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GUIDE TO ENGINE OIL SYSTEM MONITORING

FOREWORD

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

a. Oil system operation monitoring (monitoring the oil system for proper operation)

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 are established or still under development and whether they involve on-aircraft equipment only or whether they require off-aircraft equipment or facilities. Figure 1 also indicates these classifications.

Oil system monitoring is one of the methods that constitute an engine monitoring system, as discussed in ARP1587. Frequently, oil system monitoring data are complimentary to information obtained from other components of the engine monitoring system (EMS). This is especially true for 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.

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FOREWORD (Continued)

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 1950's 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 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. Sophisticated oil debris monitoring methods have since been built around this principle. In the early 1960's, 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 1960's. The origins of this technique go back to condition monitoring efforts on railroad diesel engines in the 1940's. Today, it is in wide use by most military services and many airlines throughout the world.

During the last decade, growing emphasis on reduced cost of ownership, on-condition maintenance, and automated engine monitoring has stimulated the development of new oil debris monitoring and assessment technologies.

A number of on-aircraft debris monitors, some of them based on sophisticated physical principles, are being offered and have been or are being evaluated by various engine manufacturers and users. At the same time, improved oil filtration with its well-established benefit of longer component life may reduce the effectiveness of some off-aircraft debris monitoring techniques and may stimulate the development of more sensitive instruments and methods for wear debris analysis and characterization.

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1. SCOPE:

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

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

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2.2 Related Publications:

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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

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2.2.10 Ferrography. Proceedings - Symposium Organized by the Condition Monitoring R&D Group of The British Institute of Non-Destructive Testing, October 1979

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2.3 Glossary of Acronyms:

AIR	Aerospace Information Report
BIT(E)	Built In Test (Equipment)
CMOS	Complimentary Metal Oxide Semiconductor
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
JOAP	Joint Oil Analysis Program
LCC	Life Cycle Cost
LVDT	Linear Variable Displacement Transformer
RCF	Rolling Contact Fatigue
ROI	Return on Investment
SEM	Scanning Electron Microscope
SOA(P)	Spectrographic Oil Analysis (Program)
TAN	Total Acid Number
TTL	Transistor-Transistor Logic
XRF	X-ray Fluorescence

3. BENEFITS:

The benefits, which can result from oil system monitoring include increased reliability/availability, reduced cost of ownership, improved product assurance, and enhanced safety.

3.1 Reliability/Availability:

Oil system components (including the oil-wetted components of the engine itself) are generally maintained "on condition". An oil system monitoring method with good prognostic capability can, therefore, improve operational readiness, removal scheduling and engine management, and enhance mission reliability and equipment availability.

3.2 Reduced Cost of Ownership:

An oil system monitoring method with good prognostic and diagnostic performance can provide information for trade-off decisions between aircraft availability and cost of secondary damage. Cost of ownership for the aircraft and fleet size can then be minimized. This requires a substantial amount of experience concerning failure modes and progression rates.

Reliable oil system monitoring methods can reduce cost of ownership by helping to reduce unnecessary removals, exploration, fault isolation, and secondary damage of progressive failure modes by initiating prompt maintenance action. An effective system will also help in minimizing in-flight shutdowns.

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3.2 (Continued):

A fully implemented oil system monitoring technique can often give an unambiguous indication of the location and type of defect leading to engine removal. This information can be used to direct the repair action and so expedite the return of the engine to service and reduce the repair cost.

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, Section 6.4, Cost Benefit Analysis).

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, and support personnel requirements can be dominant contributors to LCC and must be taken into account (see Figure 2).

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 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, operating temperatures, one directional thrust balance, lower weight, and on-condition maintenance continues to drive the development of debris monitoring methods with improved failure detection, prognostic, and diagnostic capability.

3.3 Product Assurance and Verification:

Oil 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 can be detected during engine acceptance test, run-in, or initial operation by proper oil system monitoring. Oil system monitoring also plays an important role during engine development for verification of proper bearing operation.

3.4 Safety:

Since bearing or gear malfunctions can lead to loss of engine power, oil system monitoring can contribute to flight safety. This is especially true for single-engine aircraft, including helicopters. In aircraft of this type, effective oil system monitoring is, therefore, especially important.

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4. OIL SYSTEM OPERATION 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 and filters or by pressure regulator malfunction. Low oil pressure can be the result of leaks, broken lines, pump failure (partial or complete), low oil level, or pressure relief valve malfunction.

In most engines, oil pressure is monitored continuously by means of pressure transducers installed on the high-pressure side of the lubrication system. These transducers are connected to cockpit instruments and can be 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, vibration and 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, LVDT, and digital types. Most of these pressure transducers are all passive, as they require an input excitation voltage.

In addition to pressure transducers for continuous oil pressure indication, most aircraft gas turbine engines are provided with a low-pressure switch to alert the crew to a critical engine condition. 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. The British Civil Airworthiness Requirements have similar provisions. An oil pressure indicator is also required by applicable specifications for U.S. military engines.

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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. 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 with an on-board computer could provide excellent diagnostics but might not be cost-effective.

4.2 (Continued):

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

4.3 Oil Quantity:

Monitoring oil quantity and oil added can provide information about excessive oil consumption, oil system leakage, or fuel contamination from defective fuel/oil heat exchangers. Most engine oil tanks are equipped with sight gauges or simple dipsticks for pre or postflight oil level checking. Some commercial and some 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. New developments in this area include electro-optics (Figure 4a) and fiber optic (Figure 4b) oil quantity sensors.

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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 filters 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 bypass 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.

5. OIL SYSTEM CONSIDERATIONS FOR ON-AIRCRAFT DEBRIS MONITORING:

All on-aircraft debris monitors, whether in production or experimental, rely on the debris transport characteristics of the oil system. Most 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. Some of the experimental sensors listed in 6.1.2 contain electronics and are not suitable for installation on the hot scavenge side where oil temperatures can exceed 200 °C (400 °F). The proper understanding of the capabilities and limitations of the debris sensor is essential to its effective operation.

