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Revised

GUIDE TO OIL SYSTEM MONITORING IN AIRCRAFT GAS TURBINE ENGINES

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1. PURPOSE AND SCOPE: The purpose of this 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 which can be considered appropriate for routine maintenance.

In agreement with industry usage, wear particle size ranges are given in µm (1 µm = 10^{-3} millimeter = 10^{-6} meter). Other dimensions are given in millimeters, with inches in parenthesis.

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

- oil system operation monitoring (monitoring the oil system for proper operation);
- oil debris monitoring (monitoring the condition of oil-wetted engine components via the oil system);
- 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 which constitute an engine monitoring system, as discussed in ARP 1587 "Aircraft Gas Turbine Engine Monitoring System Guide". Frequently, oil system monitoring data are complimentary to information obtained from other components of the 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 the interaction of debris monitoring and oil filtration.

3. HISTORY: 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.[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 failure.

The second generation of gas turbine engines was already equipped with magnetic chip collectors with automatic shut-off 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.

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

4.1 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.

4.2 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 also by helping to reduce unnecessary removals and secondary damage of progressive failure modes by initiating prompt maintenance action. An effective system will also help in minimizing in-flight shutdowns.

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 (Ref. ARP 1587, Aircraft Gas Turbine Engine Monitoring System Guide, 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, especially for large engines. However, maintenance, inspection, logistics and support personnel requirements can be dominant contributors to life cycle costs 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 is 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, operating temperatures, lower weight and on-condition maintenance continues to drive the development of debris monitoring methods with improved failure detection, prognostic and diagnostic capability.

4.3 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.

4.4 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.

5. OIL SYSTEM OPERATION MONITORING

5.1 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 and digital types. 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 (ref. 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.

5.2 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 rpm, fuel temperature to the engine (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.

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 non-linearity and lower accuracy, thermistor temperature sensors are generally not used for oil system monitoring.

5.3 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 post flight 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 multi-level transducers for in-flight cockpit or maintenance panel read out.

5.4 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 (ref. 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.

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 different rates. 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).

Parameters by which the debris can be assessed include quantity, rate of production, material, particle shape, size, size distribution and color. 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.

In selecting the debris detection method(s) for the engine monitoring system, it is necessary to determine: 1) the types of potential failure modes, 2) their criticality vs. their probability, 3) the required detection point (timeliness) and 4) cost effectiveness.

The failure mode assessment should include consideration of wear and failure mechanisms and 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 macro-pitting induced by surface fatigue.[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.

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. Gear box 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.

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.

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.

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:

- magnetic chip collector
- electric chip detector
- pulsed electric chip detector
- screen-type full-flow debris monitor

In addition, a variety of devices 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:

- centrifugal debris separator
- quantitative debris monitor
- electro-optical debris monitor
- inductive debris monitor
- indicating screen

- X-ray fluorescence monitor
- on-line ferrograph
- degaussing chip detector
- capacitative debris monitor

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 provide more information. These techniques include:

- spectrometric oil analysis (SOA)
- quantification and analysis of debris from magnetic chip collectors
- filter analysis
- ferrography
- colorimetric oil analysis
- radioactive tagging
- X-ray spectrophotometer
- scanning electron microscope (SEM)

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

Magnetic chip collectors	50 to > 1000 μm
Electric chip detectors	50 to > 1000 μm
Ferrography	1 to 100 μm
SOA	< 10 μm

For failure modes which 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 which 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 compliment the on-aircraft debris monitoring devices usually found on the engine as standard equipment with other techniques to suit his special operational requirements and capabilities.

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, these 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 gear boxes. 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 5). 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 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 matures.

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 figure 6 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 detectors 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 9. 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 gear boxes. This makes failure isolation possible.

Sophisticated and very effective oil debris monitoring methods have been developed around magnetic chip collectors.[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 section 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.

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 for turboshaft and turboprop engines by MIL-E-8593A. In Europe, magnetic chip collectors (see section 6.1.1.1) are more widely used than electric chip detectors.

Two types of electric chip detectors are in use: chip detectors with connectors for remote indication and chip detectors with touch-to-test terminals for ground check-out 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 visual inspection after a chip light occurrence, self-closing oil shut-off 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 check-out 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 steadily 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 7). 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 (.04 to .16 in.) wide. It depends on engine size (considerations are rotating component rpm 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. (.06 to .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 8) for an example).

A serious draw back 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 engine monitoring systems (EMS).

False alarms are mainly caused by background debris. A secondary cause is electrical problems. False alarms can be reduced by improving oil filtration and cleanliness during engine build-up 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 build up of fine, non-significant 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 gear boxes 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.[3] Figure 9 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 .5 mm (.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.

6.1.2 Experimental Devices

6.1.2.1 Centrifugal Debris Separator: A full-flow debris monitor without screen is shown in figure 10. Its tangential inlet nozzle creates an internal vortex which separates the entrained debris effectively down to about 100 μm with acceptable pressure drop.[4] The unit operates best in well-filtered oil systems.

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-sensitive device. An additional advantage is its ability to de-aerate the oil by means of a separate air exit nozzle. This feature is optional and does not affect debris separation.

6.1.2.2 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 11 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 section 6.1.1.4), centrifugal debris separator (see section 6.1.2.1) 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) or CMOS (complimentary metal oxide semiconductor) compatible output options for the two size ranges for interfacing with engine monitoring systems (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 condition. This system has undergone successful engine test cell and bearing test rig evaluation. It is most effective for surface-fatigue type failure modes.

6.1.2.3 Electro-Optical Debris Monitor: Under evaluation for a period of years, the unit shown in figure 12 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 ten micrometers. It may therefore be effective for failure modes involving the production of large quantities 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 12.

