or program may not be justified. Nevertheless, the general trend towards higher oil wetted component loads and operating temperatures, lower weight, and condition-based maintenance continues to drive the development of debris monitoring methods with improved failure detection, prognostic, and diagnostic capability.

3.3 Product Assurance and Verification:

Lubrication system monitoring provides product assurance by being an integral part of engine maintenance and inspection procedures and policies.

Bearings misaligned during assembly and similar build defects resulting in early abnormal wear can be detected during engine acceptance test, run-in, or initial operation by proper oil system monitoring. Lubrication system monitoring also plays an important role during engine development for verification of proper bearing and lubrication system components design.

3.4 Safety:

Bearing or gear malfunctions and impeded lubrication can lead to loss of engine power. Effective lubrication system monitoring can contribute to flight safety.

4. OIL SYSTEM PERFORMANCE MONITORING:

4.1 Oil Pressure:

Monitoring engine oil pressure provides indication of proper oil system operation and is used to detect abnormal conditions. High oil pressure can be caused by clogged oil jets. Low oil pressure can be the result of leaks, broken lines, pump failure (partial or complete), low oil level, or pressure relief valve malfunction.

Each pump has excess capacity, with a pressure regulator consisting of a ball in an orifice backed by a spring. It may have an adjustment screw. Within the balance of the regulatory system and sump capacity, oil pressure will remain constant. Therefore, oil pressure measurements contain usable monitoring information only when extreme changes occur in the oil system flow areas.

Oil pressure is monitored continuously by means of pressure transducers installed on the high-pressure side of the lubrication system, which measures the pressure across the oil jets relative to a reference pressure. These transducers are connected to cockpit instruments and interfaced with on-aircraft engine monitoring systems.

Transducer selection should address environment, linearity, repeatability, hysteresis, resolution, temperature errors, calibration errors, reliability, and mechanical/electrical interface requirements. The environmental parameters include temperature, contamination, vibration, shock, acoustic noise, and conducted and radiated EMI (electromagnetic interference).

There are a variety of pressure transducer technologies available on the market. These include strain gage, capacitive, inductive, potentiometric, piezoresistive, and LVDT.

In addition to pressure transducers for continuous oil pressure indication, most older aircraft gas turbine engines are also provided with a low-pressure switch to alert the crew to a critical engine condition. Modern engines incorporate oil pressure transducer redundancy. A low limit is set in the software that alerts the cockpit of low pressure conditions.

Federal Airworthiness Requirements (Reference FAR items 23.1305, 25.1305, 27.1305 and 29.1307) require a low oil pressure warning and/or an oil pressure indicator, depending on the type of aircraft. An oil pressure indicator is also required by applicable specifications for U.S. military engines.

4.2 Oil Temperature:

Oil temperature must be monitored to assure that it does not exceed the operating temperature limitations of the oil. In conjunction with other oil system parameters, high oil temperature may also indicate and help isolate engine subsystem malfunction. If oil temperature is sensed at the scavenge side, extreme bearing distress or hot section seal leakage may be detected or it could be caused by over servicing (overfilling the system). If the sensor is located downstream of the oil cooler, its clogging may lead to an over-temperature indication. However, slow or small changes cannot be determined in advance of a real problem. This is due to the wide range of independent variables that affect system temperature levels. These variables include engine revolutions per minute, fuel temperature and flow rate to the cooler (if used for oil system heat sink), ambient air temperature (if air/oil cooling is used), altitude, and Mach number. No simple diagnostic set of limits can be derived for multiple sensing or single sensing locations. Sensing multiple temperatures and monitoring them with the aid of an EMS could provide excellent diagnostics but might not be cost-effective.

In general, oil temperature is sensed by thermal resistance sensors that produce a change in electrical resistance with respect to temperature (Figure 3). Resistance temperature sensors are generally of the metallic type. Due to nonlinearity and lower accuracy, thermistor temperature sensors are generally not used for oil system monitoring.



FIGURE 3 - Thermal Resistance Sensor

4.3 Oil Quantity and Consumption:

Monitoring oil quantity and oil added can provide information about excessive oil consumption, oil system leakage, fuel contamination from defective fuel/oil heat exchangers, or over filling. Most engine oil tanks are equipped with sight gauges or simple dipsticks for pre or postflight oil level checking. Many commercial and military engines also have oil quantity transducers. These transducers are usually of the mechanical float/reed-switch, capacitance, or thermistor types, which can operate in this high-temperature environment. There are single point (low level) switches (Figure 4) as well as multilevel transducers for in-flight cockpit or maintenance panel readout.



FIGURE 4 - Oil Quantity Sensor

4.4 Filter Bypass Indicator:

Since a clogged oil filter would otherwise lead to oil starvation, gas turbine engine filters have bypass valves, which open under increased differential pressure. Most filter assemblies have provisions to indicate this condition externally by means of a mechanical or electrical bypass indicator. An impending bypass indicator is required by the FAR (Reference items 23.1019, 25.1019, 27.1019, 29.1019, and 33.71) and is also required by the U.S. military (MIL-E-8593). The impending bypass indicator is set below the bypass cracking pressure, since the oil wetted components can be damaged by recirculating debris if the engine is operated with a bypassing filter. A thermal lockout prevents indication due to cold oil.

The mechanical indicators are pop-up buttons and can often only be inspected by removing cowlings, etc. The electrical bypass switch permits cockpit or maintenance panel indication.

4.5 Filter Pressure Drop Monitoring:

Filter element pressure drop is monitored by mechanical, electrical, and combination indicators as well as differential pressure transducers to indicate when a filter element requires replacement. The pressure drop across a filter element can also be utilized as an indication of accelerated component wear, impending failure, poor maintenance, or oil breakdown.

4.5 (Continued):

An indicator provides a single signal to the operator at the point when filter element servicing is required. The indicator incorporates a thermal lockout feature to prevent a false indication during cold start conditions. Since there is no warning prior to indicator actuation, most normal filter element servicing is performed on a time interval to permit scheduling convenient to the operator. In this case, indicator actuation would require an evaluation of the system's condition since short filter element life is an indication of a lubrication system problem.

The transducer provides continuous signal output to the engine monitoring system allowing for operational limits to be established within the applications software without the need to change hardware. The thermal lockout function is now accomplished through the monitoring of the oil temperature. Continuous monitoring of the pressure build up across the filter element provides the operator the ability to service the filter on condition. In addition, the transducer provides the ability to identify some lubrication system failure modes by using trending techniques.

A single transducer can be used to monitor both the filter element and its bypass valve performance and the transducer can be validated for proper operation.

5. OIL DEBRIS MONITORING:

5.1 General Considerations:

In addition to its function as a lubricating and cooling fluid, the oil serves as a transport medium for the debris generated by the rolling and sliding surfaces, which are subject to wear. Normal wear, accelerated wear, and incipient failure involve the removal of material, although at different rates, and often in different particle size ranges. The debris generated in these processes contains valuable and detailed information about the condition of wear surfaces and the type of wear or incipient failure in progress. This forms the basis for engine monitoring via the oil system (oil debris monitoring).

The major objective of engine oil debris monitoring is the prompt detection of failure modes with rapid progression, particularly those with short time to onset of significant secondary engine damage. Wear modes with slow progression rates usually do not lead to engine failure by themselves. However, they can initiate secondary modes with faster progression rates. For example, a bearing surface damaged by corrosion can begin to spall eventually. Detection of this secondary mode, which progresses at a faster rate, then becomes essential if hazardous or catastrophic failure is to be avoided.

Sudden failures of oil wetted components caused by fatigue cracking, such as gear tooth or bearing race fracture, are not normally detectable by any of the methods described in this AIR. Their failure modes produce little or no debris prior to component disintegration. However, this type of failure is rare in a production engine and can be prevented by proper design and quality assurance. Vibration/acoustic and electrostatic analysis techniques are being developed to try to identify these types of defects.

5.1 (Continued):

In selecting the debris detection method(s) for the engine monitoring system, it is necessary to determine the following:

- a. The types of potential failure modes
- b. Their criticality versus their probability
- c. The required detection point (timeliness)
- d. Cost-effectiveness
- e. Weight (for on-aircraft systems)
- f. Logistics requirements

Most debris monitoring methods discussed in this AIR have at least some trending capability. Trending can provide essential information in distinguishing correct from spurious indications of the debris monitoring system or method. Trending also aids in determining the criticality of the wear or incipient failure mode under investigation.