5.1 Sensor Integration Into The Oil System:

The probability of detecting an incipient failure increases with the amount of debris available to the sensor. Figure 18 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 18 illustrates, the debris transport efficiency n_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 18 traps all particles larger than the openings of the pump screen. Its n_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 sumps and reservoirs.

The debris capture efficiency n_C applies to sensors that capture the debris for failure detection (e.g., magnetic chip collectors, electric chip detectors). It is a function of sensor characteristics, particle size, fluid velocity, and the design of the cavity or pocket in which the sensor is located.

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

The overall debris detection probability is given by Equation 1:

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

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

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. As examples, Figure 19 shows a variety of scavenge line installations of chip collectors and electric chip detectors with their respective capture efficiencies at comparable flow rates.

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5.2 Oil System Consideration For Optimum Prognostic and Cost-Effectiveness:

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. For cost-effectiveness, 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. This "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 bearing return lines and in the accessory gearbox. 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.

5.3 Oil Debris Monitoring and Filtration:

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 turboshaft engines incorporate an ultrafine filter with a rating of 3 μm abs while many others have gone to 7 and 10 μm abs. Field experience with the 3 μm engines have demonstrated that SOA becomes ineffective at these filtration levels. However, SOA still operates at the 10 μm abs filtration level and is considered effective down to 7 μm abs.

Additionally, the U.S. military has evaluated SOA techniques that can detect wear particles in ultrafine filtered systems. However, it is somewhat less effective than traditional methods and will require revised guidelines.

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 should stimulate the development of more sensitive techniques. Among on-aircraft monitoring systems, it should favor those that have "single-pass" capability, i.e., which do not require debris enrichment of the oil through recirculation.

Fine filtration enhances the effectiveness of magnetic chip collectors and electric chip detectors since it removes recirculating nonsignificant debris generated by normal wear.

6. OIL DEBRIS MONITORING:

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 a different rate, and often in different wear particle size ranges. The debris generated in these processes contains valuable and detailed information about the condition of wear surfaces. This forms the basis for engine monitoring via the oil system (oil debris monitoring).

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6. (Continued):

While each engine generates its own debris profile in terms of type, quantity, shape, rate of production, color, and size distribution, classification of oil particles can be useful for determining cause and action required for other engines. 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.

These types of data can assist maintenance personnel to more accurately make decisions on component conditions.

The various debris monitoring methods generally differ with respect to the parameters, which 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.

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.

Rolling contact fatigue (RCF) is an example, applicable to all applications, of a guaranteed wear mode that cannot be readily controlled by other procedures such as hard time overhaul, and is primarily reliant on wear debris monitoring. 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 follow the degradation pattern of RCF and other modes in the flight critical category through their serious condition/failure stages first and foremost, and secondly have sufficient width of dynamic range to give adequate warning.

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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

The failure mode assessment should include consideration of wear and failure mechanisms and consideration of the materials of critical oil wetted engine components.

Wear and failure mechanisms are a result of lubrication and load conditions and of the mechanical design characteristics of engine components. Under full-film elastohydrodynamic (EHL) lubrication 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

6. (Continued):

by surface fatigue (see 2.1.2). 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 μm). Under such lubrication conditions, abrasive and adhesive type accelerated wear modes are more common. Bearing skidding can occur when bearing loads are light. It produces very small debris particles (<25 μm) and can progress rapidly when bearing surface speeds are high.

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.

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 analysis techniques are being developed to try to identify these types of defects.

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. In the future, bearings in some engines may be made from ceramic materials.

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 nonferrous particles down to 500 to 750 μm in size but systems are not in production.

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 of 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.

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6. (Continued):

On-aircraft debris monitoring techniques are based on sensors or debris collectors, which are permanently installed in the engine lubrication system. They can be augmented by off-aircraft analysis of the collected debris. Sensors may further require signal conditioners, cockpit readouts, and/or interface hardware with engine monitoring systems.

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. Additionally, it establishes the credibility of the monitoring system to allow verification of signal by visual inspection of the debris on the sensor. If flow-through sensors are used, a high efficiency debris capturing device downstream of the sensor should be incorporated.

The main advantages of on-aircraft debris monitoring methods are fast response and minimal logistics requirements. This category includes the following well-established devices in use on current production engines:

a. Magnetic chip collector
b. Electric chip detector
c. Pulsed electric chip detector
d. Screen-type full-flow debris monitor
e. Centrifugal debris separator

In addition, a variety of devices and techniques have been or are currently being developed without, so far, having been included on production engines. Most of these devices have the additional advantage that they can be interfaced with an on-aircraft engine monitoring system:

a. Quantitative debris monitor (limited production)
b. Electro-optical debris monitor
c. Inductive debris monitor
d. Indicating screen
e. X-ray fluorescence monitor
f. On-line ferrograph
g. Degaussing chip detector
h. Capacitative debris monitor
i. Combined magnetic plug/eddy current debris monitor
j. Magnetoresistive sensor
k. Through-flow inductive bridge sensor
l. Through-flow intermittent electromagnetic inductive sensor

Due to complexity, cost, and weight, some of these devices are currently only suited for test stand use during engine development. However, they are included in this AIR since they may eventually be refined for on-aircraft use.

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:

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6. (Continued):

a. Spectrometric oil analysis (SOA)
b. Quantification and analysis of debris from magnetic chip collector
c. Filter debris analysis
d. Ferrography
e. Colorimetric oil analysis
f. Radioactive tagging
g. X-ray spectrophotometer (X-ray fluorescence)
h. Scanning electron microscope (SEM/EDAX)

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.

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6.1 On-Aircraft Debris Monitoring:

6.1.1 Established Techniques:

6.1.1.1 Magnetic Chip Collector: Also referred to as magnetic plugs or magnetic chip detectors, the devices have been used in gas turbine engines since the late 1950's. 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 6). 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.

The period between inspections of the magnetic chip collector(s) of an engine should be in relation to its known failure modes. Intervals vary widely, but are generally 25 to 50 h where chip collectors are used as primary failure detection devices. If a problem exists, more frequent

6.1.1.1 (Continued):

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 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).

