Combining On-Site and On-Line Voltammetric Analyses to Better Understand the Different Degradation Mechanisms of Industrial Lubricants and Equipment.
Part II: Joint Strike Fighter Engine

By

Robert E. Kauffman
University of Dayton Research Institute
Dayton,OH
and
Jo Ameye
Fluitec International
Brussels, Belgium

Introduction

The Joint Strike Fighter (JSF) is designed as a single engine aircraft with the engine having both diagnostic and prognostic capabilities to detect and evaluate the wide range of operational problems experienced by aircraft engines (1). Wear debris analyses of the oil samples and the filters removed during the JSF engine test program were used to evaluate the capabilities of on-line wear debris sensors to detect component wear and predict engine failure (1). Due to the high oil make-up rate of jet engines, oil changes and lubricant condition monitoring are usually not performed by engine maintenance facilities or laboratories. However, several operational problems of aircraft engines, which were not detected by wear debris analysis, were detected by on-site oil condition monitoring techniques prior to engine damage (2-6). Therefore, on-line sensors capable of monitoring lubricant condition in different engine locations were developed for the JSF engine to improve the engine's capability to diagnose lubricant related problems prior to component failure and engine damage.

The on-line voltammetric oil condition monitoring (OCM) sensors used in this study are based on voltammetric measurement techniques and have been previously described in detail (4). The electronics of the OCM apply a voltage waveform to the two-wire sensor of the OCM in contact with the heated oil, liquid or vapor, causing a current to flow (below 1 microamp) between the surfaces of the two wires. The current flow is converted into a voltage and recorded/displayed by a data acquisition system as well as being displayed on the face of the OCM as a series of lights. As the antioxidants deplete in the circulating oil, the oil degradation rate accelerates and the current flow between the sensor wires/voltage output of the OCM increases.

All of the previously reported research with the voltammetric based OCM sensors had been performed on used aircraft oils in vials heated in the laboratory to simulate on-line testing of engine reservoirs and liquid lines. The laboratory research (2-4) demonstrated that the OCM sensors had potential to detect oils undergoing long term oxidation due to antioxidant as well as oils undergoing rapid degradation due to hot spots/oil fires. Antioxidant analyses with an off-line, portable voltammetric instrument (RULER™) were needed to distinguish between the two types of oil degradation, i.e., OCM reading increases with antioxidant depletion (oxidation) versus OCM reading increases without antioxidant depletion (hotspot/oil fire).

Although RULER™ analyses were needed in the laboratory to differentiate the different degradation mechanisms, it was theorized that on-line OCM sensors could differentiate between the degradation mechanisms by the timing, size and rate of changes in the OCM readings. Over months of flight, long-term oxidation would cause a slow, steady rise in the OCM readings followed by an accelerated rise as the oxidation accelerated due to loss of antioxidants, e.g., oxidation due to cracked seals experienced by C-130 and A-10 aircraft (2-4). Degradation due to hot spots/oil fires would cause a rapid, large increase in the OCM readings during a single flight, e.g., black oil problem of F-16 aircraft (4,5). Contamination by other fluids (motor oil, phosphate ester based hydraulic fluid and ethylene glycol antifreeze) would cause the OCM readings to increase between flights.

The development and optimization of the on-line voltammetric OCM sensors for evaluation on the JSF engine test stand were performed in two main phases. In the first phase, the on-line OCM sensors were optimized in the laboratory for use in both liquid (reservoir and return lines) and vapor (breather tube, bearing compartment and scavenge line) lubricant environments. The sensors' capabilities to detect oil oxidation, oil fires/hot spots and oil contamination by other fluids were tested. In the second phase, the optimized OCM sensors were incorporated into the various liquid and vapor lubricant environments of the JSF engine test stand. The OCM sensors were used to monitor the oil as seeded faults were introduced into the engine in an attempt to cause known engine and lubricant failure modes. The OCM test results from the laboratory and engine tests are described and discussed in full detail in the following paper.