The oil debris monitoring methods currently in use or under development can be divided into on-aircraft and off-aircraft debris monitoring techniques. This classification is useful since the two categories have different hardware and logistics requirements.

5.2 Wear Modes, Failure Modes and Debris Particles:

Wear and failure mechanisms are a result of lubrication and load conditions, and of the mechanical design characteristics of engine components, including materials. Under full-film elastohydrodynamic lubrication (EHL) conditions, where the film thickness is large compared to the average surface roughness, the predominant failure mode of rolling-contact bearings is spalling or macropitting induced by surface fatigue (see References 2.1.2 and 2.1.15). This process produces mostly large debris particles with a typical size range from 100 to 1000 μm . In the boundary lubricated and mixed-mode (partial EHL) regimes, where asperity contact occurs, the debris particles are of smaller size ($<100 \mu\text{m}$). Under such lubrication conditions, abrasive and adhesive-type accelerated wear modes such as fretting, bearing skidding, cage rubbing, gear scuffing, spline wear and bearing race (fixed) rotation are more common. Bearing skidding can occur when bearing loads are light. It produces very fine debris particles ($<25 \mu\text{m}$) and can progress rapidly to loss of rolling element tracking when bearing surface speeds are high. Certain cage wear modes also produce only small particles, until cage failure occurs. The rate of fatigue wear accelerates in the presence of water contamination.

5.2 (Continued):

While each engine model may generate its own debris profile in terms of type, material, quantity, shape, rate of production, color, and size distribution, classification of particles can be useful for determining cause and action required for other engine models and types. Figure 5 shows an oil debris classification chart for troubleshooting a military gas turbine engine. The figure displays debris type, description, quantity, and size of particles and illustrates how oil debris monitoring can be used in determining the probable cause and required action. Figures 5A and 5B show photographs of the type of debris that has been classified while Figure 5C illustrates how to use the data in determining the condition of a component.

Computers make it possible to develop more comprehensive and accessible data bases (Reference 2.1.5). These types of data can assist maintenance personnel to more accurately make decisions concerning component condition.

The various debris monitoring methods generally differ with respect to the parameters that are observed, and the range in which they are measured. Depending on the failure mode, debris production may increase dramatically in one size range but not in another. As a result, the timeliness of detection of a given incipient failure mode can vary from method to method.

Rolling contact fatigue (RCF) is an example of a wear mode that cannot be eliminated by design or readily controlled by other procedures such as hard time overhaul, and is primarily reliant on oil debris monitoring. If left undetected, RCF can initiate rapid fracture modes in gears and in bearings. It is, therefore, essential for the selected monitoring method or combination of methods to be able to provide adequate warning and, if possible, follow the degradation pattern of RCF and other critical modes through their serious condition/failure stages.

In gas turbine engines, main shaft bearings are among the most critical oil wetted components. In turboshaft and turboprop engines, planetary reduction gear components are also critical. Today, main shaft bearings are generally made from double vacuum-remelted steel with high amounts of chromium and molybdenum. Cages are also generally made from steel and silver plated. Gearbox bearings may contain bronze cages, as do main shaft bearings of older engines. Ceramic materials are being used in bearings in some engines currently in development.

An effective oil debris monitoring system should, therefore, as a minimum, respond to the presence of bearing-type (ferrous) particles in the oil system. There have been further developments in inductive flow-through monitors that can detect larger size ranges of nonferrous particles.

Oil Debris Classification

DEBRIS TYPE	DESCRIPTION	QUANTITY/SIZE	CAUSE/ACTION REQUIRED
A. Flake (steel) [significant]	Thin, flat, oblong particles with rounded or scalloped sides. Like corn flakes.	SIZE: Up to 0.040 long and very thin. QUANTITY: Generally more than 10 particles per event.	Typically result from spalling of bearings. Usually indicates bearing wear and, sometimes, gear wear.
B. Chunk/ Fragment (steel) [significant]	Sometimes identifiable as fragment from specific component in engine. Shape varies widely. Sometimes shows distinct fracture surface.	SIZE: Varies greatly. QUANTITY: Usually 1 to 6 particles per event	Indicates possibility of major failure of part; e.g., gears, bearings or other dynamic elements. Can sometimes be maintenance-induced or residual debris from previous failure.
C. Granule (steel) [significant]	Fine, powder-like clumps, irregular shaped debris. Like coffee grounds.	SIZE: Length and width are similar and generally 0.010. Thickness varies, but is generally one-half length-width. QUANTITY: Usually more than 50 per event.	Usually bearing or gear wear, scoring. Generally associated with fretting or components spinning in housings or on shafts. May be mixed with flakes or fragments.
D. BRONZE [significant]	Granular, chunks, fragments, or powder-like golden particles.	To be significant, 25 particles, any size, per event.	Bearing cage wear or failure and usually preceded by chip light event with small quantities of magnetic debris.
E. Wire/hair Splinter/sliver [possibly significant]	Long, thin wire or hair-like particles. May have jagged edges and exhibit fracture planes. Like steel wool or wood splinters	SIZE: Length generally does not exceed 0.080, width and thickness 0.010 to 0.012. QUANTITY: Generally 1 to 20 particles per event.	Generally not a significant wear mode. Often associated with maintenance-induced debris.
F. Cutting/Turning [possibly significant]	Curled, twisted debris of varying length and thickness. Like lathe turnings.	SIZE: Length to 0.08, width 0.10 to 0.08. Thickness varies greatly. QUANTITY: 5 to 20 particles per event.	Usually maintenance-induced and not significant. However, recurrence of large quantity usually indicates abrasive wear by bearings or seals rotating in housing.
G. Chrome/Silver [possibly significant]	Large flat particles. Like shavings, peelings.	To be significant, must be greater than 3 particles which are more than 0.08 long.	Platings or coatings separating from parts; e.g., bearings.
H. Aluminum/ Magnesium [possibly significant]	Granular, powder-like chunks or turning particles. Can be bright silver-white to gray if very fine.	To be significant, 20 to 30 large pieces.	Not usually significant. Wear of housing or failure of shims, spacers, cases.
I. Carbon [possibly significant]	Black, usually granular, powder, may include chunks or slivers.	Usually requires large quantity to be significant.	Generally due to wear of carbon seals. Usually, other operational symptoms occur, such as increased oil consumption, smoking, filter bypass, or leaking.
J. Epoxy/ Phenolic [possibly significant]	Varies in color and can be fibers or peelings or plating-like particles.	Variable	Manufacturing debris or coating peeling.

Note: Dimensions are in inches.