The engine maintenance manual should include good illustrations of typical debris (see Figures 5a, 5b, and 7 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. This is discussed in Section 8. 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 recording, retention, and quantification of collected debris for trending and analytical techniques for diagnosis and fault isolation. These techniques are more fully described in 6.2.2.

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, magnetic chip collectors can also be effective for detection of smaller debris generated by bearing skidding, gear and pump scoring, spline wear, and rotating bearing races. Failures of bronze bearing cages have been detected when sufficiently far advanced to induce generation of magnetic debris.

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6.1.1.2 Electric Chip Detector: Electric chip detectors are essentially magnetic chip collectors with electric continuity indication capability. They are used in many U.S. engines and are required for military turbojet and turbofan engines by MIL-E-5007D and MIL-E-87231 and for turboshaft and turboprop engines by MIL-E-8593A. In Europe, magnetic chip collectors (see 6.1.1.1) are more widely used than electric chip detectors.

Two types of electric chip detectors are in use: (1) chip detectors with connectors for remote indication, and (2) chip detectors with touch-to-test terminals for ground checkout with an ohmmeter or continuity tester.

Remotely, indicating chip detectors are usually wired to cockpit 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 most U.S. designed helicopter engines, some single-engine aircraft with gas turbine engines, and some military long-range patrol aircraft.

Chip detectors for ground checkout are used in many U.S. military propulsion engines. Continuity checks must be carried out at frequent intervals (10 flight hours or less). After deposition of debris, the contact resistance increases due to the action of hot oil. In order to eliminate the need for frequent checks, the chip detector can be wired to a lock-on indicator, which can be located on a maintenance panel.

The chip sensitive area of an electric chip detector consists of two electrodes and a magnet to attract magnetic debris (Figure 8). 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) wide. It depends on engine size (considerations are rotating component revolutions per minute and size of wear surfaces), quality of oil filtration (good filtration permits smaller gap spacing), and criticality of failure mode. Optimum gap spacing may be 1.5 to 2.0 mm (0.06 to 0.08 in). A gap of this size range will indicate when only a few spalling flakes are captured. This is especially important if debris transport within the lube system is not very effective or where a bearing failure progresses rapidly to secondary engine damage.

As in the case of magnetic chip collectors, provisions must be made in the lubrication system to ensure effective chip detector installation. Electric chip detectors are most effective in detecting failure modes, which generate large debris particles. A disadvantage, compared to magnetic chip collectors, is the fact that debris is more difficult to inspect and remove.

To provide assistance in the decision to remove the engine for repair, engine maintenance manuals should contain instructions for debris interpretation (see Figure 5c for an example).

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6.1.1.2 (Continued):

A serious drawback of electric chip detectors is that they have no trending capability and that they have a high false-alarm rate. They are, therefore, not well suited to being interfaced with EMS.

False alarms are mainly caused by background debris, although all debris should be evaluated, especially with newer engines using superfine filtration (3 μm) or after initial system cleanup by test cell slave filter. A secondary cause is electrical problems. False alarms can be reduced by improving oil filtration and cleanliness during engine buildup to reduce background contamination. Further, high-reliability connectors should be used to eliminate electrical problems.

6.1.1.3 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, nonsignificant wear debris on the chip detector. These can be suppressed by delivering a current pulse from a capacitor to the chip detector, melting the fine debris.

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 engines, although their main area of application to date is in helicopter transmissions. Since production of fine debris at an increased rate can signify bearing failure, a pilot-initiated system provides earlier warning and permits limited trending. For automatically initiated systems, such trending is also possible if the current pulses are recorded by mechanical counters or an EMS.

6.1.1.4 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 (see 2.1.3). Figure 10 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.

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6.1.1.5 Centrifugal Debris Separator: A full-flow debris monitor without screen is shown in Figure 11. Its tangential inlet nozzle creates an internal vortex, which separates the entrained debris effectively down to about 100 μm with acceptable pressure drop (see 2.1.4).

Since the internal vortex is driven hydraulically, the unit must be installed on the pressure side of the scavenge pump. The debris sensor can consist of a magnetic chip collector, electric chip detector, or other debris-sensing device. An additional advantage is its ability to deaerate the oil by means of a separate air exit nozzle. This feature is optional and does not affect debris separation.

6.1.2 Under Evaluation:

6.1.2.1 Quantitative Debris Monitor: Two of the most characteristic parameters for 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.

Figure 12 shows a quantitative debris monitoring system consisting of a sensor and signal conditioner. This system provides real-time signals in response to the arrival of discrete magnetic particles whose mass are in excess of the detection threshold of the device.

The sensor can be installed in a screen-type full-flow housing (see 6.1.1.4), centrifugal debris separator (see 6.1.1.5) or other high-efficiency scavenge system pocket to enhance debris capture efficiency. It collects the debris particles for visual inspection like a magnetic chip collector and also has a self-closing valve. The signal conditioner can record discrete particle arrivals on a mechanical counter and differentiate them into two size ranges. It also has TTL (transistor-transistor-logic) of CMOS (complementary metal oxide semiconductor) compatible output options for the two size ranges for interfacing with EMS or event recorders. A BIT (built-in-test) feature is included.

An important feature of the quantitative debris monitor is that its output signal can be trended readily. This provides prognostic information about oil wetted component conditions. This system has undergone successful engine test cell and bearing test rig evaluation and is in limited production. It is most effective for surface-fatigue type failure modes.

6.1.3 Experimental Devices:

6.1.3.1 Electro-Optical Debris Monitor: Under evaluation for a period of years, the unit shown in Figure 13 optically scans the oil flow for entrained debris and oil condition. Metallic particles entrained in the lubricant scatter the light from an infrared light source. The scattered light is detected by a phototransistor and related to particle concentration. Attenuation is also determined and related to oil condition. The system is most sensitive for particles below 10 μm. It may, therefore, be effective for failure modes involving the production of large quantities

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6.1.3.1 (Continued):

of fine particles. Since the device is sensitive to entrained air, it should be located on the pressure side of the oil system, after the oil has been deaerated in the reservoir. The unit also requires a signal conditioner, which is not shown in Figure 13.

