



AEROSPACE INFORMATION REPORT

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(R) Guide to Engine Lubrication System Monitoring

RATIONALE

This SAE Aerospace Information Report (AIR) was developed to provide information and guidance for the selection and use of technologies and methods for lubrication system monitoring of gas turbine aircraft engines. Benefits of effective engine lubrication system monitoring include increased reliability, reduced cost of ownership, improved product assurance, and enhanced safety of the equipment. The guidance within this report will support developers, operators, and maintainers to improve the effectiveness of lubrication system monitoring in existing and future applications. This edition incorporates new content on available oil quality monitoring technologies, the increased adoption of automated on-line chip analysis devices, and hybrid-ceramic bearing failure characteristics.

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1. SCOPE

This SAE Aerospace Information Report (AIR) provides information and guidance for the selection and use of technologies and methods for lubrication system monitoring of gas turbine aircraft engines. This AIR describes technologies and methods covering oil system performance monitoring, oil debris monitoring, and oil condition monitoring. Both on-aircraft and off-aircraft applications are presented. A higher-level view of lubrication system monitoring as part of an overall engine monitoring system (EMS) is discussed in ARP1587.

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

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

2. REFERENCES

These references contain useful information that may have been used in this report or may be beneficial in understanding the subject. The documents referred to hereafter are all current at the time of writing of this AIR. It is likely that they will continue to be relevant should they be revised in future.

2.1 Applicable Documents

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

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 1-877-606-7323 (U.S. and Canada only) or 1-724-776-4970 (outside U.S. and Canada), www.sae.org.

AIR5433	Lubricating Characteristics and Typical Properties of Lubricants Used in Aviation Propulsion and Drive Systems
AIR1871	Lessons Learned from Developing, Implementing, and Operating a Health Management System for Propulsion and Drive Train Systems
ARP1587	Aircraft Gas Turbine Engine Health Management System Guide
ARP6275	Determination of Costs and Benefits from Implementing an Integrated Vehicle Health Management System
AS5780	Specification for Aero and Aero-Derived Gas Turbine Engine Lubricants

Lotan, D., "Spectrometric Oil Analysis - Use and Interpretation of Data," SAE Technical Paper 720303, 1972, <https://doi.org/10.4271/720303>.

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- 2.1.2.8 Smith, H.A. (1983, May). *Complete oil breakdown rate analyzer (COBRA) for identifying abnormal operating turbine engines*. International Oil Analysis Workshop, Pensacola, FL, USA.
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- 2.1.2.14 *Lubrication of rolling bearings – Principles, lubrication methods, lubricant selection and testing, storage and handling* (TPI 176 J). Schaeffler Group.
- 2.1.2.15 Toms, L., and Toms, A.M. (2008). *Machinery oil analysis - Methods, automation & benefits* (3rd ed.). Society of Tribologists and Lubrication Engineers.
- 2.1.2.16 Toms, A.M., Jordan, E., and Humphrey, G.R. (2005, July 10-13). *The success of filter debris analysis for J52 engine condition based maintenance* [Conference paper]. 41st Joint Propulsion Conference and Exhibit, Tucson, AZ, USA.
- 2.1.2.17 Toms, A.M., and Cassidy, K. (2008) Filter debris analysis for aircraft engine and gearbox health management. *Journal of Failure Analysis and Prevention*, 8(2), 183-187. <https://doi.org/10.1007/s11668-008-9120-2>.
- 2.1.2.18 Lastinger, W., Overman, R., and Yates, L. (2006). Finding bearing failures through filter debris analysis. *Reliability and Information and Analysis Center (RIAC) Journal*, 14(1), 8-12.
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- 2.1.2.28 Byington, C., Brewer, R., Nair, V., and Mott, A. (2007, May 6-10). *Experiences and testing of an autonomous on-line oil quality monitor for diesel engines* [Conference paper]. STLE 62nd Annual Meeting and Exhibition, Philadelphia, PA, USA.
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- 2.1.2.30 Kallappa, P., Byington, C., and Donovan, B. (2005, September 12-16). *Fault detection and lubricant health monitoring for slow bearings in extreme operating conditions* [Conference paper]. World Tribology Congress III, Washington, DC, USA.
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- 2.1.2.34 Moffatt, J., Byington, C.S., and Minnella, C.M. (2012, May 1-3). *Lubricant condition assessment system (LUCAS), an enabler for condition based maintenance best practice* [Conference paper]. 68th American Helicopter Society International Annual Forum, Fort Worth, TX, USA.
- 2.1.2.35 U.S. Army. (1989). *UH-1H/UH-1V maintenance decision removal criteria guide for use with ODDS equipped aircraft*.

2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Information Report.

2.2.1 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9500, www.astm.org.