FIGURE 5 - Oil Debris Classification Chart



FIGURE 5A - Oil Debris Photographs Type A-D

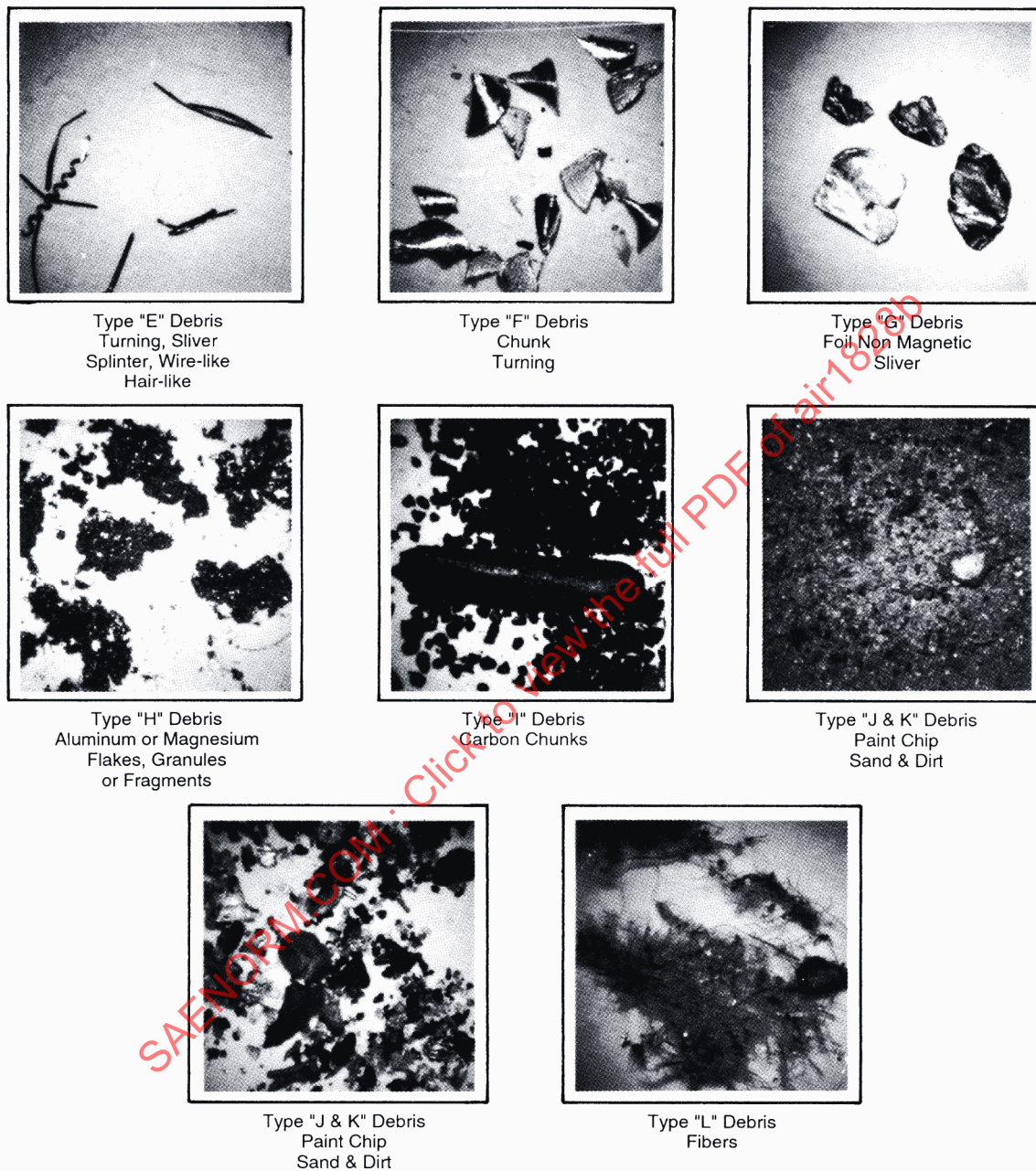
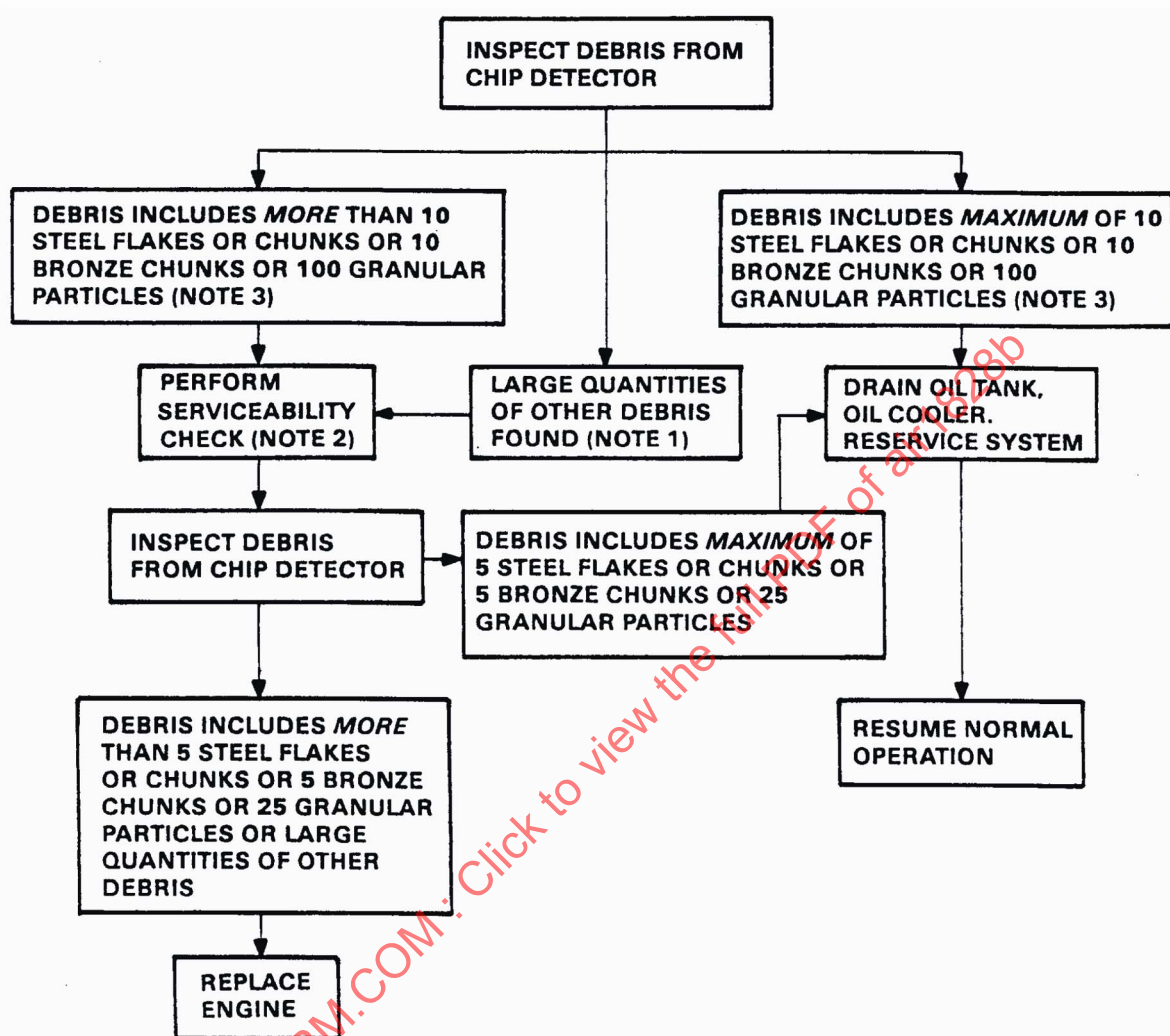


FIGURE 5B - Oil Debris Photographs Type E-L



NOTES

1. DEBRIS CAN INCLUDE SLIVERS, SPLINTERS, METAL WIRE OR HAIR, CUTTINGS, TURNINGS, CHROME FOIL, SILVER FOIL, ALUMINUM, MAGNESIUM, CARBON, CORROSION PRODUCTS, AND DIRT.
2. DRAIN AGB, OIL TANK, OIL COOLER. RESERVICE SYSTEM. HAVE QUALIFIED PILOT START AND RUN ENGINE AT FLIGHT IDLE UNTIL TEMPERATURES STABILIZE. CHECK INSTRUMENT READINGS. THEN HOVER FOR 30 MINUTES.
3. REFER TO TABLE 6-5 FOR DEBRIS CLASSIFICATIONS.

WARNING

IF FRAGMENT CAN BE IDENTIFIED AS PIECE FROM SPECIFIC INTERNAL PART, REPLACE ENGINE.

FIGURE 5C - Engine Oil Contamination Troubleshooting Chart

5.2 (Continued):

The most widely used debris monitoring methods and the respective particle size ranges in which they are most effective are:

- a. Magnetic chip collectors: 50 to >1000 μm
- b. Electric chip detectors: 50 to >1000 μm
- c. Ferrography: 1 to 100 μm
- d. SOA: 10 μm

For failure modes that produce debris in more than one of these size ranges, the user can, therefore, obtain corroborating information from two or three different techniques. This can help significantly in making the decision to remove the engine or engine module for repair.

There are, however, failure modes that produce only large or only small particles or in which small particles are generated much later than large particles and vice-versa. It is, therefore, important to understand that the user, in collaboration with the engine manufacturer, must decide how to complement the on-aircraft debris monitoring devices usually found on the engine as standard equipment with other techniques to suit the users' special operational requirements and capabilities.

It should be noted that debris particle "size" or "size range" are ambiguous classifications. A "large" particle collected on a chip collector may be 1000 μm in length, while a "large" particle collected in an oil sample is likely to be less than 100 μm long. While size is often referenced by the largest dimension of the particle, the volume of the particle, which includes the other two dimensions, determines the mass. Particles with the same length can have a great range of masses.

The emerging generation of electronic debris sensors (see 5.4.6) requires a better definition of their sensitivity than "particle size". When their operating principle is inductive their indication sensitivity is less a function of particle size than of mass, shape, and magnetic properties of the debris material. Oil flow velocity and viscosity may also play a role. Therefore, the performance of such a system should be defined in accordance with the operating principle of the device.