6.1.3.2 Through-flow Inductive Debris Monitors: There are several types of inductive debris monitors which have been under development. The devices consist of one or more inductive coils enclosing an oil line. Metal particles in the oil stream cause a change in the inductance of the coil as the particle passes through. This change is used to measure the particle size and whether it is ferromagnetic or nonferromagnetic. In a single coil version, the inductance coil is part of a high frequency resonant circuit. The particle changes the inductance, disturbing the resonant condition. The size of the particle is determined by the magnitude of the signal and the magnetic properties are determined by the phase change. Particle detection sizes depend on the sensor/line diameter. Particle sizes greater than 100 μm are detectable in a 1/2-in diameter line, while 250 μm particles are detectable in a 1-in diameter line. Tests have shown comparable capabilities for both ferromagnetic and nonferromagnetic particles detection, with the sensor capable of providing valid results in the presence of large quantities of air in the oil.

A second implementation uses two coils which form the arms of an inductance bridge device driven by an oscillator. Metal particles in the oil stream cause phase change and out of balance conditions, which increase with particle size. These signals are then amplified and counted. The system has been undergoing evaluation for a number of years at several engine and helicopter companies. The particle detection range for this sensor is:

a. 100 μm for ferrous particles
b. 500 μm for nonferrous particles

The detection threshold again is a function of the sensor/scavenge line diameter. For example, detection of 180 μm particles requires using a 1/2 to 3/4-in diameter line. For nonferrous particles, 850 μm particles have been detected in a 3/4 line. While this technique can discriminate and detect nonferrous as well as ferrous material, noise rejection requirements have limited its application to ferrous only in most applications.

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

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6.1.3.3 Indicating Screen: Based on a patented weave of conducting wire and insulating spacer rods, a screen made from this material becomes a directly indicating full-flow debris monitor. It is unaffected by finer wear debris. The minimum particle size threshold is determined by the smallest screen openings, which can be achieved in production. Figure 14 illustrates a unit designed for installation in an external scavenge line.

6.1.3.4 X-Ray Fluorescence Monitor: Under development since the mid 1960's, the system employs radioscope excited X-ray fluorescence (XRF). A small radioactive source is used to excite metal atoms suspended in the oil as wear debris to emit characteristic X-rays. The X-rays pass through an X-ray transparent window out of the flow chamber, and are detected by a gas-filled proportional counter and signal conditioner, and then they are used to provide an in-line measure of wear-metal quantity. The sensitivity of the unit is at the ± 1 ppm level.

The use of an X-ray monitoring system using a radioisotope excitation source on board aircraft is prohibited due to current shielding technology. The use of this technique would require compliance with safety regulations relative to the storage, use, and disposal of the radioactive material. Evaluation of an on-line X-ray system by a government agency and an engine company have determined that such a system is not practical. This is due to size of the system and the slow response time.

6.1.3.5 On-Line Ferrograph: The principle of ferrograph, described in 5.2, has been used to develop a real-time device suitable for installation in engine lubrication systems. The unit samples the oil stream and measures the concentration of two size ranges of magnetic particles by depositing them on a surface effective capacitive sensor in a high-gradient magnetic field. Installation guidelines must be followed to ensure delivery of a hot, representative oil sample to the sensor. A signal conditioner is also required. As currently configured, the unit is designed for stationary applications and engine test stand operation. No further development of an on-line system has occurred and, therefore, this device should be considered inactive.

6.1.3.6 Degaussing Chip Detector: An electric chip detector with the capability to demagnetize itself after particle capture would give multiple indications in response to continuing debris production. Two devices of this type have been proposed. The first is a chip detector with an electromagnet, rather than a permanent magnet. When a particle bridges the chip gap, an external signal conditioner shuts off the DC current to the electromagnet and turns on a decaying AC current to demagnetize the pole shoes. After a particle drops off, the DC current is turned on again. The second unit has a permanent rare earth magnet but an additional electromagnet is used to impose an opposite magnetic field on it for a short period of time, thus making it effectively nonmagnetic. The high remanence of the rare earth magnet restores the permanent field after the electromagnet has been turned off.

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6.1.3.7 Capacitive Debris Monitor: Several years ago a unit was evaluated which sensed capacitively the amount of debris deposited between two electrodes by means of a vortex (see 2.1.5). Although the unit was found to have mechanical problems, which precluded its evaluation, the principle may be promising.

6.1.3.8 Combined Magnetic Plug/Eddy Current Debris Monitor: This device consists of an active electromagnetic coil assembly and associated electronics, which detect a buildup of ferrous debris on the sensor and gives an output equivalent to the gross accumulation of mass. Individual large particles are also indicated. The detection range for this sensor is:

a. Mass: 0.1 mg - Output will be triggered by a buildup of fines or a few larger particles as long as their accumulated mass is 0.1 mg or above.

b. Individual: 0.8 mg and above.

This system has undergone testing by a U.S. Government agency and at least one engine manufacturer, a helicopter operator, and a helicopter manufacturer.

6.1.3.9 Magnetoresistive Sensor: This sensor consists of an almost complete ring of magnets and pole pieces. Two small gaps are left in this magnetic circuit into which are inserted two magnetoresistors. The two magnetoresistors determine the density of the magnetic flux flowing across the gaps. One of the gaps is exposed to the flowing oil stream to collect ferrous wear particles. Ferrous particles bridging the gap in the magnetic circuit cause the flux to bypass the exposed gap, while the overall flux circulating within the magnet is now greater as the impedance has been reduced. The changing flux densities sensed by the magnetoresistors indicate the amount of debris accumulating.

6.1.3.10 Through-Flow Intermittent Electromagnetic Inductive Sensor: This device consists of two coils wound concentrically around the oil scavenge line. The outer coil in combination with pole pieces forms an electromagnet, which is energized periodically to collect ferrous debris from the oil stream. The inner coil forms an inductor to an RF oscillator circuit. As debris is accumulated by the electromagnet, the inductance of this inner coil changes. The rate of change of the oscillating frequency is proportional to the concentration of the ferromagnetic material present in the oil stream. When the electromagnet is de-energized, the accumulated debris is released back into the oil stream ready for the cycle to recommence.

