



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 updates content, formatting, and incorporates new content on oil quality monitoring and off-aircraft oil debris monitoring.

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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 SAE Publications

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

AIR5433	Lubricating Characteristics and Typical Properties of Lubricants Used in Aviation Propulsion and Drive Systems
ARP1587	Aircraft Gas Turbine Engine Monitoring System Guide
ARP4176	Determination of Costs and Benefits from Implementing an Engine Health Management System
AS5780	Core Requirement Specification for Aircraft Gas Turbine Engine Lubricants
SAE Paper 720303	Lotan, D., "Spectrometric Oil Analysis - Use and Interpretation of Data," SAE Technical Paper 72030, 1972, https://doi.org/10.4271/720303 .

2.2 Other Publications

- 2.2.1 R. C. Hunter: Engine Failure Prediction Techniques, Aircraft Engineering, March 1975.
- 2.2.2 P. Cooper: Wear Debris Monitoring of Rolling Bearings, The British Journal of Non-Destructive Testing, Volume 25, Number 2, March 1983.
- 2.2.3 T. Tauber: Full-Flow Oil Debris Monitoring in Gas Turbine Engines, ASME Paper No. 81-GT-60, March 1981.
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- 2.2.8 J. A. Alcorta, L. L. Packer, J. H. Mohn: Bearing Wear Detection Using Radioactive Iron - 55 Tagging, ASLE Preprint 81-AM-GA-3; Presented at the 36th Annual ASLE Meeting, Pittsburgh, PA, May 1981.

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- 2.2.10 S. H. Loewenthal, D. W. Moyer: Filtration Effects on Ball Bearing Life and Condition in a Contaminated Lubricant, ASME Paper No. 78-Lub-34, June 1978.
- 2.2.11 S. H. Loewenthal, D. W. Moyer, W. M. Needelman: Effects of Ultra-Clean and Centrifugal Filtration on Rolling-Element Bearing Life, ASME Paper No. 81-Lub-35, March 1981.
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- 2.2.14 J. E. Tucker, A. Schultz, C. Lu, T. Sebok, C. Holloway, L. L. Tankersley, T. McClelland, P. L. Howard and J. Reintjes, "LaserNet Fines Optical Wear Debris Monitor," International Conference on Condition Monitoring, pp. 445-452, University of Wales, Swansea, UK, April 1999.
- 2.2.15 Schaeffler Group Report, "Lubrication of Rolling Bearings- Principles, Lubrication methods, Lubricant selection and testing, Storage and handling", TPI 176 J
(http://www.schaeffler.com/remotemedien/media/_shared_media/08_media_library/01_publications/schaeffler_2/tpi/downloads_8/tpi_176_de_en.pdf)
- 2.2.16 Toms, L. and A. M. Toms, "Machinery Oil Analysis - Methods, Automation & Benefits", 3rd Edition, STLE, Park Ridge, IL 2008, ISBN: 978-0-9817512-0-7.
- 2.2.17 Toms, A. M., E. Jordan, and G. R. Humphrey, "The Success of Filter Debris Analysis for J52 Engine Condition Based Maintenance", Proc. 41st AIAA, AIAA-2005-4338, Tucson, AZ, July 2005.
- 2.2.18 Toms, A. M. and K. Cassidy, "Filter Debris Analysis for Aircraft Engine and Gearbox Health Management", J. Fail Anal. Prev., Vol. 8, Iss 2, Apr., pp. 183-187, 2008.
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- 2.2.21 Madhavan P., "The Filter Element as a Diagnostic Tool for Condition Monitoring in Aerospace Power and Propulsion Lubrication Systems", STLE; 58th Annual Meeting, April 28 – May 01, 2003, New York, NY.
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- 2.2.24 Madhavan P., "Monitoring Fluid System Debris Via Diagnostic Filters', Proceedings of Technology Showcase - Integrated Monitoring, Diagnostics and Failure prevention, April 22-26, Mobile, AL, 1996.
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- 2.2.26 Neale, M.J., "Component Failures: Maintenance and Repair," (Warrendale, Society of Automotive Engineers, Inc., 1995), ISBN 978-1-5609-1451-8.