5.3 Filtration Considerations for Oil Debris Monitoring:

The benefits of improved filtration for longer bearing life are well established (see 2.1.10 and 2.1.11) and widely accepted. For this reason, there is an increasing trend to use finer filters on aircraft gas turbine engines. Currently, several modern engines incorporate a filter elements with a rating of 3 μm absolute while many others have gone to 7 and 10 μm absolute. Field experience with fine filtration has demonstrated that spectrometric oil analysis (SOA) becomes ineffective.

The trend towards finer filtration is expected to increase the number of engines in the field for which traditional off-aircraft debris monitoring methods will be of limited effectiveness. This has stimulated the development of more sensitive spectrometric techniques, such as plasma spectrometers.

Fine filtration enhances the effectiveness of magnetic chip collectors, electric chip detectors and debris-capturing inductive sensors since it reduces recirculating, non-significant debris generated by normal wear.

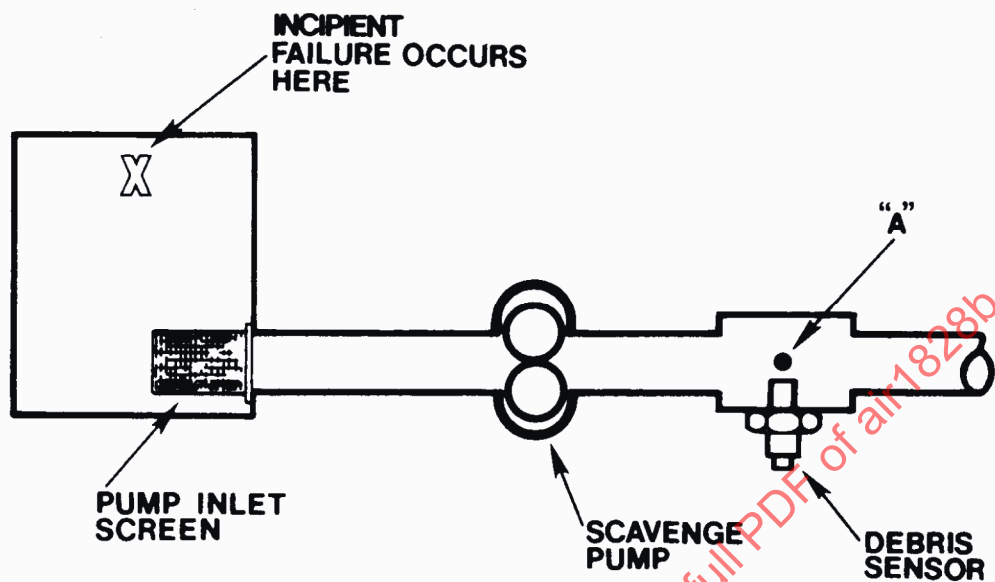
5.4 On-Aircraft Debris Monitoring:

On-aircraft debris monitoring techniques are based on sensors or debris collectors that are permanently installed in the engine lubrication system. Some collect the debris for later inspection while others do not. On-aircraft debris monitoring techniques can be augmented by off-aircraft analysis of collected debris. Sensors may further require signal conditioners, software, cockpit readouts, maintenance-crew alert devices and/or interface hardware or software with engine monitoring systems. The main advantages of on-aircraft debris monitoring methods are to provide diagnostic capability either on aircraft or at line maintenance.

All on-aircraft debris monitors rely on the debris transport characteristics of the oil system. All respond to debris in a size range considerably larger than the separation capability of the oil filter and are therefore, installed upstream of the filter. The proper understanding of the capabilities and limitations of the debris sensor is essential to its effective operation.

The probability of detecting an incipient failure increases with the amount of debris available to the sensor. Figure 6 shows a section of a typical engine oil system schematic with a debris generating site, pump screen, scavenge pump, and debris sensor to illustrate this relationship. The debris available for detection at the sensor site depends on the transport efficiency of the oil system.

As Figure 6 illustrates, the debris transport efficiency η_T determines what fraction of the debris generated by the source arrives at the sensor location. It depends on oil system layout, fluid velocity, and particle size. For example, the scavenge system shown in Figure 6 traps all particles larger than the openings of the pump screen. Its η_T for this size range is, therefore, equal to zero. Additionally, in an actual lubrication system, particles can stick to cavity walls, be trapped in corners, or sedimented in bearing compartments, sumps, and reservoirs. They can also be mangled.



TRANSPORT EFFICIENCY

$$\eta_t = \frac{\text{PARTICLES TO POINT "A"}}{\text{PARTICLES GENERATED}}$$

CAPTURE EFFICIENCY

$$\eta_c = \frac{\text{PARTICLES ON DEBRIS SENSOR}}{\text{PARTICLES TO POINT "A"}}$$

INDICATION EFFICIENCY

$$\eta_i = \frac{\text{PARTICLES INDICATED}}{\text{PARTICLES ON DEBRIS SENSOR}}$$

DEBRIS DETECTION PROBABILITY

$$\eta_d = \eta_t \cdot \eta_c \cdot \eta_i = \frac{\text{PARTICLES INDICATED}}{\text{PARTICLES GENERATED}}$$

FIGURE 6 - Factors Influencing Debris Detection

5.4 (Continued):

The debris capture efficiency n_C applies to sensors that capture the debris for failure detection (e.g., magnetic chip collectors, electric chip detectors, particle-capturing electronic debris sensors). It is a function of sensor characteristics, particle size and material, fluid velocity, and, most important, the design of the cavity or pocket in which the sensor is located. Debris capture efficiency is enhanced by passing the entire oil flow through the debris monitor (full flow debris monitoring) and by including positive means to separate the debris from the oil. Figure 7 illustrates how widely n_C can vary as a result of cavity design, everything else being equal.

The debris indication efficiency n_I represents the sensitivity of the sensor and system to a particle of given size or mass, shape and material.

The overall debris detection probability is given by Equation 1:

$$n_D = n_T n_C n_I \quad (\text{Eq. 1})$$

and corresponds to the fraction of particles indicated versus those that are generated at the failure site.

Effective diagnostic capability requires optimizing these quantities during oil system design and development and, if possible, measuring them through oil system rig testing. If the debris transport and/or capture efficiencies are low, as is the case in many older engines, the sensitivity n_I of the sensor must be high to compensate for it. This, in turn, makes the system more susceptible to false alarms. Even then, incipient failures that release only a few large particles may not be detected in time to avoid secondary damage or loss of functionality.

The requirement to detect more failure modes with greater reliability increases sensor and system cost. At the same time, the requirement for fault isolation to an engine module or bearing set requires multiple sensor locations. In an advanced system, the functions of failure detection (requiring one sophisticated sensor and in-flight signal processing capability) and isolation (requiring several sensors for ground checkout only) can be separated for increased cost-effectiveness. Such a "master/slave" system is incorporated in Figure 1. A high-performance full-flow debris monitor ("master") is installed in the main scavenge line. For the purpose of failure isolation, additional probes ("slaves") are located in each of the main shaft bearing return lines and in the accessory and reduction gearboxes, if applicable. These can consist of simple magnetic chip collectors whose capture efficiency is kept low so as not to interfere with the operation of the master detector.