ASTM D7685-11	Standard Practice for In-Line, Full Flow, Inductive Sensor for Ferromagnetic and Non-ferromagnetic Wear Debris Determination and Diagnostics for Aero-Derivative and Aircraft Gas Turbine Engine Bearings
ASTM D664-11A	Standard Test Method for Acid Number of Petroleum Products by Potentiometric Titration
ASTM D974-11	Standard Test Method for Acid and Base Number by Color-Indicator Titration
ASTM D6971	Standard Test Method for Measurement of Hindered Phenolic and Aromatic Amine Antioxidant Content in Non-zinc Turbine Oils by Linear Sweep Voltammetry
ASTM D7596	Standard Test Method for Automatic Particle Counting and Particle Shape Classification of Oils Using a Direct Imaging Integrated Tester
ASTM E2412-10	Standard Practice for Condition Monitoring of In-Service Lubricants by Trend Analysis Using Fourier Transform Infrared (FT-IR) Spectrometry

2.2.2 Code of Federal Regulations (CFR) Publications

Copies of these documents are available online at www.ecfr.gov.

Title 14, Aeronautics and Space

2.2.3 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

AC 120-42B	Extended Operations (ETOPS and Polar Operations)
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2.2.4 ISO Publications

Copies of these documents are available online at www.iso.org/store.

ISO 12103	Road Vehicles - Test Dust for Filter Evaluation
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2.2.5 NIST Publications

Available from NIST, 100 Bureau Drive, Stop 1070, Gaithersburg, MD 20899-1070, Tel: 301-975-6478, www.nist.gov.

NBSIR 73-252	Proceedings of the 18th Meeting of the Mechanical Failures Prevention Group (1972)
NBS Special Publication 436	Proceedings of the 22nd Meeting of the Mechanical Failures Prevention Group (1975)
NBS Special Publication 494	Proceedings of the 26th Meeting of the Mechanical Failures Prevention Group (1977)
NBS Special Publication 547	Proceedings of the 28th Meeting of the Mechanical Failures Prevention Group (1978)
NBS Special Publication 622	Proceedings of the 32nd Meeting of the Mechanical Failures Prevention Group (1980)

2.2.6 Other Publications

- 2.2.6.1 Sawyer, J. (1980). *Sawyer's turbomachinery maintenance handbook, volume III: Support services & equipment*. Turbomachinery International Publications.
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- 2.2.6.4 *Ferrography: a symposium*. (1979). Condition Monitoring R&D Group of The British Institute of Non-Destructive Testing.
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- 2.2.6.6 *Proceedings of the 1998 Joint Oil Analysis Program Conference*. (1998). Joint Oil Analysis Program.
- 2.2.6.7 Roylance, B.J., and Hunt, T.M. (1999). *Wear debris analysis*. Coxmoor Publishing Co.
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2.3 Acronyms

ACFTD	Air Cleaner Fine Test Dust
ADM	Advanced Debris Monitor
AIR	Aerospace Information Report
AN	Acid Number
ANN	Artificial Neural Network
ARP	Aerospace Recommended Practice
ASTMD	American Society for Testing and Materials
BIT(E)	Built-In Test (Equipment)
CBM	Condition-Based Maintenance
CCD	Charge-Coupled Device
CFR	Code of Federal Regulations
DR	Direct Reader
DRF	Direct Reader Ferrograph
EDX	Energy Dispersive X-Ray
EDAX	Energy-Dispersive X-Ray Analysis
EHL	Elastohydrodynamic Lubrication
EIS	Electrochemical Impedance Spectroscopy

EMI	Electromagnetic Interference
EMS	Engine Monitoring System
ETOPS	Extended Operations
FAR	Federal Aviation Regulation
FDA	Filter Debris Analysis
FTIR	Fourier Transform InfraRed spectroscopy
HUMS	Health and Usage Monitoring System
ICP	Inductively Coupled Plasma
JOAP	Joint Oil Analysis Program
LCC	Life Cycle Cost
LIBS	Laser Induced Breakdown Spectroscopy
LVDT	Linear Variable Displacement Transducer
OCM	Oil Condition Monitor
ODM	Oil Debris Monitor
OEM	Original Equipment Manufacturer
ppm	Parts per Million
QDM	Quantitative Debris Monitor
RCA	Root Cause Analysis
RCF	Rolling Contact Fatigue
RDE	Rotating Disc Electrode
RF	Radio Frequency
RFS	Rotrode Filter Spectrometer
ROI	Return On Investment
RTD	Resistant Temperature Detector
RUL	Remaining Useful Life
RULER	Remaining Useful Life Evaluation Routine
SEM	Scanning Electron Microscope
SOA(P)	Spectrographic Oil Analysis (Program)

TAN	Total Acid Number
TDR	Time Domain Reflectometry
XRF	X-Ray Fluorescence

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

3. INTRODUCTION

Lubrication system monitoring for gas turbine engines can be classified into three different aspects:

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

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

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

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

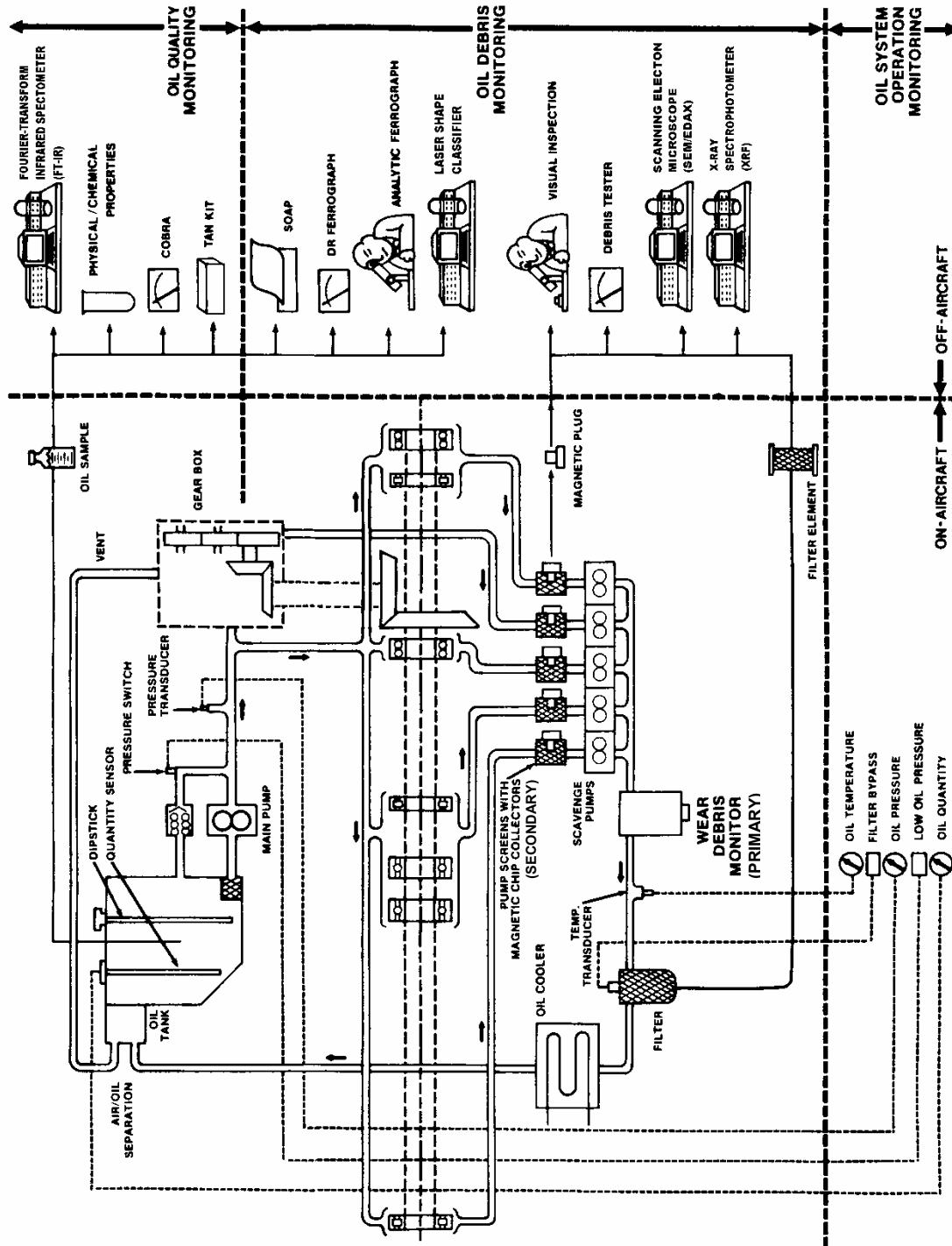


Figure 1 - Lubrication system monitoring in aircraft gas turbine engines

Oil system performance 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.

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

The introduction of gas turbine engines with their high-speed ball and roller bearings brought new failure modes with high secondary damage potential. The airlines successfully applied the earlier techniques to these engines by developing a method to regularly remove the screen-type oil filters, back-flush the filters, and analyze their content visually in terms of debris quantity, size, shape, color, and material (refer to ARP1587). 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 from the aircraft. Even today, regular filter inspection is used in some applications and is a valuable source of additional information when other methods provide ambiguous indications of incipient failures.

The second generation of gas turbine engines was already equipped with magnetic chip collectors with automatic shutoff valves to retain the oil and simplify routine inspection. Effective oil debris monitoring methods have since been built around this principle. In the early 1960s, electric chip detectors began to replace the magnetic chip collectors in U.S. military engines. In Europe, however, magnetic chip collectors are still in wide use today in military, as well as commercial, aircraft. When employed, a single master electric chip detector is typically located in the combined scavenge line, with individual magnetic chip collectors located within each individual scavenge line of the pump. The magnetic chip collectors are used to diagnose the scavenge line source of debris upon annunciation by the master detector. The wear debris monitor indicated in Figure 1 can either be a passive device that is inspected periodically or an active sensor that interfaces to the EMS. Figure 2 illustrates the ranges of debris particle sizes detectable with various technologies and provides an indication of which stages of fault progression each technology is suited for.