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- 2.2.32 Byington, "Advances in Real-Time Oil Analysis and Smart Sensor Developments," Invited Speaker to Practicing Oil Analysis International Conference and Exposition, October 24-26, 2000.
- 2.2.33 Byington, Merdes, Kozlowski, "Fusion Techniques for Vibration and Oil Debris/Quality in Gearbox Failure Testing", International Conference on Condition Monitoring at Swansea, April 12-15, 1999.
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- 2.2.36 UH-1H/UH-1V Maintenance Decision Removal Criteria Guide for use with ODDS Equipped Aircraft, U S Army, Ft. Eustis, 1989.

2.3 Related Publications

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

- 2.3.1 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.
- 2.3.2 ASTM D664-11A Standard Test Method for Acid Number of Petroleum Products by Potentiometric Titration.
- 2.3.3 ASTM D974-11 Standard Test Method for Acid and Base Number by Color-Indicator Titration.
- 2.3.4 ASTM D6971 Standard Test Method for Measurement of Hindered Phenolic and Aromatic Amine Antioxidant Content in Non-zinc Turbine Oils by Linear Sweep Voltammetry.
- 2.3.5 ASTM D7596 Standard Test Method for Automatic Particle Counting and Particle Shape Classification of Oils Using a Direct Imaging Integrated Tester.
- 2.3.6 ASTM E2412-10 Standard Practice for Condition Monitoring of In-Service Lubricants by Trend Analysis Using Fourier Transform Infrared (FT-IR) Spectrometry.
- 2.3.7 ISO 12103 Road Vehicles – Test Dust for Filter Evaluation.
- 2.3.8 National Bureau of Standards Publication NBSIR 73-252 (Proceedings of the 18th Meeting of the Mechanical Failures Prevention Group, Gaithersburg, Maryland, 1972).

- 2.3.9 National Bureau of Standards Special Publication 436 (Proceedings of the 22nd Meeting of the Mechanical Failures Prevention Group, Anaheim, California, 1975).
- 2.3.10 National Bureau of Standards Special Publication 494 (Proceedings of the 26th Meeting of the Mechanical Failures Prevention Group, Chicago, Illinois, 1977).
- 2.3.11 National Bureau of Standards Special Publication 547 (Proceedings of the 28th Meeting of the Mechanical Failures Prevention Group, San Antonio, Texas, 1978).
- 2.3.12 National Bureau of Standards Special Publication 622 (Proceedings of the 32nd Meeting of the Mechanical Failures Prevention Group, Santa Monica, California, 1980).
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- 2.3.21 AC 120-42B FAA Advisory Circular related to ETOPS (ExTended OperationS).
- 2.3.22 Code of Federal Regulations (CFR) Title 14 - Aeronautics and Space.

2.4 Glossary of Acronyms

AN	Acid Number
ANN	Artificial Neural Net
AIR	Aerospace Information Report
BIT(E)	Built In Test (Equipment)
CFR	Code of Federal Regulations
DRF	Direct Reader Ferrograph
EDAX	Energy-Dispersive X-ray Analysis
EHL	Elastohydrodynamic Lubrication
EMI	Electromagnetic Interference
EMS	Engine Monitoring System

ETOPS	Extended Operations
FAR	Federal Airworthiness Regulation
FDA	Filter Debris Analysis
ICP	Inductively Coupled Plasma
JOAP	Joint Oil Analysis Program
LCC	Life Cycle Cost
LVDT	Linear Variable Displacement Transducer
OCM	Oil Condition Monitor
ODM	Oil Debris Monitor
RCF	Rolling Contact Fatigue
RDE	Rotating Disc Electrode
ROI	Return on Investment
RUL	Remaining Useful Life
SEM	Scanning Electron Microscope
SOA(P)	Spectrographic Oil Analysis (Program)
TAN	Total Acid Number
XRF	X-ray Fluorescence