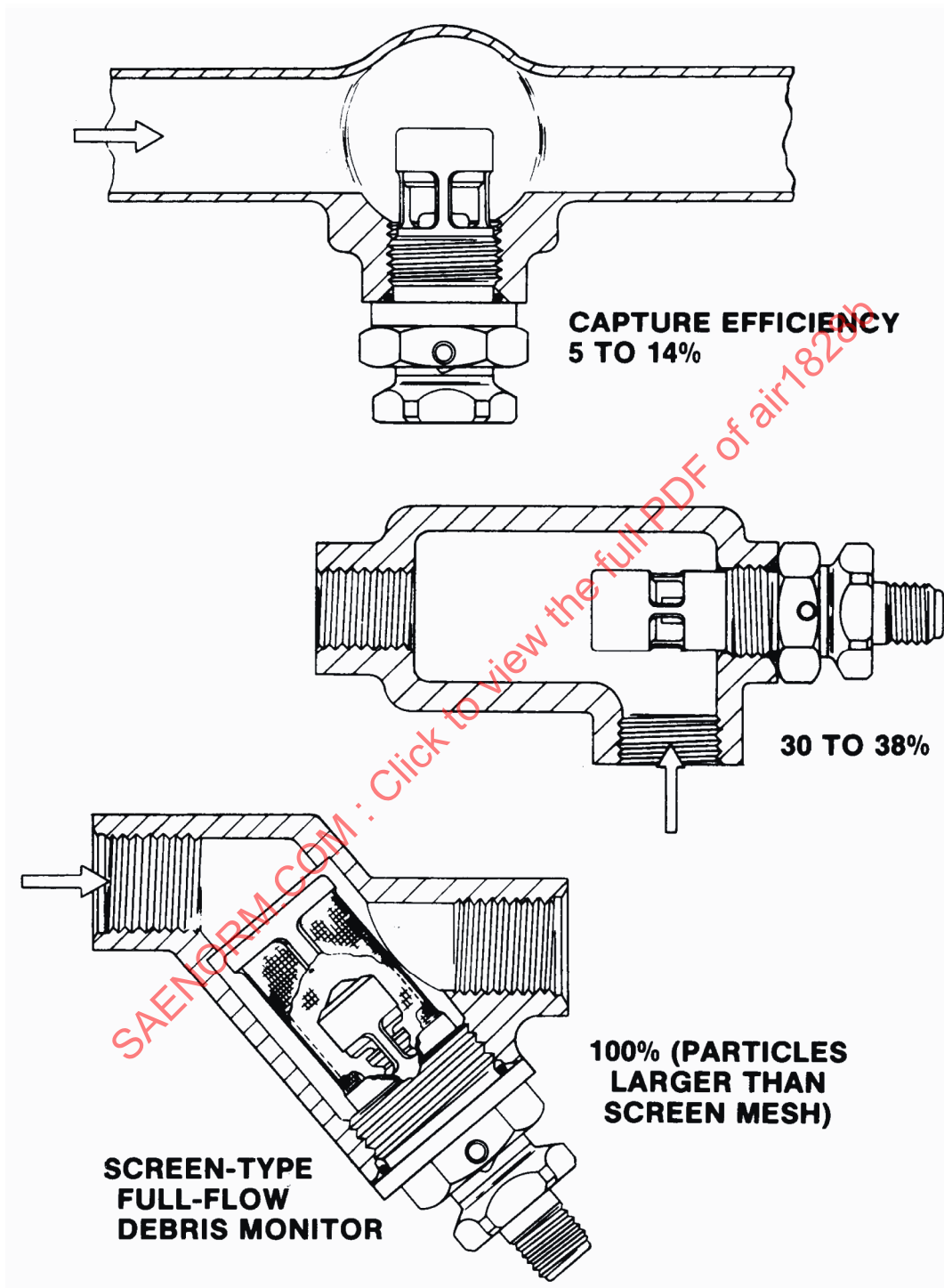


FIGURE 7 - Capture Efficiency for Debris Particles

5.4 (Continued):

The category of on-aircraft debris monitoring devices includes the following:

- a. Magnetic chip collector
- b. Electric chip detector
- c. Pulsed electric chip detector
- d. Screen-type full-flow debris monitor
- e. Centrifugal debris separator
- f. Inductive particle counter/collector (Quantitative Debris Monitor)
- g. Inductive flow-through oil debris monitor
- h. Inductive ferrous particle sensor/collector
- i. Electrostatic oil debris monitor

Items a through d are well-established and widely used. Item e is a high-efficiency device used to separate debris from the oil and deposit it on a debris collector or sensor. Items f, g, h, and i belong to a new generation of electronic debris sensors, which are in service or are being developed.

With the recent advancements in flow-through monitors, particle retention must not be forgotten. Recovering debris from the sensor that generates the indication gives additional diagnostic and prognostic information. If flow-through sensors are used, a high efficiency debris capturing device downstream of the sensor should be incorporated. Additionally, it establishes the credibility of the monitoring system to allow verification of signal by inspection of the debris.

- 5.4.1 **Magnetic Chip Collector:** Also referred to as magnetic plugs or magnetic chip detectors, these devices have been used in gas turbine engines since the mid-1950s. They are usually installed in main or individual scavenge lines and accessory or reduction gearboxes. If located below the oil reservoir level, they should have self-closing valves, which permit the inspection of the magnetic probe without the need to drain the oil. Figure 8 shows an example. Most units manufactured today have high-reliability quick-disconnect locks, which eliminate the need for tools or lock wiring. Rare-earth magnets are used increasingly to enhance magnetic strength and chip capture efficiency.



FIGURE 8 - Magnetic Chip Collector with Self-Closing Valve

5.4.1 (Continued):

The period between inspections of the magnetic chip collector(s) of an engine should be in relation to its known failure modes and is the result of in-service experience and coordination between engine manufacturer and user. Intervals vary widely but are generally 125 to 500 hours where chip collectors are used as primary failure detection devices. If a problem exists, more frequent inspections (even daily or after each flight) may be justified for a short period of time. Inspection intervals can be extended as experience is gained and the engine type matures.

An optimum location for at least the most critical unit(s) would be behind a separate access panel or near the oil filter or pressure fill fitting so that they can be inspected without the need to open engine cowlings. Poor accessibility results in checking of magnetic chip collectors at infrequent intervals or only when an incipient failure is suspected (for example, after abnormal SOA readings).

5.4.1 (Continued):

The engine maintenance manual should include good illustrations of typical debris (see Figures 5A and 5B for an example), together with guidelines relating debris particle size and quantity to likely failure mode and severity. This enhances the effectiveness of magnetic chip collectors considerably, since maintenance personnel can compare appearance and quantity of collected debris. However, removal decisions are more accurate if maintenance personnel are experienced in debris interpretation (especially concerning the engine model in question and its predominant failure modes) or can get support from a laboratory facility.

The proper location of magnetic chip collectors within the lubrication system is essential to high chip capture efficiency. Magnetic chip collectors should, therefore, be located in well-designed "pockets" or inside full-flow debris separators (see Figure 7 for examples). Since magnetic chip collectors are relatively inexpensive, they can be installed cost-effectively in different parts of the engine, such as individual scavenge lines and accessory or reduction gearboxes. This makes failure isolation possible.

Sophisticated and very effective oil debris monitoring methods have been developed around magnetic chip collectors (see 2.1.1 and 2.1.7). They involve transfer, retention, recording, and quantification of collected debris for trending and analytical techniques for diagnosis and fault isolation. These techniques are more fully described in 5.5.2.

Magnetic chip collectors are most effective for the detection of failure modes involving the production of large magnetic particles (100 μm and larger) such as surface fatigue spalling of bearings, gears, and pump elements. Where provisions have been made by means of special "pockets" to reduce oil flow velocity and/or separate debris through centrifugal action so that debris capture efficiency is very high, smaller debris particles will also be collected in sufficient quantity. This will allow magnetic chip collectors to be effective for detection of failure modes that generate predominantly small particles, such as bearing skidding, gear and pump scoring, spline wear, and rotating bearing races.

5.4.2 Electric Chip Detector: Electric chip detectors are essentially magnetic chip collectors with electric continuity indication capability. They are used in many engines and are required for some military turbojet and turbofan engines by MIL-E-5007D and JSSG-2007, and for turboshaft and turboprop engines by MIL-E-8593A.

Remotely indicating chip detectors are usually wired to cockpit or maintenance panel indicators. Their main advantages are immediate response and absence of scheduled inspections. To simplify removal for visual inspection after a chip light occurrence, self-closing oil shutoff valves are usually incorporated. This type of chip detector is used in some helicopter engines, some propulsion engines for commercial aircraft, single-engine aircraft with gas turbine engines, and some military long-range patrol aircraft.

Chip detectors for ground checkout, with simple touch-to-test terminals, are used in older U.S. military turboprop engines. Continuity checks must be carried out at frequent intervals.