This system has undergone testing by a U.S. and Canadian Government agency, a helicopter operator, and a helicopter manufacturer.

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6.2 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 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 scruffing, 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 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 involving oil sampling are also affected by the degree of oil filtration. This is more fully addressed in 5.3.

6.2.1 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 transmitted to a laboratory where the suspended metal particle content is determined spectrometrically in parts per million. The results are then converted into a format that can be used for determining required maintenance action. For instance, this format may be 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 different types of instruments are commonly employed: (1) the atomic emission, and (2) the atomic absorption spectrometer.

The atomic emission spectrometer uses a high voltage arc to burn a small portion of the oil sample and measures the resultant light intensity in specific narrow frequency ranges utilizing a diffraction grating and photomultiplier tubes. These are located at points where specific spectral lines of interest are projected. The results can be printed out directly by a computer connected to the instrument. Samples can be processed quickly, and this method is, therefore, the most common.

The atomic absorption spectrometer measures the absorption of specific light frequencies associated with trace elements of interest. High-intensity light is passed through a flame (usually fueled by an air-acetylene or oxygen-acetylene mixture) into which the suitably diluted oil

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6.2.1 (Continued):

sample is aspirated. The light source is monochromatic and associated with the element of interest. Free atoms of that element in the flame absorb the incident light to a degree proportional to the amount of trace element present, with the remaining light being transmitted through the flame and measured electronically. The test is then repeated, utilizing different light sources for each element. Atomic absorption spectroscopy is more sensitive than atomic emission spectroscopy, but it is more time-consuming.

For diagnostic purposes, many users have established wear-metal concentration guidelines for each method, since emission and absorption spectrometers may give different results due to the differences in the way the sample is burned.

The upper limit of particle size, which can be detected, is in the range of 10 μm for the emission spectrometer and somewhat less for the absorption spectrometer. This is due to the mechanism in which the particles are delivered and burned and holds true even if the sample contains larger particles.

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.

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6.2.1 (Continued):

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

Modern spectrometers provide the capability of analyzing at least 20 different elements. However, the majority of SOA programs limit analysis to 6-9 of the most common elements found in lube systems. The detection limit depends on the nature of the instrument and on the vaporization temperature of the element of interest. For example, the detection limit for iron in an emission spectrometer is approximately 1 ppm, and in an absorption spectrometer 0.1 ppm.

Some of the more common elements detectable with routine sampling and their significance are:

a. Iron: Possible wear in gears, splines, bearing races, and/or rolling elements

b. Molybdenum: Possible wear in bearing elements made from high temperature, high strength steel such as M50

c. Aluminum: Possible wear of some gear cases, shims, and spacers

d. Copper: Possible wear in alloyed components of bronze, for example, bearing cages

e. Silver: Possible wear in plated parts such as bearing cages

f. Titanium: Possible wear in bearing hubs

Further developments have indicated that SOA can also detect presence of magnesium, zinc, tin, antimony, and silica.

Typically, spectrometers are calibrated for each element with commercially available standards.

Depending on the result of the analysis in parts per million, further action is triggered either by exceedances in wear-metal concentration or in rate-of-change in concentration. Thresholds are set on the basis of large sample populations from engines considered to be operating normally, recommendations from the engine manufacturer, metallurgical information concerning engine components, from other engine models of similar design, and from correlation with inspection results after removals. Rate-of-change in concentration is a more significant parameter than concentration itself since it relates directly to rate of wear-metal production (see 2.1.6). For engines with significant oil consumption, taking oil replenishment into account may yield better results. However, in large, dispersed fleets this may not be cost-effective.

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6.2.1 (Continued):

Despite the complete qualification of the data, their interpretation is somewhat subjective and requires experience and communication between laboratory and maintenance personnel. Concentration or rate-of-change-of concentration exceedances usually lead to resampling to confirm or disprove abnormal readings. If readings are confirmed, additional maintenance actions such as inspection of chip detectors, screens, and filters are usually recommended. Previous maintenance actions or special conditions affecting the engine need to be considered. The sample also can be filtered and the residue examined microscopically to determine if larger debris is present to confirm an incipient failure.

Typical wear-metal patterns can be used for failure isolation if certain engine components have characteristic compositions. Reference 2.1.6 describes a method to identify debris sources in terms of characteristic wear-metal concentration rates.

Spectrometric oil analysis programs have been applied widely to both military and commercial gas turbine engines. Important advantages of the technique are the ability to quantify and trend data easily and to detect the presence of various types of wear metals, including nonferrous, and of foreign contaminants in the lubrication system. The disadvantages of SOA are high initial equipment cost, the logistics of application (especially the time delay between sampling and maintenance action), the requirement for sample cleanliness and integrity, and the delayed response to rapidly progressing, surface-fatigue type failure modes, which may be detected only at an advanced stage when some of the larger debris has been ground up into smaller particles.

6.2.2 Quantification and Analysis of Debris from Magnetic Chip Collectors: Some airlines and military services have developed effective failure detection, prognostication, and isolation systems based on magnetic chip collectors (see 2.1.1 and 2.1.7). The magnetic probes (such as the one shown in Figure 6), are removed from the engine at regular intervals, typically every 25 to 50 h, and replaced with clean spares.

An initial assessment of the severity of contamination, if any, is made on the flight line. The probes are then sent to a laboratory for washing, visual inspection under a 20X microscope and classification, recording, and archiving of the collected debris. The amount of debris can be measured with an inductive instrument called a debris tester. The reading can be trended and compared to predetermined rate-of-change thresholds. This provides a more objective basis than mere visual observation. The predominant failure modes of a given engine model are usually recognizable to experienced personnel by shape, size, and quantity of debris. As an incipient failure develops, the inspection interval is reduced until the engine is removed with the certainty that a problem exists. If a scanning electron microscope with energy dispersive capability is available, debris material can be identified. This aids in diagnosis and fault isolation.