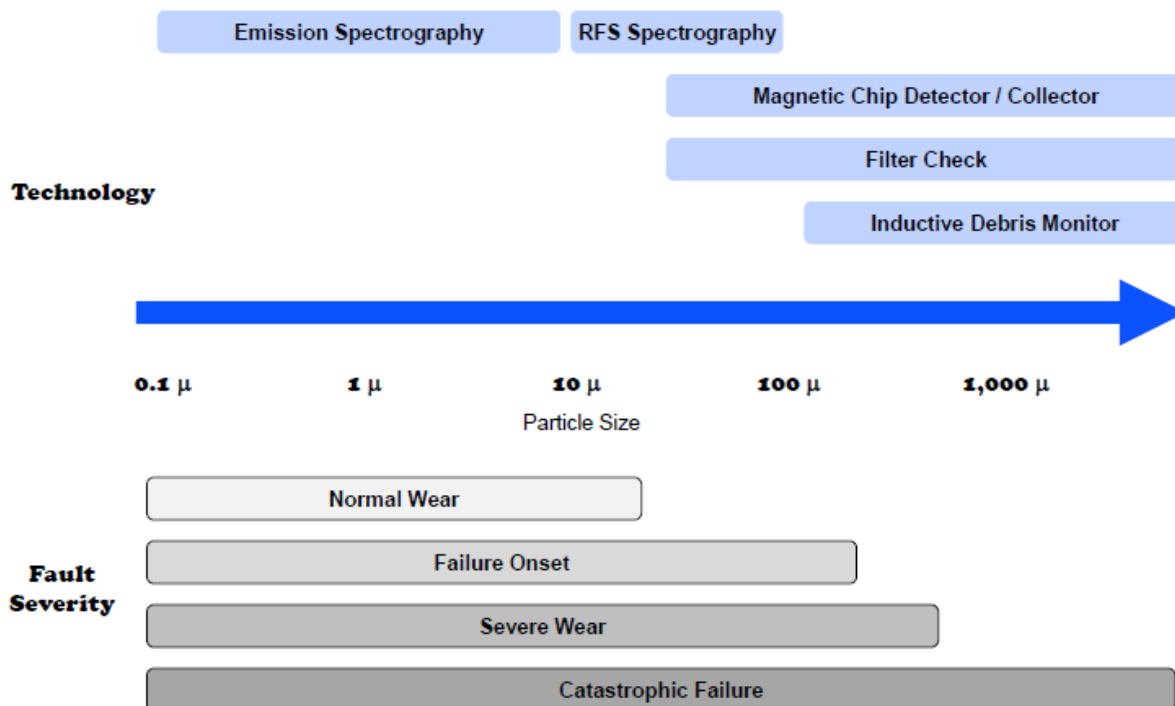


Figure 2 - Detectable debris particle sizes

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

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

The trend toward on-aircraft monitoring can also be seen in oil condition monitoring. While there are few of these systems in service on aviation applications today, there are more examples on ground vehicles. Due to the ability of oil condition monitoring to improve engine reliability by detecting deficiencies in the oil before a mechanical fault develops (as compared to oil debris monitoring which detects the fault after it develops), interest in the aviation industry for on-board oil condition monitoring capability has grown.

4. OVERVIEW

4.1 Oil System Performance Monitoring

Oil system performance monitoring involves continuous, real-time monitoring of the oil system's ability to properly lubricate the engine's oil-wetted components. The high-speed and high-temperature operating environment of a gas turbine engine drives the need for lubricating oil within specified pressure and temperature ranges. These parameters are monitored in flight by engine monitoring systems (EMS) and/or flight crews and require immediate action if they deviate from the required ranges. To ensure that a clogged filter does not impede the flow of oil, modern lubrication systems incorporate mechanical or electronic means of alerting the maintainer when the filter backpressure causes the filter bypass to be activated. In those systems that measure the pressure drop across the filter, insight can be developed into the current and future state of the filter (amount of dirt, filter utilization rate, etc.) by monitoring this pressure drop over time.

4.2 Oil Debris Monitoring

Oil debris monitoring involves the detection and identification of debris particles within the engine lube oil in order to provide an indication of the condition of the oil-wetted components. In addition to its function as a lubricating and cooling fluid, the oil serves as a transport medium for any debris generated by the rolling and sliding surfaces, which are subject to wear. Normal wear, accelerated wear, and incipient failure involve the removal of material, although at different rates and often in different particle size ranges. The debris generated in these processes contains valuable and detailed information about the condition of wear surfaces and the type of wear or incipient failure in progress.