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

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

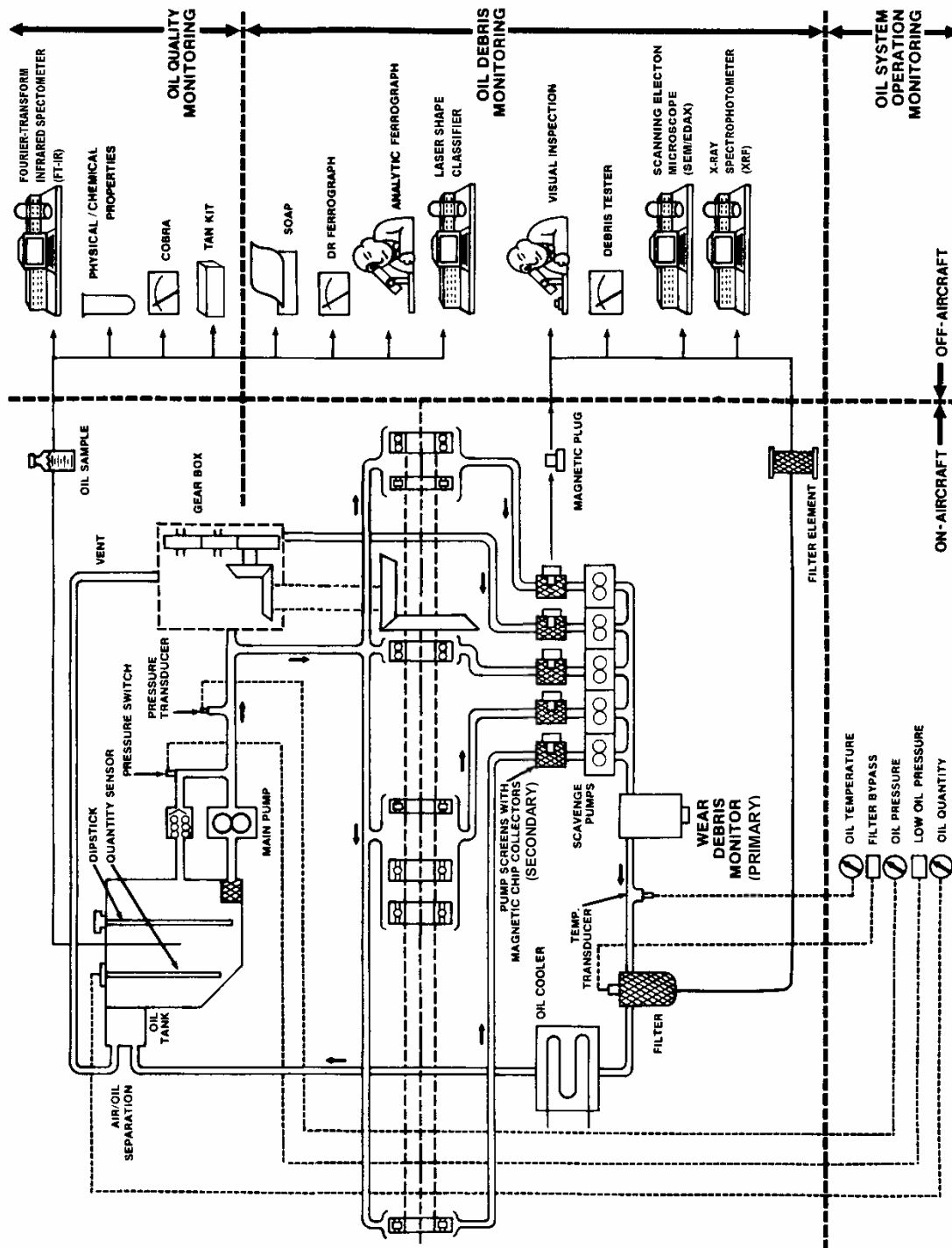


Figure 1 - Lubrication system monitoring in aircraft gas turbine engines

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 engine monitoring system. 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.