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6.2.2 (Continued):

This system is particularly effective for engines with lubrication systems specifically designed for optimum oil debris monitoring. This depends on number, location, and capture efficiency of the magnetic chip collectors (see Section 5).

6.2.3 Filter Debris Analysis: A quick visual assessment of the debris content of the oil filter is often performed in an attempt to verify SOA or chip detector indications. This is especially applicable to engines in which chip detector installations have low capture efficiencies. However, so-called "educated filter checks" have been used by some airlines for many years (see 2.1.1). This involves the careful backwashing, ultrasonic cleaning or disassembly of the filter element, and subsequent microscopic analysis of the debris collected on a piece of filter paper. Prognostic information can be obtained by analyzing size, size distribution, quantity, color, and shape of debris. Previous experience is used to judge the severity of a progressing failure.

6.2.4 Ferrography: Under development during the last several years, ferrography is both a laboratory technique for the microscopic classification of wear debris suspended in oil samples, and a method to quantify the data in a simple way for working use. As is the case with magnetic chip collectors, the visual analysis of the debris requires skill and training; as with SOA, sample cleanliness and sampling method are critical.

The technique depends on magnetic precipitation of ferrous particles. It is most sensitive to particles in the range of 1 to 100 μm. This range overlaps that of SOA at the small end and of magnetic chip collectors at the large end, and the technique, therefore, has high potential.

There are two types of ferrograph: (1) the direct reader (DR), and (2) the analytical ferrograph.

In the DR ferrograph, the oil sample, diluted with a solvent, is passed through a sloping glass tube, which is positioned above the poles of a magnet. The downward velocity of a ferrous particle in the magnetic field is approximately proportional to the square of its size. Hence, there is a maximum distance that can be travelled by a particle of a given size. Particles become deposited on the wall of the tube graded according to size. The amount of debris is measured optically at two positions, namely at a "large" position (D_L) and a "small" position (D_S). These two readings

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6.2.4 (Continued):

are related to wear particle concentrations and may be combined to give a severity-of-wear index. There are several different forms of this index, such as Equation 2:

$$D_L \qquad \text{(Eq.2)}$$

$$D_L\,(D_L - D_S)$$

$$D_L^2 - D_S^2$$

$$\frac{(D_L - D_S)}{(D_L + D_L)}$$

The user may determine the form that is most suitable to their needs.

In the analytical ferrograph, an oil sample is caused to flow over a glass or plastic substrate in the presence of a strong magnetic field gradient, which pulls the particles to the substrate. The oil is then washed away with a solvent, leaving the particles clean, aligned, and fixed to the substrate surface. The resulting particle display (ferrogram) is a permanent record. When nonferrous metal particles are present in the oil, they are usually magnetic enough to separate, especially when they were generated at a ferrous/nonferrous interface. Contamination particles, both organic and inorganic, can also be separated. Therefore, the analytical ferrograph can be used for contamination studies in a variety of fluid systems. The ferrous metals can be differentiated into broad alloy classes by their temper color. The shape and morphology of the particles reveal the mode of wear, such as abrasive and adhesive wear, scuffing, corrosion, or lack of lubrication. A special microscope/camera system called a ferroscope is available, which has a number of features to permit rapid analysis of the ferrograms.

The DR and the analytical ferrograph satisfy different requirements in debris monitoring. It appears that the most satisfactory method is to use the DR ferrograph to monitor the severity-of-wear index, and when this or its rate-of-increase becomes large, the analytical ferrograph can be used to determine the type of wear.

As is the case with SOA, special consideration must be given to sample integrity. Since the wear particles addressed by ferrograph are larger than those for SOA, settling and the effect of filtration is an even more important consideration in obtaining representative wear particle distributions.

6.2.5 Colorimetric Oil Analysis: Colorimetric Oil Analysis was developed and used for monitoring iron and copper in turbine lubricants during the late 1960's. This technique involves the analysis of the wear metal by acid extraction from the lubricant, buffering of the extraction solution and

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6.2.5 (Continued):

subsequent chelation with an appropriate indicator to produce a colored metal complex. The concentration of each wear metal is determined by measuring the intensity of the color formed and comparing it with standard calibration data.

Using this approach, a Colorimetric Oil Analysis Kit for measuring the iron concentration in lubrication oils has been developed. It is designed for use at remote locations where spectrometric oil analysis is not available. This kit weighs 25 lb and requires an analysis time of approximately 10 min. The colorimeter reads directly in parts per million iron. The wear-metal guidelines and threshold values required for the evaluation of the data are the same as those established for the atomic absorption spectrometer.

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Development of a Colorimetric Oil Analysis Kit for titanium has recently been completed using the same principle as that for the iron kit. These two kits are being developed into one Colorimetric Oil Analysis Kit.

6.2.6 Radioactive Tagging: Since the early 1960's, various radioactive techniques have been investigated and applied to test systems for measuring bearing wear and the monitoring of wear debris in the lubrication system. These techniques were sufficiently sensitive and yielded repeatable wear measurements but utilized radiation levels that are unacceptable for turbine engine monitoring. The practical constraints of radioactive tagging include consideration of safety, handling, and maintenance procedures.

A safe, low level radiation technique for the detection of wear occurring with mainshaft bearings has been developed and demonstrated, using high speed cylindrical roller bearings in a test rig (see 2.1.8). Iron-55 is employed as the active tag and is obtained through the neutron irradiation of the bearing rollers. Iron-55 provides a low radiation level, long half-life, and homogeneity of the isotope in the rollers. The low level of radiation in the tagged wear particles requires the separation of the wear debris from the oil by filtration or some other means. Testing shows that the tagging method would provide a means of identifying tagged roller wear at the ±0.5 ppm level in a 5 gal capacity test system. Radioactive tagging techniques would be most suited for identifying abnormal wear occurring with a critical or problem related mainshaft bearing.