Experimental

Lubricating Oils

The five lubricating oils used in this study were commercial and military MIL-L-23699 type aircraft engine oils (6) from different manufacturers. The tested oils included both Generation I and II (HTS-High Temperature Stability) oils with pentaerythritol ester type basestocks. The Generation I oils use antioxidant systems based on secondary aromatic amines. Generation II oils use antioxidant systems with higher temperature capability than the more traditional secondary aromatic amines.

Analytical Procedures

Off-line Oil Condition Monitoring Techniques

The RULER™(2-6) is a portable, voltammetric instrument and was used to perform the on-site antioxidant analyses of the stressed oils obtained from the laboratory tests and JSF engine test stand. The total acid number (TAN) measurements of the stressed oils obtained from the laboratory tests and engine test stands were performed with the RULER™ (5) and ASTM D-974 test methods, respectively. The kinematic viscosity measurements of the stressed oil samples from the laboratory tests were performed at 40°C. The Complete Oil Breakdown Rate Analyzer (COBRA) measurement readings of the stressed oils from the engine test stands were performed on-site and are related to the conductivity of the analyzed oils (3).

On-Line Oil Condition Monitoring (OCM) Sensors

The on-line OCM sensors are based on voltammetric analytical techniques and have been previously described in detail (4). For this study, the sensing portion of the OCM sensors submerged in the liquid oil or suspended in the oil vapor consisted of two, parallel wires (316 stainless steel or nickel). The wires were 1mm in diameter, 10-30mm in length (depending on application) and spaced apart 3mm (Figure 1). The electronics of the OCM sensors were connected to the sensing wires by way of a shielded coaxial cable (input: ±3 V, square wave applied). The continuous output of the OCM sensor (0-5Vdc) was displayed on a ten-light strip (each light representing 0.5V) and was also recorded by hand from the outputs of a digital voltmeter, strip chart and/or computer acquisition system.

Laboratory Stressing Tests

Accelerated Oxidation Test

A simple thermal-oxidation test was used to stress the aircraft oils studied during this project. The oil (300 mL) was heated at 210°C (410°F) for 72 hours in a 500-ml Erlenmeyer flask with dry air bubbling through the oil at a rate of 10 liters per hour. The heated oil was sampled (10 mL) at 5- 12 hour intervals and the samples were analyzed for antioxidant concentration and TAN using the RULER™ instrument and for kinematic viscosity at 40°C. Two OCM sensors were added to the flask used by the oxidation test to provide continuous monitoring of the heated oil. The stainless steel wires of one OCM sensor were submerged in the heated oil. The wire pair of the other OCM sensor was positioned across the open mouth of the heated flask so that escaping oil vapors could condense and form a droplet between the wires. The outputs of the two OCM sensors were displayed on a digital voltmeter and were recorded each time the heated oil was sampled.

Fire Test

A simple fire test was used to stress the aircraft oils studied during this project. A small pool (5-mL) of oil was placed on a watch glass and ignited with a butane lighter. The vapor OCM sensor was positioned (3 inches above oil) so that the resulting smoke passed over and through the wire pair of the vapor OCM sensor. On duplicate tests, a drop of oil (same as pool) was placed on the wire pair of the vapor OCM sensor (oil drop bridged the entire length of the exposed wires). After 15 seconds, the fire was extinguished by placing a second watch glass directly on top of the first watch glass. The pool of oil was allowed to cool to room temperature. The wire pair of the liquid OCM sensor was then inserted into the oil to make a reading. The outputs of the vapor OCM sensor were displayed using a strip chart recorder (5V full scale) since the output changed rapidly once the fire was ignited while the outputs of the liquid OCM sensor were recorded using a digital voltmeter since the output was constant after the fire was extinguished.