5.4.2 (Continued):

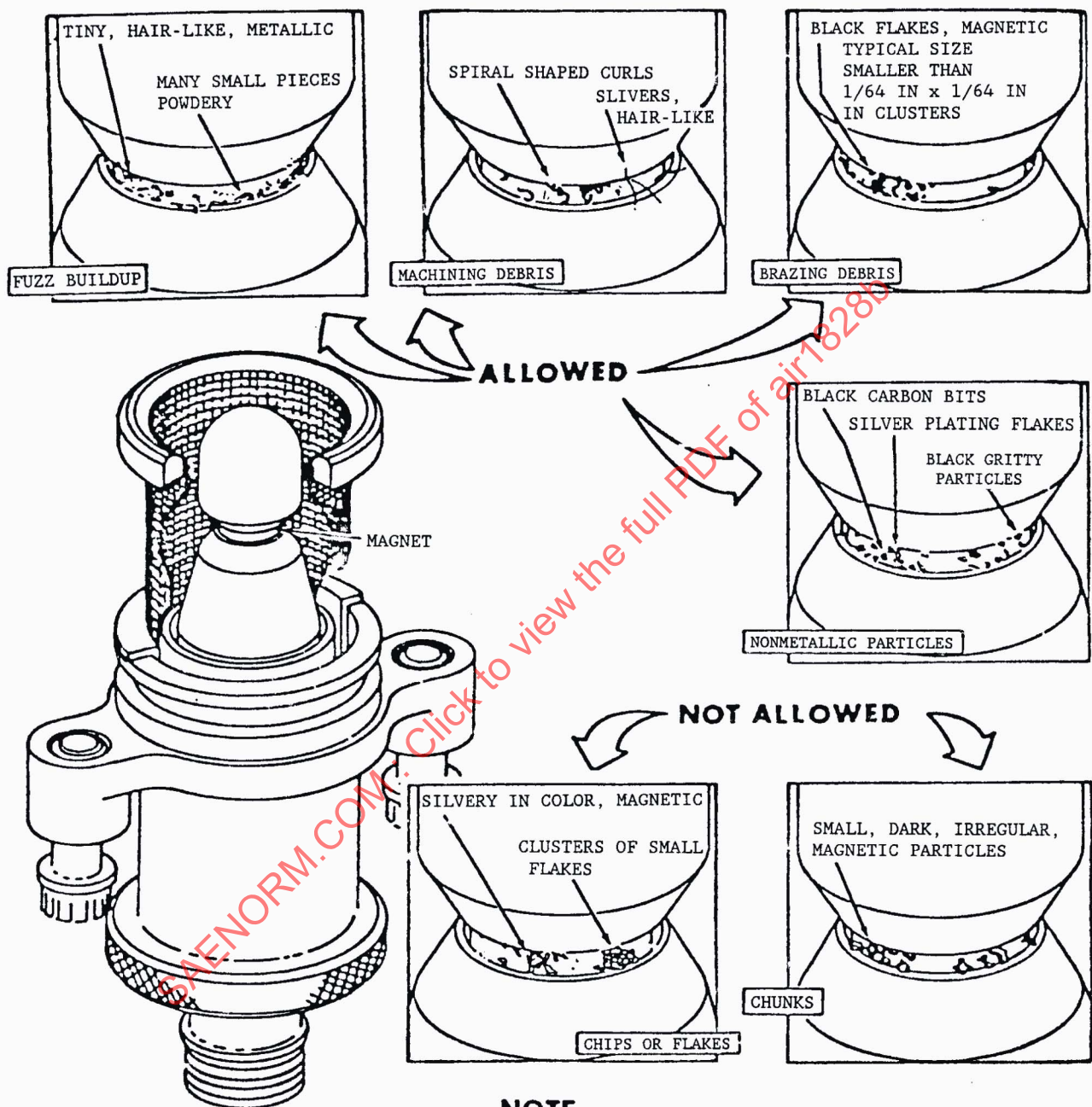
The chip sensitive area of an electric chip detector consists of two electrodes and a magnet to attract magnetic debris (Figure 9). The electrodes are bridged if enough debris has accumulated, either in the form of a few large particles or many smaller ones. The spacing between these electrodes is generally 1 to 4 mm (0.04 to 0.16 in), depending on engine type (shaft speed, load, and gear train characteristics), degree of oil filtration (finer filtration permits smaller gap spacing), and criticality of failure mode.



FIGURE 9 - Electric Chip Detector

As in the case of magnetic chip collectors, provisions must be made in the lubrication system to ensure effective chip detector installation.

To provide assistance in the decision to remove the engine for repair, engine maintenance manuals should contain instructions for debris interpretation (see Figure 10 for an example).

**NOTE**

DURING NORMAL ENGINE OPERATION, SOME BUILDUP OF FUZZ-LIKE MAGNETIC PARTICLES WILL BE FOUND ON THE CHIP DETECTOR WHEN IT IS REMOVED AND INSPECTED. OTHER MATERIALS SUCH AS NONMETALLIC SLUDGE, METALLIC SLIVERS, NONMAGNETIC FLAKES, BRONZE POWDER, OR MACHINING CHIPS (THE LATTER ESPECIALLY ON NEW ENGINES) WILL BUILD UP ON THE DETECTOR. THE AMOUNT WILL VARY BUT SHOULD NOT BE CAUSE FOR ENGINE REMOVAL.

FIGURE 10 - Maintenance Manual Excerpt for Chip Detector Debris Interpretation

5.4.2 (Continued):

A serious drawback of electric chip detectors is that they have a high false-alarm rate due to non-critical debris (normal wear particles or debris left over from manufacturing or repair activities). They also have no trending capability since they generate only an on/off signal (one bit of information). This restricts their usefulness as an input device for an EMS. False alarms are mainly caused by background debris especially with newer engines. False alarms can be reduced by improving oil filtration and cleanliness during engine buildup to reduce background contamination.

- 5.4.3 Pulsed Electric Chip Detector: In lubrication systems with conventional filtration levels, (coarser than 15 μm), false chip indications of electric chip detectors are predominantly caused by buildup of fine, non-significant wear debris on the chip detector.

These can be suppressed by delivering a current pulse to the chip detector, locally melting the fine debris or the contacts between small debris particles. This does not affect significant, failure-related debris, which has a larger cross section. The current pulse can be initiated automatically when the gap is bridged, or manually by the pilot after chip light illumination.

Due to their simplicity and success in dealing with false indications of this type, these systems have found acceptance in helicopter transmissions and some engines. Since production of fine debris at an increased rate, causing more frequent indications, can signify bearing failure, a pilot-initiated system permits limited trending. For automatically initiated systems, such trending is also possible if the current pulses are recorded by an EMS.

- 5.4.4 Screen-Type Full-Flow Debris Monitor: In engines of older design, the chip detectors are often installed in scavenge lines or accessory gearboxes with no provision to capture the debris other than by magnetic attraction and sedimentation. In such installations, most of the debris can bypass the chip detector and find its way into the oil filter. This can cause delayed or unreliable failure detection.

A full-flow debris monitor is designed to screen the entire scavenge flow. This increases failure detection efficiency (Reference 2.1.3). Figure 11 shows a screen-type full-flow debris monitor for a modern turboshaft engine. The screen can be removed for cleaning. Located inside is an electric chip detector. The screen openings are on the order of 0.5 mm (0.02 in), giving the device a capture efficiency of 100% for particles above that size. Such units are also in use with self closing valves and with separate housings for installation in external oil lines. They can function as scavenge pump inlet screens.



FIGURE 11 - Screen-Type Full-Flow Debris Monitor

5.4.4 (Continued):

Screens are available that can also indicate the presence of metallic debris. Indicating screens are based on a mesh woven from conducting wire and insulating spacers with the minimum particle size threshold determined by the size of screen openings. They indicate ferrous and non-ferrous conductive debris. Indicating screens are often used in conjunction with electric chip detectors.

- 5.4.5 Centrifugal Debris Separator: Centrifugal debris separators have been developed to achieve a high level of capture efficiency. This is particularly useful in systems that generate very small amounts of normal wear debris. It is placed in the full scavenge flow path. It is used in conjunction with some type of debris sensor.

An example is shown in Figure 12. Its tangential inlet nozzle creates an internal vortex, which separates the entrained debris effectively down to about 100 μm with some pressure drop (Reference 2.1.4). An additional feature is its ability to efficiently de-aerate the oil by means of a separate air exit nozzle, thus combining two functions. This feature is optional and does not affect debris separation.