6.2.7 X-Ray Spectrophotometer (X-Ray Fluorescence): This instrument, which may be available in materials laboratories of major airlines, in military services, in engine manufacturers, and in commercial metallurgical laboratories, permits determination of material composition of debris particles. In an evacuated chamber, debris particles are irradiated by an X-ray tube. Their atoms emit secondary X-rays with characteristic energies. The intensity of this emission is proportional to the amount of the element present in the sample. In this way, alloys can be identified precisely. However, if the sample contains particles of different materials, the resulting spectrum is a mixture of the spectra of the individual particles and must be interpreted.

6.2.8 Scanning Electron Microscope (SEM/EDAX): This instrument is also only available in well-equipped materials laboratories. It permits viewing of individual debris particles at great magnification. This can provide information about the process of their generation and, therefore, about the failure of wear mode that produced them. Energy-dispersive X-ray analysis (EDAX) provides spectra of secondary X-rays emitted by the SEM sample, which are characteristic for a given element. Individual alloys can, therefore, be identified precisely. The advantage of the EDAX over the X-ray spectrophotometer is that it can determine the composition of individual debris particles.

7. OIL CONDITION MONITORING:

7.1 Physical/Chemical Properties:

Physical/chemical property analysis of used oil can provide information about the condition of the oil as well as certain engine malfunctions.

The rate and degree of oil degradation in a turbine engine is dependent on aeration, temperature, oil consumption, oil system capacity, and oil formulation. For normally operating engines, the rate of degree of oil degradation is low and is compensated by oil consumption and replenishment. A change in an engine operating condition resulting in higher aeration (increased oxygen availability) or higher oil temperature such as seal wear can cause a significant increase in the rate of oil degradation. Tests for oxidation, additive depletion, solids content, fuel dilution, viscosity, and total acid number can be performed in the laboratory to determine lubricant serviceability. However, they are rarely performed routinely in the field because they are equipment and labor intensive.

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7.2 Complete Oil Breakdown Analyzer (COBRA):

Increased oil degradation produces changes in its electrochemical properties, which the COBRA instrument is designed to measure routinely (see 2.1.9).

The instrument measures 10 x 5 x 5 in, weighs 8 lb, and is battery powered. After the instrument is calibrated, obtaining a COBRA measurement, including data recording, takes approximately 1 min and requires only two drops of the lubricant.

The small test volume permits use of residual SOA samples thus eliminating the cost and time required for separate oil sampling. The COBRA instrument has been used successfully in identifying engines having high rates of lubricant degradation caused by deteriorating O-rings, cracked valves, and bad carbon seals.

7.3 Total Acid Number Kit (TAN Kit):

The TAN kit was developed as a field go/no-go determination of the acidity of MIL-L-23699 lubricating oil. It is composed of a bottle of acetone solution neutralized to pH 7.0 and a vial of aqueous sodium hydroxide, which reacts with a 5.0 ml volume of sample oil to produce a color change that indicates either a "go" (<2.0 TAN) or "no-go" (≥ 2.0 TAN) condition.

7.4 Antioxidant Package Level Indicator:

This new technique was developed to detect the relative amount of antioxidant constituent remaining in an oil formulation. By monitoring the depletion rate of the antioxidant, predictions can be made as to when the next oil change interval would occur.

This method requires that a small amount of an oil sample be mixed with 3 ml of a patented solvent system; this analysis sample is then subjected to a voltametric analysis; the subsequent oxidation/reduction wave height is representative of the relative amount of antioxidant content remaining in the sample.

The technique is very fast with a response time of less than 10 s.

8. GENERAL REQUIREMENTS:

The design and use of oil system monitoring should consider the following factors:

a. LCC (including inspection and support requirements)
b. Type and criticality of oil wetted component wear and failure modes
c. Detection and fault isolation capability
d. Engine modularity
e. Debris transport within the oil system
f. Degree of oil filtration
g. Qualitative and quantitative criteria for engine or module removal
h. Human factors
i. Maintenance crew training
j. Coordination and participation of equipment suppliers, engine and aircraft manufacturers, and users
k. Documentation (i.e., manuals)

For on-aircraft oil debris monitoring methods, the following additional considerations apply:

a. Sensor integration into the oil system
b. Environment
c. Weight and reliability of on-aircraft equipment, including wiring, connectors, and signal conditioners
d. Accessibility
e. Inspection and/or cleaning requirements
f. Location of annunciators and displays (cockpit or maintenance panel)
g. Interfaces (including interfaces with engine monitoring systems)
h. BITE (built-in test equipment)

Additional considerations unique to off-aircraft oil debris monitoring methods are:

a. Sampling provisions and equipment
b. Sampling frequency
c. Response time
d. Cost of laboratory and support equipment and personnel

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8. (Continued):

e. Logistics
f. Oil consumption and replenishment
g. Calibration requirements

The guidelines of ARP1587 also should be reviewed and applied to ensure that oil system monitoring is effectively integrated into the overall engine monitoring system.