Contaminant Test

A simple contaminant test was used to simulate oil make-up with incorrect fluids and fuel leaks. Contamination levels of 1, 5 and 10% (by volume) were produced by dispensing 0.03, 0.15 and 0.30 mL of each fluid, respectively, into empty 5-mL glass vials and diluting to 3 mL with the selected oil. The fluids studied during this project were commercial hydraulic fluid (phosphate ester based), military hydraulic fluid (petroleum based), motor oil, antifreeze, and jet fuel. The vials were heated to 150°C (302°F) and the wire pair of the liquid OCM sensor was submerged into the heated oil to simulate on-line monitoring during normal operating oil temperatures for aircraft engines. The readings were recorded with a digital voltmeter at 5 minute intervals for 30 minutes to determine if the contaminants changed or degraded the oil with continued heating (simulate contaminated oil circulating in the engine)

JSG Engine Test Stand

The JSF engine test stand was performed at the Pratt & Whitney, West Palm Beach, Florida facility. An engine design used by military fighters was modified for the seeded fault engine test. In a seeded fault engine test, engine components are deliberately damaged or modified in an attempt to initiate known failure modes in the operating engine. In the seeded fault pertinent to this paper, the oil cooler was by-passed up to 80% allowing the oil in the monitored return line to reach a temperature of 232°C (450°F) when the engine speed reached 9900 rpm.

The JSF seeded fault test was initiated with 12 engine runs with each engine run lasting approximately 90 minutes. Each engine run consisted of sequences simulating takeoff, flight with varying engine speeds (afterburners used at full throttle) followed by landing. The first seven engine runs were performed with normal oil temperatures followed by five additional runs with the oil cooler by-passed to induce accelerated oxidation of the oil. The oil used in the seeded fault tests was a Generation I oil commonly used by military and commercial aircraft. An oil sample was obtained at the end of each engine run and was analyzed in the Pratt & Whitney oil analysis laboratory for antioxidants (RULER™), TAN (ASTM D-974) and conductivity (COBRA). Oil additions were made to the engine at end of each run for the first seven runs to make-up for the oil loss due to sampling and normal operating conditions. Oil additions were not made during the accelerated oxidation seeded fault (engine runs 8 – 12)

Four on-line voltammetric OCM sensors were installed on the JSF engine test stand. The sensors were installed at three engine locations: supply line to a bearing compartment (2 sensors), bearing compartment and breather tube (Figure 1). Holes were drilled into the bearing compartment plate and breather tube. Fittings (¼-inch pipe) were then brazed onto the drilled holes in the components' exterior surfaces as illustrated in Figure 1. For the oil supply line, a T-connector was installed in the oil line as illustrated in Figure 1. The OCM sensors were then attached to the added fittings using Conax Buffalo fittings (pipe thread to Swagelock union) which provided the electrical isolation, gap width and liquid tight seals required by the wire pairs of the OCM sensors. The circuit boards of the OCM sensors were placed within two feet of the sensor wire pairs (Figure 1) and were strapped to the engine or to the structure used to support the engine. The power supply and output of the OCM sensors were placed 50 feet away from the engine inside the test stand control room (Figure 1). The continuous outputs of the OCM sensors were displayed on digital voltmeters and recorded on analog tapes in a second control room.

Results and Discusion

Laboratory OCM Sensor Evaluations

Accelerated Oxidation Tests

Prior to the JSF engine test, the capabilities of the on-line voltammetric OCM sensors to detect accelerated thermal-oxidation were tested. Three Generation I oils and two Generation II oils (6) were oxidized at 210°C (410°F) in a flask with a bubbling air stream to determine the capabilities of the on-line OCM sensors to detect accelerated oil oxidation during higher than normal operating temperatures in both the liquid and vapor phases. The heated oils were sampled at set time intervals and analyzed for antioxidant and TAN using the RULER™ and for kinematic viscosity at 40°C. At the end of each test, the liquid and vapor OCM, % remaining antioxidant (ratio of antioxidant in the stressed oil sample compared to fresh oil), TAN and viscosity measurements of the stressed oil samples were plotted versus the heating time. The prepared plots were then used to compare the oil condition trending capabilities of the on-line OCM results to the capabilities of the on-site (off-line) analytical tests for the different oils. Figure 2 is the plot for one of the Generation II oils and is representative of the plots produced by the different Generation I and II oils.