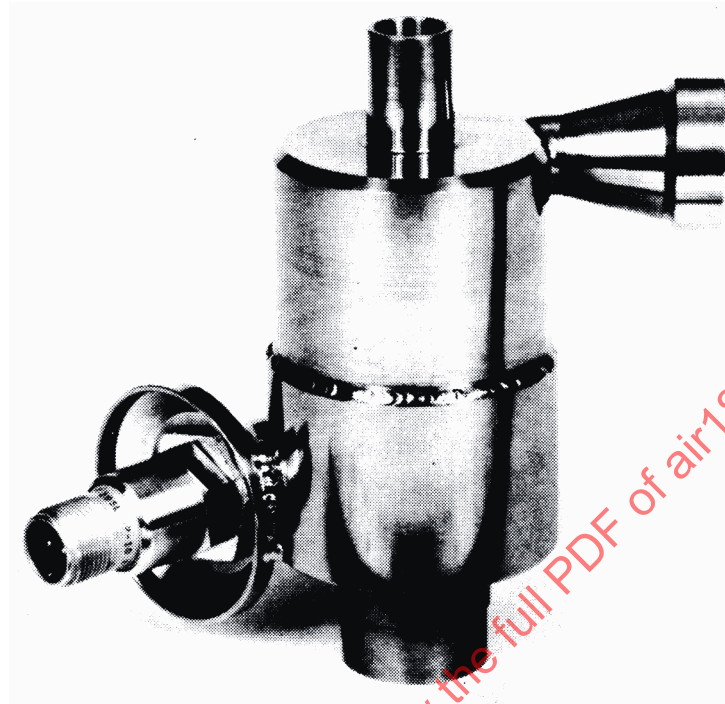


FIGURE 12 - Centrifugal Debris Separator with Oil System Deaeration Capability

5.4.5 (Continued):

Since the internal vortex is driven hydraulically, the unit must be installed on the pressure side of the scavenge pump. The pressure drop must be taken into consideration in the oil system design. The debris sensor can consist of a magnetic chip collector, electric chip detector, or other debris-sensing device.

- 5.4.6 Electronic Debris Sensors: Two of the most characteristic parameters for on-aircraft detection of an incipient failure are the rate of debris production and particle size range. Trending these parameters permits detection with high reliability and can help in determining how long the engine can be used safely.

An emerging category of electronic debris sensors uses electrical inductance as their operating principle. Particles are either counted individually, or their total accumulation is measured. Both methods can provide information about rate of debris production and particle size range.

A second category of sensors are those that detect the electrostatic charge associated with debris in the oil system.

5.4.6 (Continued):

There are two different types of devices: sensor/collectors that capture the particles, indicate them and retain them for later inspection; and flow-through devices that do not collect the particles.

Unlike most chip detectors, electronic debris sensors can follow the failure in progress and can, therefore, provide data that allow trending and prognosis. This requires the development of algorithms for maintenance crew (or even pilot) alert. Such algorithms can be derived from experience gained during bearing tests, engine development, or early in-service experience (see 5.2). For example, maintenance crews can be alerted as a result of a pre-determined number of particle counts per flight (debris production rate), or as a result of a pre-determined total number of counts, regardless of elapsed time period (total quantity). Also, procedures need to be developed and implemented for verifying that the alert is not caused by system malfunction but by a real failure of oil-wetted components. These devices incorporate a BIT system to verify that the debris monitoring system is fully functional.

Together with their associated signal conditioners, electronic debris sensors are ideally suited for interfacing with engine monitoring systems. In developing sensors, electronics and software, the requirements for interfacing sensors with EMS need to be taken into consideration (Reference 2.2.1).

Electronic debris sensors can be affected by environmental factors, such as temperature, vibration, and EMI. In order to minimize false indications under engine operating conditions, the sensitivity of the debris monitoring system may need to be reduced significantly, compared to test stand experience. Therefore, in-service experience provides the ultimate verification of on-aircraft debris monitoring system performance.

- 5.4.6.1 Inductive Particle Sensor/Collector: Figure 13 shows a quantitative debris monitoring system consisting of an inductive magnetic sensor, centrifugal debris separator and a signal conditioner. This system provides real-time signals (counts) in response to the arrival of discrete ferrous particles whose mass are in excess of a pre-set detection threshold. The sensor can be installed inside a centrifugal debris separator as shown or in other high-efficiency scavenge system pockets to enhance debris capture efficiency. It collects debris particles and makes them accessible for visual inspection and optional transfer to a laboratory for additional analysis, like a magnetic chip collector. Users can, therefore, apply established techniques to verify and diagnose failures in progress. The sensor has a built-in test (BIT) feature that can be initiated by the EMS to verify system operability in the absence of debris signals.



FIGURE 13 - Quantitative Debris Monitor



FIGURE 14 - Flow-Through Inductive Debris Monitor

- 5.4.6.2 Flow-Through Inductive Debris Monitors: Several types of flow-through inductive debris monitors are available. These devices are typically non-intrusive, consisting of one or more inductive coils enclosing an oil line. A metal particle in the oil stream causes a change in the inductance of the coil(s) as the particle passes through. This change is used to measure the volume and magnetic properties of the particle. Since the density of most materials used in bearings, gears and other load bearing, oil wetted components is similar, the devices effectively measure particle mass. For ferromagnetic particles, the mass, the magnetic susceptibility of the material, and shape of the particle determine the magnitude of the signal. For non-ferromagnetic metallic particles, the surface area and conductivity determine the magnitude of the signal. The signals for ferromagnetic and non-ferromagnetic metallic particles can be differentiated because they are of opposite phase.

Particle detection thresholds are often stated in terms of particle "size", although the mass of particles of the same linear dimension can vary by orders of magnitude, depending on their shape. Therefore, a detection threshold can be stated in terms of the size of an equivalent spherical particle of the same mass. Particle detection thresholds also depend on the sensor diameter with smaller diameters being more sensitive.

Use of this device may also include a high efficiency debris capturing device downstream of the sensor for debris signal verification.

- 5.4.6.3 Inductive Small-Particle Sensor/Collector: As discussed previously, some failure modes in gas turbine engine bearings (e.g., skidding and cage wear) produce only very fine, flour-like debris until the bearing is destroyed. The inductive small-particle sensor collects all magnetic particles and provides a signal that increases with total collected mass. By recording the signal by means of associated electronics and software, the system also indicates the arrival of discrete, large particles and is, therefore, capable of indicating all failure modes that produce magnetic debris particles, regardless of size. A BIT feature is included. The effectiveness of this sensor is greatly enhanced by installing it inside an efficient debris separator or "pocket" to provide the necessary high debris capture efficiency for small particles.
- 5.4.6.4 Electrostatic Oil Debris Monitor: The technique is still under development, however, there is evidence that the electrostatic charge present on oil debris is generally greater as a result of freshly generated wear particles. This means the system is inherently less sensitive to benign system build debris, which is advantageous in terms of false detects. Other advantages of this technique are that the sensor detects most material types (including ferrous, non-ferrous/metallic and non-metallic, e.g., ceramic) and a wide range of particle sizes.

- 5.4.6.4.1 Oil-line Sensor: This is a full-flow oil-line sensor, which needs to be installed in the oil-line where a representative sample of wear debris particles will pass through the sensor. The sensor is passive and non-intrusive; it comprises dual ring elements, which are sensitive to the electrostatic charge on the wear debris. The sensor system computes velocities associated with the wear debris and its output may be broadly related to the size and quantity of wear debris present, although the system does not currently provide specific particle sizing information.
- 5.4.6.4.2 Wear-site Sensor: The electrostatic wear-site sensor utilizes the same detection principle as the oil-line sensor. However, its implementation is component specific, the sensor being mounted in the vicinity of oil-wetted component contacting surfaces. Sensor trials have demonstrated that 'pre-cursor' electrostatic charge events may be detected at the earliest stages of component degradation. These charge events appear to be linked to component degradation stages in advance of wear generation, for example surface cracking/tribo-emissions, localized changes in surface chemistry (for example, white layer formation) and so the wear-site sensor is capable of providing a wide prognostic view of component condition. It is also relevant for monitoring critical components, which are prone to rapid deterioration and/or hazardous component failure.
- 5.4.7 System Performance Verification: System performance can be verified in three different ways:
- a. Flow-stand testing using a simulated engine lubrication system. This requires the use of standardized, reproducible test particles and a mechanism to inject them into the flow in a way that simulates a failure in progress as closely as possible. The standard test particles should be made from a material that is identical to, or at least simulates, the materials of engine components that are subject to failure. Furthermore, the test particles should have shapes and sizes that are representative of actual debris particles.
 - b. Bearing rig testing. The performance of a debris monitoring system can be verified by installing it in a bearing test rig, downstream from the bearing. Care must be taken that the oil system actually transports all debris particles to the sensor. This is usually not the case with simple oil collecting pans scavenged by gravity. Preferably, the test rig should resemble the engine installation. The bearing is artificially damaged to accelerate the test, and often operated at higher-than-design loads, speeds or temperatures. The criterion of success for the debris monitoring system is whether it indicates the failure in a timely manner, and whether its signal (output) is comparable to the actual number or mass of those particles that arrived at the sensor location and that exceeded the sensitivity threshold of the sensor.