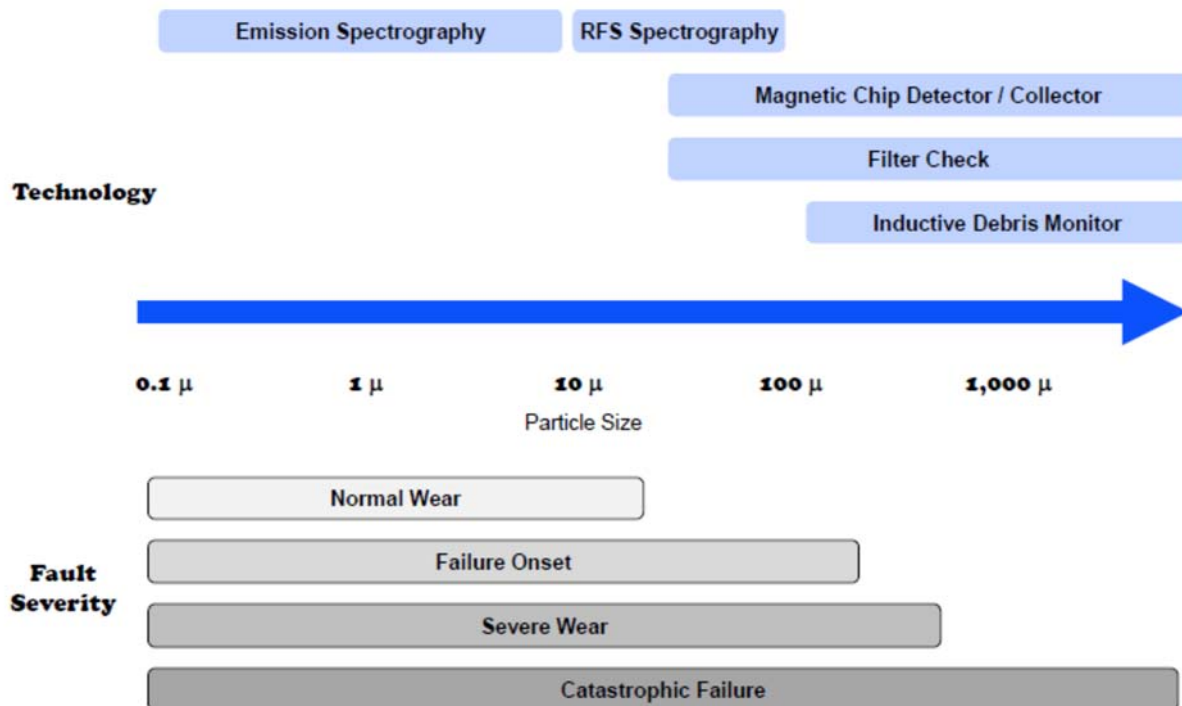


Figure 2 - Detectable debris particle sizes

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 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 (ODM) 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 (OCM) 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 as well, but usually do not produce the same outputs or fidelity as offline laboratory methods. The benefit of the online OCM 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 has 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 Operation (ETOPS) criteria do take 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, and accordingly 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 towards higher oil wetted component loads and operating temperatures, lower weight, and condition-based maintenance continues to drive the development of debris monitoring methods with improved failure detection, prognostic, and diagnostic capability.

5.4 Benefits of Oil Condition Monitoring

Per the Schaeffler Group Report (see Reference 2.2.15), 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 OCM capability. Namely, online OCM:

- 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 OCM does not necessarily replicate all the outputs of a bank of laboratory test instruments, that would not be cost effective or practical. Online OCM 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 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 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, overaeration, 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 engine monitoring systems.

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

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

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

Federal airworthiness requirements (reference FAA CFR Title 14 §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 (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.

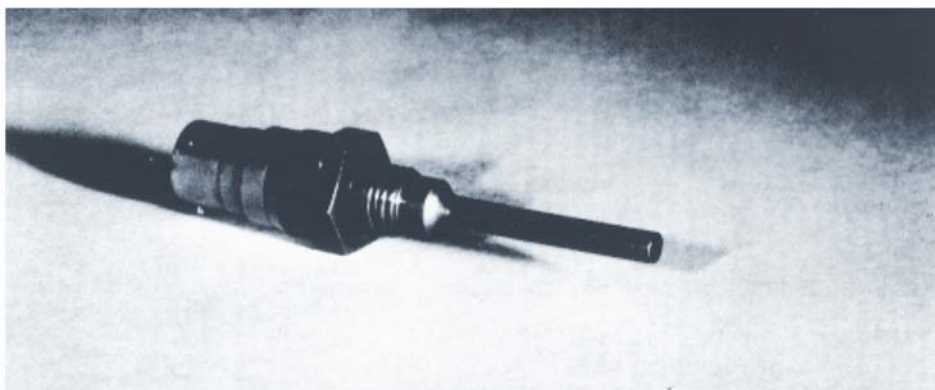


Figure 3 - Thermal resistance sensor

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 over filling. Most engine oil tanks are equipped with sight gauges or simple dipsticks for pre or postflight oil level checking. Many commercial and military engines also have oil quantity transducers. These transducers are usually of the mechanical float/reed-switch, capacitance, or thermistor types, which can operate in this high-temperature environment. 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 (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.