The plot in Figure 2 shows that the OCM (vapor and liquid), TAN and viscosity measurements undergo minimal increases as the % remaining antioxidant decreases to 40 % of the original concentration of the fresh oil during the first 40 hours of heating. The oil drop that forms during the first 40 hours of heating between the wire pair of the vapor OCM sensor was yellow in color (oil vapor condensing). Between 40 and 20 % remaining antioxidant (40 – 60 hours in Figure 2), the OCM (liquid and vapor), TAN and viscosity measurements begin to increase at an accelerated rate, i.e., the useful life of the oil has ended. The drop on the vapor OCM sensor became thin and colorless (degradation products condensing in place of oil vapor) as the bulk oil darkened rapidly. Although, the rate of increase in the liquid OCM readings slowed with extended heating (Figure 2), the vapor OCM (5V maximum reading) and TAN measurements continue to increase rapidly until the end of the test. All of accelerated oxidation tests for the Generation I and II oils produced plots similar in shape to Figure 2. However, the useful lives of the Generation I oils ended at 15 – 30 hours compared to 50 – 60 hours for the Generation II oils (6) and the baseline OCM readings of the fresh oils at 210°C were 3 –5 times higher for the Generation II oils than for the Generation I oils.

Regardless of the oil type, the rapid rate of increase in the OCM readings was always in good agreement with the depletion of the antioxidant and the rapid increase in the TAN and viscosity measurements, i.e., the oil condition measurements of the on-line OCM and on-site analytical techniques were the same regardless of oil type.

Oil Fire Test

Next, the capabilities of the on-line voltammetric OCM sensors to detect oil fires were tested. A small pool (5-mL) of oil was placed on a watch glass and ignited with a butane lighter. The vapor OCM sensor was positioned so that the resulting smoke passed over and through the wire pair of the vapor OCM sensor. After 15 seconds, the fire was extinguished. For every oil tested, when the vapor OCM sensor was dry (no oil drop), the sensor had a minimal (0.1 to 0.3V) response to the smoke. However, when a drop of oil was placed on the wire pair prior to igniting the oil, the oil drop turned black in color and the sensor went off scale (> 5V) in less than 10 seconds for every oil tested. For every oil tested at room temperature, the liquid OCM sensor reading was below 0.2V before the fire and was off-scale (> 5V) after the fire.

Therefore, both the vapor and liquid OCM sensors are capable of detecting oil fires within seconds as long as the vapor OCM sensor has an oil drop bridging its wire pair.

Oil Contamination Test

The final laboratory test was to evaluate the capabilities of the on-line voltammetric OCM sensors to detect liquid contaminants. External liquids enter the oil supply of the engine due to oil additions with the wrong fluid (motor oil, hydraulic fluid or antifreeze) or due to fuel leaks (fuel can leak into oil lines through breach in oil cooler walls). To test the OCM sensors capabilities to detect contaminant fluids in Generation I and II oils, oils were prepared with 1, 5 and 10% contaminants and dispensed into 5-ml vials. The vials were heated to 150°C (302°F) and the wire pair of the liquid OCM sensor was submerged into the oil to simulate on-line monitoring during normal operating oil temperatures for aircraft engines. The typical results for Generation I and II oils are listed in Table 1.