5.4.7 (Continued):

- c. Engine development testing and in-service experience. Because failures can generally not be induced in engines under development, and certainly not in in-service engines, final performance verification must await the inevitable occasional in-service failures. Under engine operating conditions, during development or in-service, unanticipated failure modes may occur. The criteria for the performance of the debris monitoring systems are:
 - detection of failures in a timely manner, before the onset of secondary failures (hits and the absence of misses);
 - absence or at least minimization of false indications, especially those that cannot be verified easily by other means.

5.5 Off-Aircraft Debris Monitoring:

With the exception of filter and magnetic plug debris analysis, the off-aircraft debris monitoring techniques discussed in this section rely on sampling of the oil. The sampling process is most useful when a representative and homogeneous dispersion of debris particles is available for interrogation. This condition is most nearly met when fine wear particles are present in the oil system, and when the sample has been obtained in accordance with prescribed procedures. These methods are, therefore, most effective for accelerated wear modes which produce substantial quantities of fine particles, such as fretting, bearing skidding, cage rubbing, gear scuffing, bearing race rotation, and other forms of abrasive and adhesive wear. They are less effective for those modes that are induced by surface (i.e., rolling contact) fatigue, such as spalling and macro-pitting. This is due to the fact that these modes produce fewer numbers of mostly larger particles, which may settle out prior to sampling or, by virtue of their small number, may not be represented in the sample.

Off-aircraft debris monitoring techniques involve the regular removal of oil samples or collected debris from the engine and their subsequent analysis in a laboratory or by means of some other ground service equipment. The advantage of these techniques is generally that the more sophisticated instruments used, the more information provided. These techniques include:

- a. Spectrometric oil analysis (SOA)
- b. Quantification and analysis of debris from magnetic chip collectors
- c. Filter debris analysis
- d. Ferrography

5.5 (Continued):

- e. Laser particle shape classifier
- f. X-ray spectrophotometer (X-ray fluorescence or XRF)
- g. Scanning electron microscope (SEM/EDAX)

Off-aircraft debris monitoring techniques involving oil sampling are affected by the degree of oil filtration. This is more fully addressed in 5.3.

- 5.5.1 Spectrometric Oil Analysis (SOA): SOA is the most widely used off-aircraft oil condition monitoring method. A small oil sample is taken from the engine and transported to a laboratory where the suspended metal particle content is determined spectrometrically in parts per million or even parts per billion. The results are automatically recorded by the computerized instrument and compared to pre-determined limits, or are converted into other formats that can be used for determining required maintenance action, for instance a trend plot.

The technique relies on the fact that oil wetted components, under certain conditions of accelerated wear, produce larger-than-normal quantities of fine wear particles, which are carried away by the oil. This leads to an increase in wear particle concentration in the oil.

The spectrometric analysis involves determination of the light spectrum generated by the oil sample as it is burned. Trace element content is determined by the frequency and intensity of the resultant spectral lines. Two types of instruments are commonly employed. Both are emission spectrometers. The first type is a rotating disc electrode (RDE) atomic emission spectrometer conforming to ASTM D 6595. The second type is an inductively coupled plasma (ICP) atomic emission spectrometer conforming to ASTM D 5185.

Atomic emission spectrometers vaporize a small portion of the oil sample and measure the resultant light intensity in specific narrow frequency ranges utilizing a diffraction grating and photomultiplier tubes or solid-state light sensors. These are located at points where specific spectral lines of interest are projected.

The RDE spectrometer uses a rotating carbon electrode that dips into the sample and carries it to the spark gap where an electric arc is struck between the top of the rotating disc and the tip of a carbon rod electrode. New electrodes are used for each sample to eliminate cross-contamination. Results are obtained in parts-per-million (ppm). Samples need not be diluted and can be processed quickly. This method is the most commonly used in the military. Field mobile RDE spectrometers are used at military airfields and shipboard by the Navy.

5.5.1 (Continued):

ICP spectrometers are characterized by higher vaporization temperatures than RDE spectrometers. In the ICP, the plasma is ignited with a radio-frequency source. It is the more sensitive of the two emission spectrometers, giving results in parts-per-billion for some elements, e.g., copper. However, the ICP requires sample dilution with kerosene or toluene and requires a laboratory environment and more highly skilled technicians for operation. Commercial labs mostly use ICP.

There is a difference in the upper particle size detected by the two techniques. RDE spectrometers lose their ability to detect particles above approximately 10 μm whereas ICP spectrometers are limited to approximately 5 μm or less. This is due to sample introduction methods and excitation temperatures.

A critical requirement for the successful application of spectrometric oil analysis to engine oil monitoring is careful and consistent oil sampling methodology. Representative oil samples, taken with clean sampling equipment, must be taken sufficiently often to allow meaningful data trending.

Sampling intervals may vary from as short as one sample per flight on some military applications to more than 50 flight hours on some commercial aircraft programs. In general, the interval is established by economic, operational, and previous failure history considerations for the engine being monitored. For example, a joint European airline consortium has established and proven the effectiveness of an 80 flight hour sampling interval.

Oil samples taken must be representative of the circulated oil in order for the analysis to be valid. The most common method used by airlines involves samples taken through a filler port with a sampling tube extended to the center of the oil tank (Figure 15). Another method involves the use of special sampling valves (Figure 16). The U.S. military services, through their Joint Oil Analysis Program (JOAP), have developed two standard sampling kits for all military equipment in the program. They consist of a 17 ml glass bottle and polyethylene tubes in two different lengths. Sampling is performed from the oil reservoir (Figure 17) or through chip detector valves. When samples must be taken through tank drain fittings, procedures should be used to avoid unrepresentative sampling (e.g., flushing the fitting before sampling).

It is recommended that samples be taken no more than 15 to 30 min after engine shutdown. Oil samples should be taken in roughly similar locations and at established times after shutdown to assure maximum consistency. Sample tube and container cleanliness is also very important.

Contamination in the sampling equipment can produce erroneous analyses and lead to unnecessary maintenance actions.

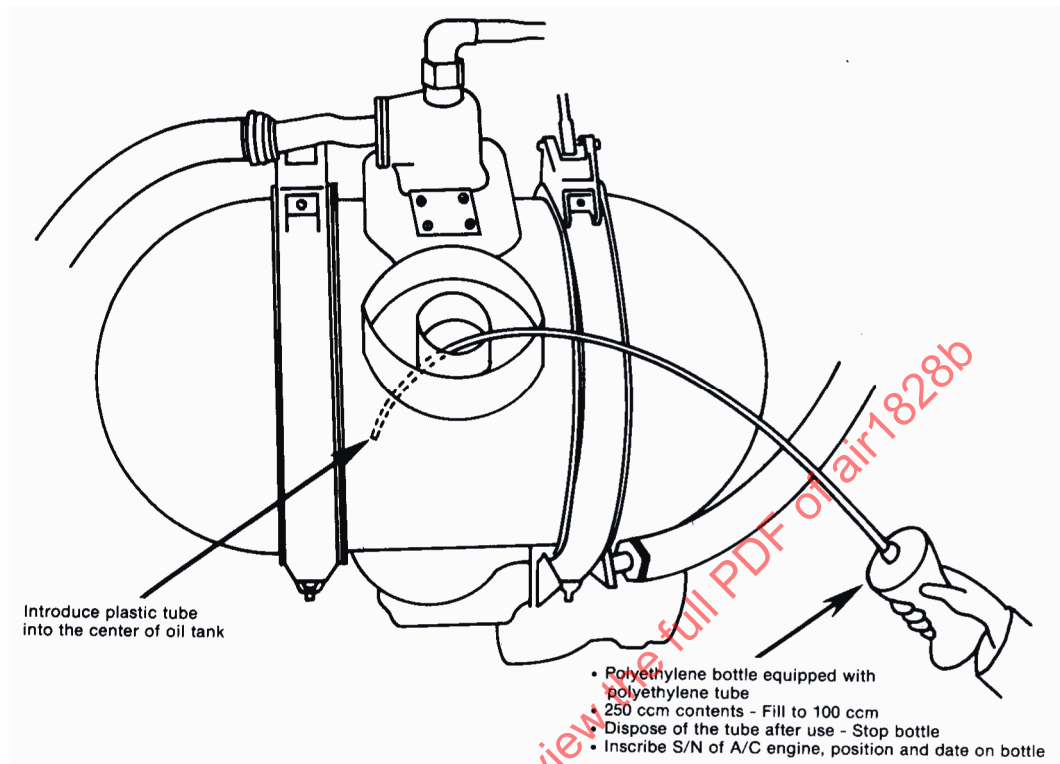


FIGURE 15 - Airline SOA Sampling Method



FIGURE 16 - Oil Sampling Valve