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 manufacturers 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 post flight with engine shutdown.



Figure 4 - Oil quantity sensor
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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 vs. 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 the FAA CFR Title 14 (reference items §23.1019, §25.1019, §27.1019, §29.1019, and §33.71) and is also required by the U.S. military (MIL-E-8593). The impending bypass indicator is set below the bypass cracking pressure, since the oil wetted components can be damaged by recirculating debris if the engine is operated with a bypassing filter. A thermal lockout prevents indication 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.

6.2.5 Filter Pressure Drop Monitoring

An alternative to the filter bypass indicators discussed in the previous section is to monitor the filter element pressure drop using differential pressure transducers to indicate when a filter element requires replacement. Trending the pressure drop across a filter element can also be utilized to indicate accelerated component wear, impending failure, poor maintenance, oil breakdown or to provide a prediction of how much life remains on the filter element. In this case, a continuous signal is output to the engine monitoring system allowing for operational limits to be established within the application's software without the need to change hardware. The thermal lockout function is now accomplished through the monitoring of the oil temperature. Continuous monitoring of the pressure build-up across the filter element provides the operator the ability to service the filter on-condition. In addition, the transducer provides the ability to identify some lubrication system failure modes by using trending techniques.

The filter element differential pressure is a function of flow rate, fluid viscosity (which is affected by temperature), and contaminant loading. Typically, the flow through the macro-porous filtration medium is considered to be laminar under normal operating temperatures so that the filter element differential pressure varies linearly, to a good approximation, with flow and viscosity for the design flow range and for low to moderate viscosities, typical of engine lubrication systems, as illustrated in Figure 5. Note that if the filter element is within the scavenge system the resultant oil and air mixture will result in a higher pressure drop than if the filter element is downstream of the air/oil separator.

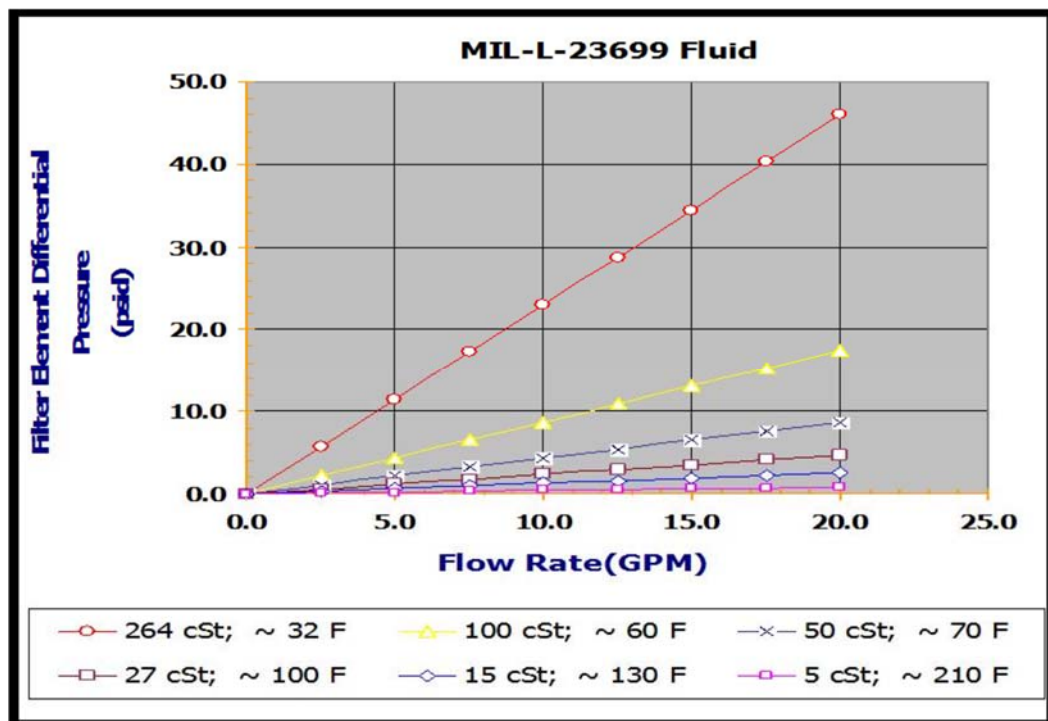


Figure 5 - Filter element differential pressure as a function of flow rate and viscosity