4.3 Oil Condition Monitoring

Oil condition monitoring is a general term used to describe analyses of in-service lubricants to provide an indication of the quality of a particular fluid to perform its intended function. These analyses, when performed by a laboratory, might include measurements of oil viscosity, total acid number (TAN), total base number (TBN), moisture (H_2O), soot, nitration, sulfation, glycol contamination, oxidation, additive depletion, diesel or gasoline contamination, etc. These vary in different applications and by machine type. This information is correlated with different threshold warning levels, which are driven by certain additives being depleted, contaminants being present, or indicators of other loss of lubricant functionality. These limits are based on extensive tribological experience and often coded in expert systems that link thresholds with equipment type and incorporate some understanding of effects that might substantially increase risk of engine component failure.

Online oil condition monitoring devices typically measure physical and electrochemical properties of the fluid that are also sensitive to these oil condition changes but usually do not produce the same outputs or fidelity as offline laboratory methods. The benefit of the online oil condition monitoring is the near real-time monitoring and associated operational safety benefits over traditional sampling and offline testing.

4.4 Off-Line, On-Line, In-Line, and At-Line

A key aspect of any monitoring approach is where and when the monitoring is done. Historically, oil debris and oil condition monitoring have been done off-line by sending samples to a lab for analysis. With evolving technology, more of the monitoring is being done with sensors installed on the aircraft. On-line monitors continuously sample and analyze a portion of the flow. In-line monitors measure the full flow continuously. At-line systems are similar to off-line monitoring in that they require periodic samples to be taken, but they are more automated and portable, allowing analysis to be done near the aircraft, rather than sending samples to a lab.

5. BENEFITS

5.1 General

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

As with any engine health monitoring capability, the potential benefits should be weighed against potential drawbacks. Potential drawbacks include added development and procurement cost, weight, and potential detriment to overall reliability, maintenance cost, and flight disruptions. Often, the monitors are less reliable than the system components they are monitoring, leading to false detections that could impact vehicle availability and result in lower credibility, which could ultimately lead to the capability being ignored or disabled. Building in enough capability without extreme complexity, thoroughly maturing it in development, and balancing the system benefits against other metrics are important.

5.1.1 Reliability

Lubrication system monitoring methods can improve various types of reliability. First, ensuring proper condition of the lubricant can decrease the likelihood of mechanical faults occurring, thus improving product reliability. Second, diagnostic/prognostic capabilities can improve operational readiness, removal scheduling, and engine management and enhance mission reliability.

5.1.2 Reduced Cost of Ownership

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

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

A cost/benefit evaluation criterion for oil system monitoring is life cycle cost (LCC). An objective of LCC trade-off analyses is to maximize return on investment (ROI) by addressing projected cost benefit. The acquisition costs of many lubrication system monitoring devices are relatively low compared to the engine components they are intended to protect. The cost/benefit ratio is, therefore, generally favorable. However, maintenance, added weight, inspection, logistics, training, and support personnel requirements can be dominant contributors to LCC and must be taken into account. Refer to ARP4176 for guidance on performing a cost/benefit analysis.

5.1.3 Product Assurance and Verification

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

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

5.1.4 Safety

Bearing or gear malfunctions and impeded lubrication can lead to loss of engine power. Effective lubrication system monitoring can contribute to flight safety. Extended Operations (ETOPS) criteria takes oil consumption into account. The airworthiness status determination must include a process for determining engine and auxiliary power unit (APU) oil quantities and consumption rates prior to ETOPS dispatch.

5.2 Benefits of Oil System Performance Monitoring

Of the four categories of benefits previously discussed, oil system performance monitoring primarily contributes to product assurance and verification and safety. It can also contribute to reduced cost of ownership through early detection of conditions that could eventually lead to faults in the oil-wetted components that can impact operations and repair costs. Oil system performance monitoring can affect mission reliability and can affect product reliability if monitored in such a manner that problems can be detected and addressed before they lead to mechanical faults.

Oil system performance monitoring is one of the primary mechanisms for ensuring proper, safe engine operation. Maintaining oil temperature and pressure is necessary. Accordingly, they are monitored in flight and require immediate action if they deviate from the required ranges.

5.3 Benefits of Oil Debris Monitoring

Oil debris monitoring does not prevent wear or damage to oil-wetted components, but rather provides information on the condition of these components such that damage events can be managed effectively. Early indication of damage allows maintenance actions to be taken before severe damage or even catastrophic failure occurs, which translates into reduced cost of ownership and enhanced safety. Some technologies allow for the trending of detected debris over time, thus providing a prognostics capability that contributes to improved operational readiness and mission reliability. Debris monitoring is also quite beneficial in product assurance and verification activities as it is very effective in providing advanced warning of bearing damage, allowing appropriate action to be taken and minimizing secondary damage to key engine assets during development and acceptance test activities.