The results in Table 1 indicate that the liquid OCM sensor can detect commercial hydraulic fluid (phosphate ester based), motor oil and antifreeze immediately at contamination concentrations above 5% and within minutes at concentrations below 5% due to increases in the OCM reading with time. The higher initial readings of the Generation II oil decrease the ability of the OCM sensor to immediately detect motor oil below 5%. The liquid OCM sensor was unable to detect jet fuel or military hydraulic fluid (petroleum based) at concentrations below 20% in Generation I or II oils.

With regard to the vapor OCM sensor positioned at the open mouth of the heated vial, the 10 and 5% fuel dilutions caused the oil drop to thin and drop from the wire pair (OCM reading went from 0.3 to 0.02V). Conversely, the vapor OCM sensor readings increased rapidly as the oils containing 10 % contamination of commercial hydraulic fluid, motor oil or antifreeze were heated.

Consequently, the liquid OCM sensor has better contamination detecting capabilities for commercial hydraulic fluid, motor oil and antifreeze while the vapor OCM sensor has better contamination detection capabilities for fuel. Neither sensor was able to detect military hydraulic fluid below 20% contamination.

JSF ENGINE TEST STAND OCM SENSOR EVALUATIONS

Accelerated Oxidation Seeded Fault Test

Set-up of Engine Test Stand

Once the on-line voltammetric OCM sensors were evaluated and optimized using laboratory testing, three OCM sensors were packaged for testing on the JSF engine test stand. Minor modifications were made to engine components selected to be monitored by the sensors. Connectors containing the sensing wires were attached to fittings incorporated into an oil return line (2 sensors) and brazed onto the exterior surface of the breather tube (Figure 1). The connectors supplied a liquid tight, electronically isolated seal around the wires while providing the desired gap width of the wire pair submerged in liquid lubricant or exposed to lubricant vapor. Additionally, 40 – 50 feet of cable was added between the OCM circuit board/sensor wires and the power supply to allow the power supply to be located in the control room (Figure 1).

To initiate the JSF engine stand test, seven engine runs (Runs 1 – 7) were made under normal lubricant operating conditions (seeded fault was a bearing race with indents). Then five more engine runs (Runs 8 – 12) were made with the oil cooler by-pass valve closed up to 80% resulting in increased oil temperatures and accelerated oxidation. The oil in the monitored return line reached a temperature of 232°C (450°F) when the engine speed reached 9900 rpm during the accelerated oxidation seeded fault. At the end of each engine run [approximately 90 minutes simulating take-off, flight with different engine speeds (with afterburners) then landing], oil samples were obtained for on-site oil analyses. The on-site analytical techniques used in this study were the RULER™ (% remaining antioxidant), the COBRA (oil degradation), and TAN (buildup of organic acids from oil oxidation) measurements.

Liquid OCM Sensor Evaluation

For the first evaluation of the on-line monitoring capabilities of the three OCM sensors, the liquid OCM readings taken at 8600 rpm and the on-site oil condition measurements of the oil samples obtained at the end of each engine run were plotted versus the engine run number in Figure 3. The results in Figure 3 show that the oil was stable for engine runs 1-3 due to the high oil make-up rate between engine runs, i.e., the RULER™ readings were ≈100% remaining antioxidant and the COBRA, TAN and OCM sensor measurements were constant. During runs 3–8, the oil additions were minimized allowing the antioxidants to deplete at an accelerated rate due to the minimized antioxidant replenishments. By the end of engine run 8, the % remaining antioxidant levels of the oils decreased to approximately 60% of the original concentration while the OCM, COBRA and TAN measurements remained constant (Figure 3) indicating that the oil was still stable but had reduced oxidation protection. The capability to detect rapid antioxidant depletion allows the RULER™ to detect accelerated oil oxidation prior to the on-line OCM sensors and off-line COBRA and TAN condition monitoring techniques.