6.1.2.4 Inductive Debris Monitor: This device consists essentially of two coils which enclose two sections of the oil scavenge line. One coil is for reference. A large particle entrained in the oil induces a voltage pulse in the unit which is amplified and counted. The system has been undergoing evaluation for a number of years and at least one engine company has reported good results from bearing test stand evaluations.

6.1.2.5 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 fine wear debris. The minimum particle size threshold is determined by the smallest screen openings which can be achieved in production. Figure 13 illustrates a unit designed for installation in an external scavenge line.

6.1.2.6 X-Ray Fluorescence Monitor: Under development since the mid 1960's, the system employs radioisotope 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 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 not 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.

6.1.2.7 On-Line Ferrograph: The principle of ferrograph, described in section 6.2, 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 effect 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.

6.1.2.8 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 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 the 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 non-magnetic. The high remanence of the rare earth magnet restores the permanent field after the electromagnet has been turned off.

6.1.2.9 Capacitative Debris Monitor: Several years ago, a unit was evaluated which sensed capacitatively the amount of debris deposited between two electrodes by means of a vortex.[5)] Although the unit was found to have mechanical problems which precluded its evaluation, the principle may be promising.

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 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 which 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 section 9.3.

6.2.1 Spectrometric Oil Analysis (SOA): Spectrometric oil analysis is the most widely used off-aircraft oil 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: the atomic emission and 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 photo multiplier 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 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 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 14). Another method involves use of special sampling valves (figure 15). 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 16) 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 minutes 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.

Modern spectrometers provide the capability of analysing 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:

- Iron - possible wear in gears, splines, bearing races and/or rolling elements
- Molybdenum - possible wear in bearing elements made from high-temperature, high-strength steel such as M50
- Aluminum - possible wear of some gear cases, shims and spacers
- Copper - possible wear in alloyed components of bronze, for example, bearing cages

- Silver - possible wear in plated parts such as bearing cages

- Titanium - possible wear in bearing hubs

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.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.

Despite the complete quantification 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 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 non-ferrous, 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.[1),7)] The magnetic probes (such as the one shown in figure 6), are removed from the engine at regular intervals, typically every 25 or 50 hours, 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 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 the 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.

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 9).

6.2.3 Filter 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.[1)] This involves the careful back-washing, 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 the 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, the Direct Reader (DR) and 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 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:

$$D_L$$

$$D_L \ (D_L - D_S)$$

$$D_L^2 - D_S^2$$

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

The user may determine which form is most suitable to his 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 non-ferrous metal particles are present in the oil they are usually magnetic enough to separate, especially when they were generated at a ferrous/non-ferrous 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 Direct Reader 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 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 compare 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 pounds and requires an analysis time of approximately 10 minutes. 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.

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 which 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.[8)] Iron-55 is employed as the active tag and is obtained through the neutron irradiation of the bearing rollers. Iron-55 provides low radiation levels, 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 part per million level in a 5 gallon 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: This instrument, which may be available in materials laboratories of major airlines, military services and 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): 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 or wear mode which 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 and degree of oil degradation are low and are compensated by oil consumption and replenishment. Change in 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.

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.[9)]

The instrument measures 10 x 5 x 5 inches, weighs 8 pounds and is battery powered. After the instrument is calibrated, obtaining a COBRA measurement, including data recording, takes approximately one minute 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.

8. GENERAL REQUIREMENTS: The design and use of oil system monitoring should consider the following factors:

- life cycle cost (including inspection and support requirements)
- type and criticality of oil wetted component wear and failure modes
- detection and fault isolation capability
- engine modularity
- debris transport within the oil system
- degree of oil filtration
- qualitative and quantitative criteria for engine or module removal
- human factors
- maintenance crew training
- coordination and participation of equipment suppliers, engine and aircraft manufacturers and users
- documentation (i.e. manuals)

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

- sensor integration into the oil system
- environment
- weight and reliability of on-aircraft equipment, including wiring, connectors, and signal conditioners
- accessibility
- inspection and/or cleaning requirements
- location of annunciators and displays (cockpit or maintenance panel)
- interfaces (including interfaces with engine monitoring systems)
- BITE (built-in test equipment)

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

- sampling provisions and equipment
- sampling frequency
- response time

- cost of laboratory and support equipment and personnel
- logistics
- oil consumption and replenishment
- calibration requirements

The guidelines of ARP 1587 (Aircraft Gas Turbine Engine Monitoring System Guide) also should be reviewed and applied to ensure that oil system monitoring is effectively integrated into the overall engine monitoring system.

9. 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 section 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.

9.1 Sensor Integration Into The Oil System: The probability of detecting an incipient failure increases with the amount of debris available to the sensor. Figure 17 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 17 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 17 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 sumps and reservoirs.

The debris capture efficiency η_C applies to sensors which 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 η_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

$$\eta_D = \eta_T \eta_C \eta_I$$

and corresponds to the fraction of particles indicated versus those which 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 η_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 which 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 18 shows a variety of scavenge line installations of chip collectors and electric chip detectors with their respective capture efficiencies at comparable flow rates.

9.2 Oil System Layout 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 gear box. 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.

9.3 <u>Oil Debris Monitoring And Filtration</u>: The benefits of improved filtration for longer bearing life are well-established[10),11)] and widely accepted. For this reason, there is an increasing trend to use finer filters on aircraft gas turbine engines. At least one modern turboshaft engine family incorporates an ultrafine filter with a rating of 3 micron absolute. Field experience with this engine has demonstrated that SOA becomes ineffective at these filtration levels.

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 which 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 non-significant debris generated by normal wear.

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