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, which may be especially true in the early years after service introduction. In engines where this is not the case, an expensive oil debris monitoring system or program may not be justified. Nevertheless, the general trend toward higher oil-wetted component loads and operating temperatures, lower weight, and condition-based maintenance continues to drive the development of debris monitoring methods with improved failure detection and prognostic and diagnostic capability.

5.4 Benefits of Oil Condition Monitoring

Per the Schaeffler Group report (see 2.1.2.14), it is estimated that over 60% of mechanical equipment failures are tribological and lubricant effectiveness related (more so than bending fatigue or load driven). Oil-wetted components (gears, bearings, etc.) are typically designed such that stresses are limited to the point that component lives exceed the specified engine life. Failures of these components are typically caused by improper lubrication, contamination, or assembly errors. By ensuring that the proper oil is used and is in good condition, a major cause of failures in oil-wetted components can be nearly eliminated. Thus, effective lubrication maintains safe, high-performance operation and enables longer engine and gearbox operation. Through effective lubricant monitoring and servicing, the effective reliability is also improved. This enhanced engine and gearbox reliability makes it possible to operate longer on wing and extend service lives without adding additional risk. Oil condition monitoring may be accomplished using sampling and offline laboratory analysis or a range of different sensing devices that are currently being evaluated in aircraft and other domains.

There are some benefits to moving from relying on traditional offline laboratory-based analysis to more online, real-time oil condition monitoring capability. Namely, on-line oil condition monitoring:

- Possesses much less (near zero) lag time between sampling and analysis results. Offline analysis results are more typically days or weeks in delay.
- Does not require man-in-the-loop nor produce sampling/transmission/testing errors. There have been many documented instances of contamination occurring outside of the sampling process. In addition, sampling is another opportunity to introduce contamination and increase the risk of maintenance-induced failures.
- Is often more repeatable than lab analysis, which may be conducted by different labs using different methods. The online measurements are being collected and trended directly by the device in the system. (It is important to note, though, that as with any device it may need calibration checks from time to time. These are typically much longer intervals than sampling intervals for offline analysis, and many devices have self-calibration and built-in-test capability. Online oil condition monitoring does not necessarily replicate all the outputs of a bank of laboratory test instruments; that would not be cost-effective or practical. Online oil condition monitoring devices are typically focused on trending specific parameters known to be sensitive to the oil degradations of interest for the equipment and application.)
- Has less recurring cost in both labor and downtime associated with sampling and offline testing.
- Can be directly integrated to the overall engine or vehicle health management system, health and usage monitoring system, or digital engine controller.
- Can more effectively drive oil system servicing and oil change intervals as part of an overall condition-based maintenance (CBM) approach and can also complement oil usage-based algorithms that may incorporate time and temperature.

One very significant concern with traditional schedule-based sampling and offline testing is that these methods will miss sudden changes in oil condition that can lead to higher risk of equipment failure. The sudden change may be due to a significant contamination event, incorrect oil addition, or other significant degradation occurring between these intervals that may be months apart. Thus, online monitoring of oil condition has substantial operational safety, condition-based maintenance, and reliability benefits by ensuring healthy oil for the system in question. Some of these devices can also be used to indicate oil level, over-aeration, and confirm loss of oil conditions, which is useful to minimize these risks.

6. OIL SYSTEM PERFORMANCE MONITORING

6.1 General Considerations

The selection and placement of sensors to monitor oil system performance is a critical and well-established part of engine design. Design considerations include sensor reliability, robustness of fault detection, timeliness of fault detection, etc.

6.2 Failure Modes/Monitored Parameters

6.2.1 Oil Pressure

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

In a pressure-regulated lube system, each pump has excess capacity, with a pressure regulator consisting of a ball in an orifice backed by a spring and often an adjustment screw. Within the balance of the regulatory system and sump capacity, oil pressure will remain constant. Therefore, oil pressure measurements from a pressure-regulated lube system contain usable monitoring information only when extreme changes occur in the oil system flow areas. In a full-flow lube system, the pressure is not regulated, so the pressure will vary with different engine speeds. Once the variation in speed is accounted for, smaller changes in the lube system can be detected as compared to a pressure-regulated system.

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

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

There are a variety of pressure transducer technologies available on the market. These include strain gauge, capacitive, inductive, potentiometric, piezoresistive, and Linear Variable Displacement Transducers (LVDT).

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

Federal airworthiness requirements (refer to 14 CFR § 23.1305, § 25.1305, § 27.1305, and § 29.1307) require a low oil pressure warning and/or an oil pressure indicator, depending on the type of aircraft. An oil pressure indicator is also required by applicable specifications for U.S. military engines.

In order to reduce data scatter for oil pressure monitoring, it may be beneficial to measure differential pressure as a “normalized” parameter that is independent of the accessory gearbox drive shaft speed.