For the accelerated oxidation seeded fault (runs 8-12 in Figure 3), the antioxidant levels decreased to 20% remaining antioxidant (RULER™) and the readouts of the liquid OCM sensors increased at a rapid rate for engine runs 8 and 9. The rate of increase for the liquid OCM sensor outputs slowed after engine run 10 similar to the liquid OCM outputs during the laboratory oxidation test in Figure 2. The COBRA and TAN measurements in Figure 3 begin to increase after engine run 10 indicating the oil was beginning to oxidize. The results in Figure 3 also show that the two liquid OCM sensors had similar results illustrating the reproducibility of the OCM sensors' oxidation detection capabilities eventhough their wire pairs had different sensitivities to oxidation (different wire lengths due to location restraints).

Therefore, the results in Figure 3 demonstrate that the liquid OCM sensors detected accelerated oil degradation during the seeded fault test, one engine run prior to the on-site COBRA and TAN analytical tests. . The results in Figure 3 also indicate that the on-site RULER™ instrument has the capability to predict accelerated oil oxidation at an early stage of oxidation, several engine runs prior to the on-line OCM and on-site COBRA and TAN techniques.

Vapor OCM Sensor Evaluation

In addition to the liquid OCM sensor readings, the continuous readouts of the vapor OCM sensor were recorded every 10 seconds for the accelerated oxidation seeded fault test (engine runs 8 – 12). The recorded vapor OCM readings were plotted versus engine time for each engine run in Figure 4. Engine time was added arbitrarily between runs to separate the vapor OCM sensor readings into specific engine runs as shown in Figure 4. The breather air temperature varied between 93 – 193 °C (200 - 380°F) in Figure 4as the engine speed varied between 4400 rpm up to 9800 rpm, respectively, during each engine run.

The results in Figure 4 show that the readouts of the vapor OCM sensor are constant during engine runs 7 – 10. At the ends of engine runs 9 and 10, the vapor OCM sensor readings rise sharply (Figure 4) indicative of degradation products accumulating onto the sensor's wires as the breather tube air temperature decreases. At the beginning of engine run 11, the vapor OCM sensor spiked and then decreased with increasing run time (Figure 4). Inspection of the vapor sensor after run 11 found that the degradation vapors had thinned the oil film between the sensors' wires resulting in the loss of the oil drop. A new drop of oil was added to the sensor wires. As in engine runs 9 and 10, the readouts of the oil replenished vapor OCM sensor increased rapidly at the end of run 12 (condensation of degradation products) as the breather air temperature decreased.

Visual inspection of the breather tube after engine run 12 determined the presence of coke on the inner walls of the vent tube. Consequently, the oil degradation detected by the vapor OCM sensor may be due to degradation products from the bulk oil or due to the degradation products from the further oxidation of the oil (reduced antioxidant concentration) condensing on the hot walls of the breather tube.

Regardless of the source of the oil degradation products, a vapor OCM sensor could be used to detect oil oxidation in the breather air of the JSF engine. Since the oil degradation products concentrate in the breather tube, the vapor OCM sensor would have the added advantage of being less oil type dependent than the liquid OCM sensors. Small changes in the sensor designs such as the addition of Teflon mesh (tested in Pratt&Whitney oil analysis laboratory) would ensure the performance of the vapor OCM sensor in degradation rich vapor environments. Placing sensors at different positions along the inside of the breather tube at selected surface temperatures would allow degradation vapors produced from the bulk oil and produced inside the breather tube to be monitored separately.

Effects of Engine Speed and Temperature on Oxidation Detection by Liquid OCM Sensors

To determine the effects of engine speed and oil temperature on the oxidation detection of the liquid OCM sensors, the readouts of the liquid OCM sensors were also recorded during two additional engine speeds (4400 and 9900 rpm) during the accelerated oxidation seeded fault test (engine runs 8 – 12). The ranges of the oil temperature readings during the five engine runs were 126 - 154°C (260 - 310°F) for 4400 rpm, 182 - 216°C (360 - 420°F) for 8600 rpm and 216 - 229 °C (420 - 445°F) for 9900 rpm. The readouts of the liquid OCM sensors at the different engine speeds were plotted versus engine run number in Figure 5 to determine the effects of engine speed/oil temperature on the oil degradation detection capabilities of the OCM sensors.