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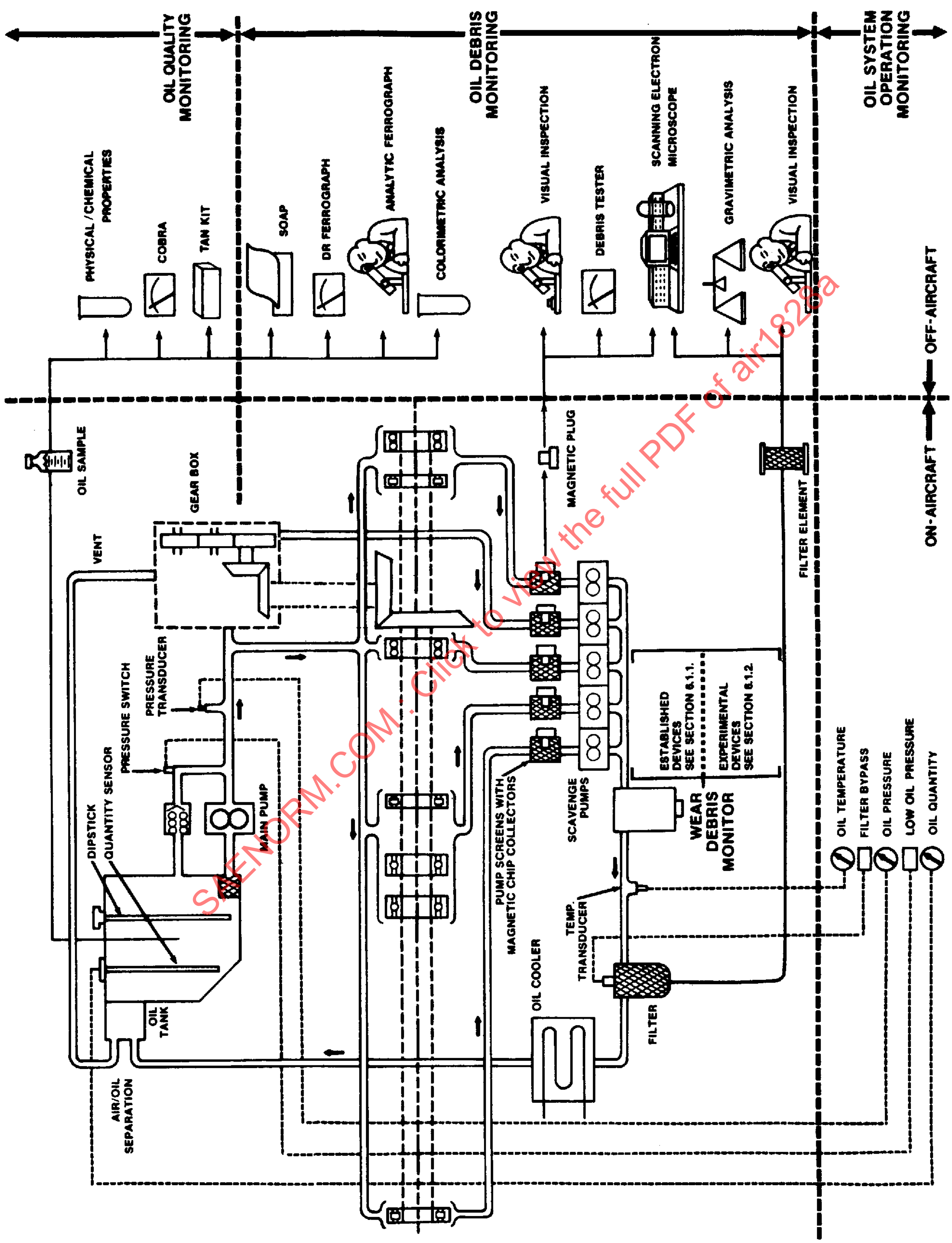

FIGURE 1 - Oil System Monitoring in Aircraft Gas Turbine Engines

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

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

FIGURE 3 - Thermal Resistance Sensor

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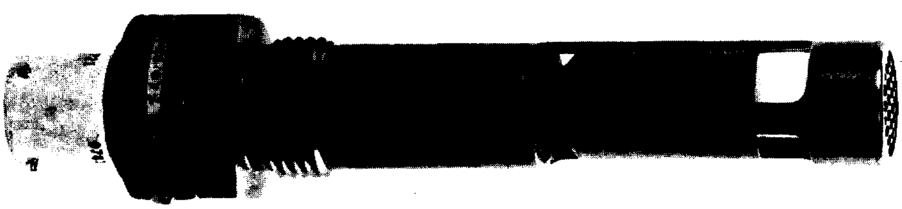

FIGURE 4 - Oil Quantity Sensor

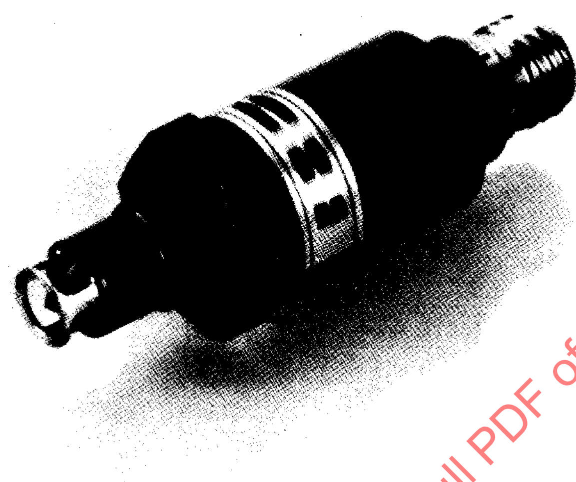

FIGURE 4a - Electro-Optic Liquid Level Sensor

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FIGURE 4b - Fiber-Optic Liquid Level Sensor

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

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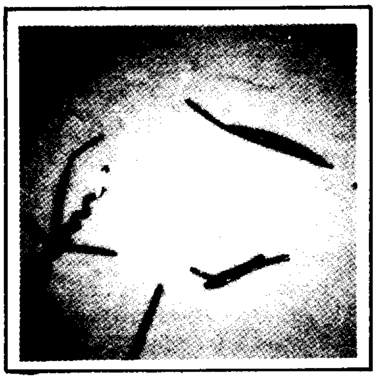
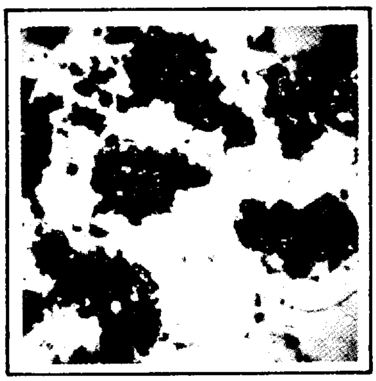


Type "E" Debris
Turning, Sliver
Splinter, Wire-like
Hair-like

Type "F" Debris
Chunk
Turning

Type "G" Debris
Foil Non Magnetic
Sliver



Type "H" Debris
Aluminum or Magnesium
Flakes, Granules
or Fragments

Type "I" Debris
Carbon Chunks

Type "J & K" Debris
Paint Chip
Sand & Dirt

Type "J & K" Debris
Paint Chip
Sand & Dirt

Type "L" Debris
Fibers

FIGURE 5a - Oil Debris Photographs Type A-D

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