6.2.2 Oil Temperature

Oil temperature must be monitored to assure that it does not exceed the operating temperature limitations of the oil. In conjunction with other oil system parameters, high oil temperature may also indicate and help isolate engine subsystem malfunction. If oil temperature is sensed at the scavenge side, extreme bearing distress or hot section seal leakage may be detected, or it could be caused by over-servicing (overfilling the system). If the sensor is located downstream of the oil cooler, its clogging may lead to an over-temperature indication. However, it may not be feasible to detect slow or small changes 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 (at individual scavenge lines, for example) and monitoring them with the aid of an EMS could provide excellent diagnostics but might not be cost-effective.

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



Figure 3 - Thermal resistance sensor
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6.2.3 Oil Quantity and Consumption

Monitoring oil quantity and oil added can provide information about excessive oil consumption, oil system leakage, fuel contamination from defective fuel/oil heat exchangers, or overfilling. Most engine oil tanks are equipped with sight gauges or simple dipsticks for preflight or postflight oil level checking. Many commercial and military engines also have oil quantity transducers. These transducers are usually of the mechanical float/reed-switch, capacitance, or thermistor types, which can operate in this high-temperature environment. Non-contact fluid level sensing technologies, such as guided wave radar, have also been successfully applied in aircraft applications. There are single point (low level) switches (see Figure 4) as well as multilevel transducers for in-flight cockpit or maintenance panel readout. If a detailed oil report is available, the oil consumption for each flight can be calculated by utilizing change in oil quantity between Taxi-out and Taxi-in phases. It may also be beneficial to monitor the consumption during the cruise phase, particularly if this is the longest part of the flight. Note that if engine oil quantity is being maintained using a “fill to spill” approach (adding oil until it overflows from the fill port), oil consumption monitoring is challenging since no quantity measurement is made during top-ups.

The ETOPS certificate holder must develop an engine oil consumption monitoring program to ascertain that there is enough oil to complete the scheduled ETOPS flight. The certificate holder's consumption limit must not exceed the manufacturer's recommendations, and the consumption monitoring program must be able to provide a trend of oil consumption based on Taxi-out to Taxi-in or oil replenished postflight with engine shutdown.

6.2.3.1 Capacitance Sensor

The oil level sensor produces a signal proportional to oil level when excited with an AC power source. The capacitive oil level sensor is comprised of two sets of concentric tubes, several insulating spacers, a tube insulator, cross-pins, and an electrical connector fastened to the mounting flange. Two pairs of concentric tubes form a variable capacitance circuit, one pair of which the reference tube is normally completely immersed in the oil provides an output proportional to the oil dielectric and the other pair provides an output proportional to the oil level along their common length.



Figure 4 - Capacitive sensor
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6.2.3.2 Resistive Sensor

Designed for immersion in lubrication oil, the transmitter is comprised of several integrated assemblies which include a circuit board, magnetically operated reed switches, a series of discrete high temperature resistors, an innovative buoyant float and magnet assembly, a supporting framework, and a tank or gearbox fitting flange assembly. The series of discrete high temperature resistors and hermetically sealed reed switches are mounted on a circuit board to provide a voltage ratio network, which operates in a similar manner to a variable potentiometer. The switches are evenly spaced along a circuit board in a ladder-rung formation. As the switches are actuated, the circuit resistance changes the output voltage ratioed to the input voltage, which provides for a highly accurate signal of oil quantity. Switch actuation is accomplished as a permanent magnet, contained within a uniquely designed float, travels with lube oil level changes.

This kind of sensor may be single or dual channel; in this last case, the float/magnet assembly is guided within a specially designed, two-channel, extruded aluminum tube or supporting framework that provides both support and vortex compensation. A second channel contains a set of guides, which positions the circuit board.



Figure 5 - Resistive sensor (float/reed switch)
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6.2.3.3 Time Domain Reflectometry (TDR) Sensor

In its simplest form, the TDR sensor is comprised of a simple wave guide sensor and an electronic controller. The system sends a Radio Frequency (RF) pulse into the fluid which is reflected off the fluid (oil/air) interfaces. The system detects and measures the time between the returned reflection(s) (also known as “electronic echoes”) from each interface in order to determine the height and quantity of each fluid within the sensor.