The results in Figure 5 indicate that during engine run 8, the engine speed/temperature had minimal effect on the readouts of the liquid OCM sensors. However, the readings for the liquid OCM sensors at the different engine speeds/temperatures diverged as the oil degraded during engine runs 9-12. The OCM readings increased the fastest at 9900 rpm and the slowest at 4400 rpm, respectively. Since the sensitivities of the OCM sensors to degradation increase with temperature, the OCM sensors at engine temperature would be expected to be more sensitive to oil oxidation than the room temperature measurements (COBRA) as seen in Figure 3.

Consequently, two methods can be used to detect oil oxidation with the liquid OCM sensors. The first method is to record the OCM sensor reading at a preset engine speed/temperature range (Figure 3). The second method is to record the difference between the readouts of the OCM sensor at two preset engine speeds (Figure 5). The second method would make the OCM oxidation detection capabilities independent of oil type, i.e., Generation II oil has higher original OCM reading than Generation I oil but rate of increase due to oxidation is similar. Therefore, increases in the absolute value and/or increases in the differences of the OCM sensor readings with temperature can be used to detect accelerated oil oxidation directly on-line. These results also indicate that the OCM readings in Figure 3 would have been even more sensitive to accelerated oxidation if the readings had been made at 9900 rpm instead of 8600 rpm.

Effects of Engine Speed and Temperature on Oxidation Detection by Vapor OCM Sensor

Since the vapor OCM readings in Figure 4 increase as the end of the engine runs as the breather tube air temperature decreases, the vapor OCM readings for a single engine run were plotted to better study the relationship between engine speed/air temperature and the OCM readings. The readings of the vapor OCM sensor and breather tube air temperature were plotted at 3 to 10 minute intervals versus the engine run time for engine run 8 in Figure 6. The breather air temperature varied between 93 – 193 °C (200 - 380°F) as the engine speed varied between 4400 rpm up to 9800 rpm, respectively, in Figure 6.

In contrast to the liquid OCM sensors, the readings of the vapor OCM sensor were inversely proportional to the engine speed/breather air temperature as shown in Figure 6. The vapor OCM sensor output increased with air temperature up to 149 - 160°C (300-320°F) and then decreased as the air temperature increased from 160 to 193°C (320 to 380°F). The vapor OCM sensor then showed the reverse trend as the breather air cooled. These results are in complete agreement with the vapor OCM sensor reading increases at the ends of engine runs 9, 10 and 12 in Figure 4, i.e., the vapor sensor readouts increased at the end of the engine run as the breather tube air cooled. It is speculated that the degradation products/oil vapors condense on the sensor wires at air temperatures below 160°C (320°F) causing the sensor readouts to increase and evaporate at air temperatures above 171°C (340°F) causing the sensor readouts to decrease.

Fire and Contamination Seeded Fault Tests

Of the planned seeded fault tests to initiate a bearing compartment fire and to introduce liquid contaminants into the engine stand lubrication system, only the fuel dilution test was accomplished. The spark plug installed into the bearing compartment failed to ignite the oil under a wide range of oil:air ratios. Due to their expected detrimental effects on oil-wetted components and the excellent laboratory results (Table 1), commercial hydraulic fluid, motor oil and antifreeze were not injected into the engine oil system to ensure the other mechanical seeded faults could be performed (1) prior to engine failure.

To test the capabilities of the liquid and vapor OCM sensors to detect fuel dilution (fuel leaks through breach in separating walls of the oil cooler), injections with Jet A fuel were made into the oil system using a modification of a selected oil return line. Although several fuel injections were made (designed to obtain a 1-2% fuel dilution), the liquid OCM readings remained constant in agreement with the laboratory results (Table 1). As expected, the readings of the vapor sensor in the breather tube showed a slight (less than 10%) decrease with the fuel injections.