As the filtration medium of the filter element loads up with solid contamination, the fluid flow paths through the filtration are reduced resulting in increased filter element differential pressure. Figure 6 shows typical differential pressure build-up plots as a function of contaminant loading for several different flow rates and viscosities. Each differential pressure build-up curve was determined at a fixed flow rate and viscosity as indicated. AC Fine Test Dust contaminant was used to load the filter elements for each fluid viscosity and flow rate (refer to ISO 12103 Road Vehicles - Test Dust for Filter Evaluation).

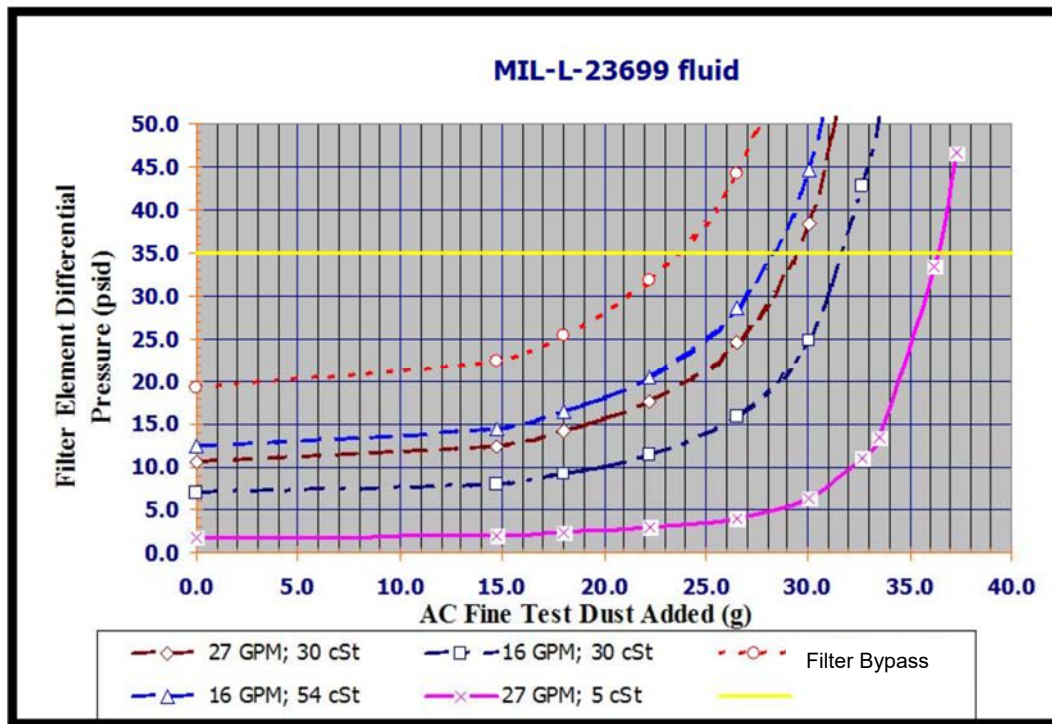


Figure 6 - Filter element differential pressure as a function of contaminant loading

As can be seen, the rate of increase of differential pressure (i.e., first derivative of the differential pressure build-up curve) increases with increased loading of the filter element, resulting in a flat curve at lower contaminant loading and increasing rapidly (exponentially) at higher contaminant loading.

6.2.5.1 Change in Pressure Drop to Detect Abnormal Debris

The origin of solid contamination in engine lubrication systems may be categorized as follows:

- Built-in debris (new engines): This includes debris from manufacturing and assembly processes (polishing compounds, machining debris such as metal chips, elastomer particles, etc.) as well as contamination in the lubricant fluid. Most manufacturers have processes for removing built-in debris, including finer filtration during start-up/'Green Run'.
- Debris ingressed/generated during engine operation: During 'normal' operation environmental contamination such as silica (sand) and other mineral compounds can be ingressed into the engine lube system via seals and vents. Wear debris generated from 'normal' component and elastomers/seal wear will be entrained in the lubricant.
- Debris introduced during maintenance: Debris can also be introduced during maintenance in the form of contaminated lubricant and contamination in replacement components, residual debris/chips from machining and other maintenance activities.
- Abnormal debris ingress/generation: External contamination can be ingressed into the lubrication system due to abnormal operating conditions, such as excessive seal wear or excessively contaminated environment. Wear debris generated during fault mode progression also accumulates in the lubrication system filter element. The rate of debris generation is based on the fault mode and load and speed of the component.