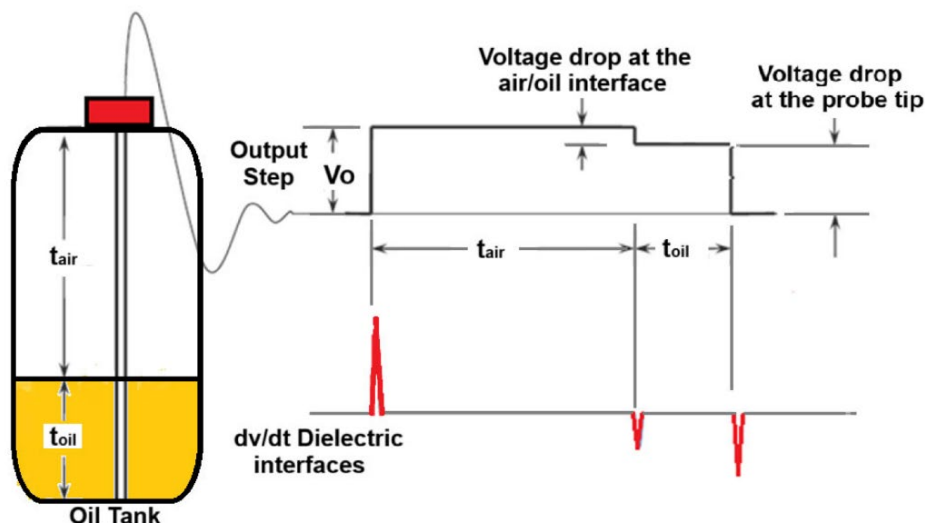


Figure 6 - TDR sensor principle of operation

6.2.4 Filter Bypass Indicator

In-system filters are universally applied to gas turbine engine lubrication systems to maintain the appropriate lubricant cleanliness level during operation. Typically, the main engine lubrication filter is incorporated either in the pressure line after the main lubricant pump or on the scavenge line prior to the lubricant tank. The filter element is a full-flow element that provides a coherent surface for capturing solid contamination in the lubricant. The filter is not restricted in terms of the chemical nature of the particulate contamination (e.g., magnetic/metallic versus ceramic), and the porosity of the filtration medium can be optimized for filtration efficiency, subject to the desired filter element service life. The contaminant loading characteristics of this full-flow lube filter element are impacted by abnormally high contaminant loading due to accelerated lube system component wear and/or impending failure, abnormal ingress of contamination into the lube system during operation or maintenance activities, and contamination generated from thermo-oxidative or hydrolytic breakdown of the lubricant.

Since a clogged oil filter would otherwise lead to oil starvation, gas turbine engine filters have bypass valves, which open under increased differential pressure. Most filter assemblies have provisions to indicate this condition externally by means of a mechanical or electrical bypass indicator. An impending bypass indicator is required by 14 CFR (refer to § 23.1019, § 25.1019, § 27.1019, § 29.1019, and § 33.71) and is also required by the U.S. military (refer to 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 of filter blockage/bypass due to cold oil as the higher viscosity of cold oil is sufficient to trigger thresholds for even a clean filter.

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.

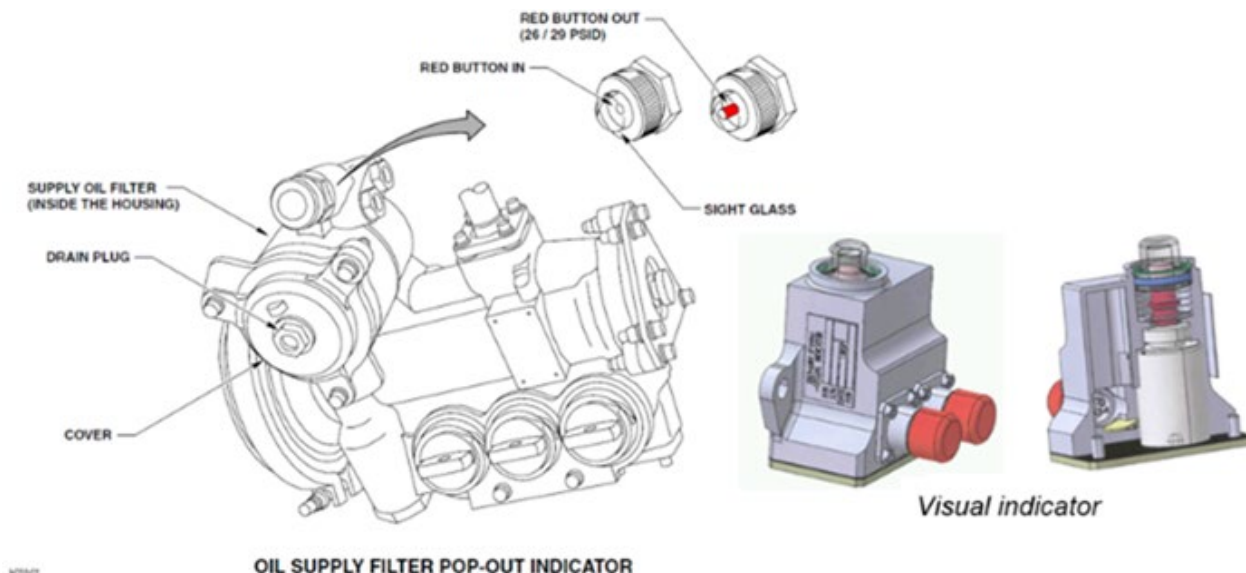


Figure 7 - Filter bypass indicators
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