Conclusions

The test results presented herein indicate that the OCM sensors, regardless of location, detected the oxidative degradation of the oil during the laboratory and JSF seeded fault engine tests in agreement with the off-line viscosity, COBRA and TAN techniques. The JSF engine results also indicate that the liquid OCM sensor outputs should be recorded at two or more selected engine speeds to minimize the oil formulation dependence of the sensors' oxidation detection capabilities. The results also indicate that the on-site RULER™ instrument could be used to detect the initiation of accelerated oil oxidation prior to detection by the on-line OCM sensors or off-line viscosity, COBRA and TAN condition monitoring techniques.

The laboratory results indicated that the vapor and liquid OCM sensors could detect oil fires within seconds of the fire initiation and contamination by other liquids above 1% within minutes of liquid addition. The laboratory and JSF engine tests indicated that only the vapor sensor had potential for detecting fuel leaks and the sensor's detection potential was dependent on locating an optimum location in the engine's breather tube.

Due to the success of the laboratory and JSF engine test stand results, the OCM sensors based on voltammetric techniques were selected as the oil condition monitoring sensors for the engine being developed by the JSF program.

Acknowledgements

The authors would like to thank Larry Sqrow and Doug Wolf of the University of Dayton Research Institute for constructing the sensor prototypes used in this study and Susan Brown, Wayne

Layman and Elizabeth Loveland of Pratt&Whitney for designing and overseeing the seeded fault JSF engine tests.

References

1. Humphrey, G.R., “Joint Strike Fighter—Analysis of Filter Debris by Energy Dispersive X-Ray Fluorescence," Technology Showcase 2000, JOAP International Condition Monitoring Conference Proceedings, Mobile, Alabama, PP 86 –98, April 2000.
2. Kauffman, R.E., "Development of a Remaining Useful Life of a Lubricant Evaluation Technique. Part III. Cyclic Voltammetric Techniques," Lub. Eng., 46,1, PP 709 – 716 (1990).
3. Kauffman, R.E. and Rhine, W.E., “Assessment of Remaining Lubricant Life,” Report No. AFWAL-TR-86-2024, November 1986.
4. Kauffman, R.E., "On-Line and Off-Line Measurements of Thermal and Oxidative Degradation in Used Lubrication Oils - Part I: Laboratory Evaluations," Lub. Eng., 51,11, pp 914-921 (1995).
5. Kauffman, R.E., “Rapid, Portable Voltammetric Techniques for Performing Antioxidant, Total Acid Number (TAN) and Total Base Number (TBN) Measurements," Lub. Eng., V54(1), pp.39 – 46 (1998).
6. Karasek, K.R., Feng, A.S. and Kauffman, R.E.,”Coke Formation from Aircraft Oils. Part II: Effects of Oil Formulation and Surface Composition," Tribology Transactions, 43, 4, pp 677 –681 (2000).

TABLE 1

OCM SENSOR READOUTS (V) FOR GENERATION I AND II OILS IN VIAL TESTS AT 150°C (302°F)

	GENERATION I				GENERATION II			
	% Contaminant				% Contaminant			
Contaminant	0	1	5	10	0	1	5	10
Hydraulic Fluid – Commercial	0.4	0.8 *	>5**	>5	0.9	1.3*	>5	>5
Hydraulic Fluid – Military	0.4	0.4	0.4	0.5	0.9	0.9	0.9	0.9
Motor Oil	0.4	0.6 *	1.3*	2.5*	0.9	1.0*	1.7*	2.4*
Antifreeze (Ethylene glycol)	0.4	0.7*	>5	>5	0.9	1.1*	>5	>5
Jet A Fuel	0.4	0.4	0.4	0.4	0.9	0.9	0.9	0.8

* Readings increase rapidly with time, >5 V in less than 30 minutes

** >5V: Off-scale