Figure 7 shows effective filter element load rates for the same engine model, operated by four different operators. The load rate is expressed in g/100 hours of AC Fine Test Dust (ACFTD) contaminant, a standard reference test contaminant utilized in laboratory evaluation of filter elements. The load rates were determined by evaluating the residual contaminant capacity of serviced filter elements, removed after the 'normal' service interval, utilizing ACFTD contaminant per a standard laboratory procedure. The load rates range from 0.8 g/100 hour to ~3 g/100 hour, implying a variation in filter element service interval of a factor of ~4 among the operators.

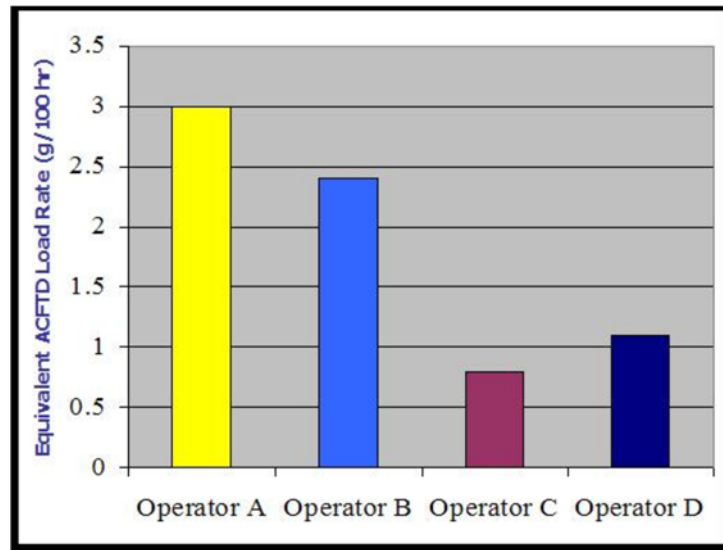


Figure 7 - Filter element load rates by operator

From the discussion above it may be concluded that under 'normal' operating conditions, an average contaminant load rate may be established for specific applications and hence, a baseline differential pressure build-up profile and filter element service interval. Deviations from normal operating conditions related to excessive contaminant ingress/generation in the lubrication system will result in a higher contaminant load rate for the filter element and hence, more rapid differential pressure build-up and reduced filter element service life. Typically in engine lubrication systems, abnormally high contaminant load rates are associated with: (1) lube system component wear and impending failure, such as wear of bearings and seals, (2) thermal break down products of the lubricant, typically carbonaceous material such as coke, and (3) ingress of environmental debris such as siliceous material.

As previously discussed, a key necessity in differential pressure monitoring for fluid system diagnostics/prognostics is the availability of real-time information on the flow rate and fluid viscosity at the filter element, in conjunction with the filter element differential pressure.

Fluid viscosity may be estimated for a specific engine lubricant by determining the fluid temperature at the filter element, accomplished by incorporating a thermocouple with the differential pressure transducer, and then using a temperature-viscosity relationship for the specific fluid. A potential drawback is the fact that many operators change lubricants, usually by topping off the lubrication system, resulting in a mixture of several lubricants having potentially different viscosities. Thus, on-line viscosity measuring devices that would satisfy requirements for aircraft engine applications would be preferable.

Flow rate information is usually obtained from engine speed, pump speed, or oil pressure. Variations in flow rate are most significant in the flight cycle when engine speeds change from the 'idle' to the 'take-off' or 'cruise' segments. The flow rate during the 'cruise' portion of a flight cycle does not vary significantly. Care should be taken to ensure that the flow rate at the filter element is consistent with the measured parameter from which it is derived since the design of the lube system may result in the flow rate at the filter element differing from the flow rate expected from the measured parameter.