Energy Dispersive X-Ray Fluorescence Evaluation of Debris from F-18 Engine Oil Filters

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Abstract: Traditionally, the primary analytical instrument that monitors the "health" of mechanical oil systems in the U.S. Department of Defense (DoD) and Canadian Department of National Defence (CDND) is rotrode atomic emission spectroscopy (AES). The engine oil filter installed in the F-18 engine captures particles from the engine oil stream as small as 0.3 microns. This phenomenon renders AES surveillance of the F-18 engine oil system ineffective in detecting abnormal wear and impending engine failure. The debris that is extracted from the F-18 engine oil filter and captured on external filter media contains all the information necessary to detect abnormal wear and engine failure in the oil wetted sections of the F-18 engine. However, the debris is not in a suitable form to be analyzed by AES and requires considerable effort, time and hazardous chemicals to transform the debris into a form suitable for analysis by AES.[1] A method has been developed at the JOAP-TSC that utilizes Energy Dispersive X-Ray Fluorescence (EDXRF) to analyze the debris extracted from the engine oil filter and captured on filter media with little effort. Warning levels for elements have been statistically derived. The EDXRF Filter Debris Analysis (FDA) method provided 100 or more operating hours of advanced warning of engine failure. In addition, the EDXRF-FDA method can indicate the areas of wear in the engine. The Canadian Forces (CF) at Trenton in conjunction with GasTops LTD have developed and tested a prototype Deployable Filter Debris Analysis (DFDA) machine that automatically cleans F-18 engine oil filters. The instrument also segregates particles according to size and ferromagnetic properties. A comparison is made between the evaluations of the particles on the DFDA filter and EDXRF analysis of the same particulate samples.

Keywords: Energy Dispersive X-Ray Fluorescence, rotrode Atomic Emission Spectroscopy, Ferrography, wear condition.

Introduction: The JOAP-TSC has developed a method to analyze the debris from lubricant filters utilizing Energy Dispersive X-Ray Fluorescence (EDXRF). EDXRF is a mature technology however, the methodology and interpretation of the EDXRF signal developed at the JOAP-TSC is a novel, cutting edge approach to applying EDXRF technology. The EDXRF- Filter Debris Analysis (FDA) technique is able to characterize debris from the F404 engine oil system, an extraordinarily fine filtered lubricant system, and yields a condition monitoring technology that can predict failure 100 hours in advance.

Background: Rotrode atomic emission spectroscopy (AES) has been used as the primary analytical tool for monitoring the condition of weapon systems in the U.S. Department of Defense (DOD) and the Canadian Department of National Defence (CDND) for a number of years. The advantages of using AES include the following:

--- high numbers of samples can be analyzed per hour --- approximately 30 samples per hour

--- simultaneous determination of 15 elements in lubricants

--- no sample preparation required

However, AES has limitations:

--- can not detect particles larger than 8-10 microns [2],

--- matrix interference from the lubricant and

--- ineffective as a condition monitoring tool for lubricant systems equipped with 3 micron absolute filtration

Particle counting offers insights into monitoring the condition of weapon systems. Particle counting yields the following:

--- high numbers of samples can be analyzed per hour --- approximately 25,

--- distribution of particles by sizes,

--- particle populations in specific particle size ranges and

--- particulate loading of the system

Particulate analysis has limitations:

--- fine filtration is a problem,

--- no information about the elemental composition of the particles,

--- no information on the source of the wear particulates and

--- yields gross indication on the wear condition of the machine.

For particulate analysis to be successful, it must be used with a technology that can identify the elemental composition of the particles.

Ferrography is a methodology in which microscopic examination of particles is performed to classify the particles by particle morphology. It offers the analyst a method to do the following:

--- Classify the shapes of particles as originating from surfaces experiencing cutting, sliding, bearing, etc. wear and

--- can be related to wear modes experienced by the machinery.

Ferrography has disadvantages:

--- time per sample is high -- up to 1 hour per sample

--- requires intensive training,

--- labor intensive

--- fine filtration of lubricant systems is a problem for ferrography of a lubricant sample and

--- only empirical identification of particles can be achieved by observing the color of particles, heat treatment of particles to observe color changes associated with temperature and by employing other, chemical analytical methods to identify particle composition.

Fine filters are employed in lubricant systems to eliminate the recirculation of particles larger than 3 microns through the lubricant system. The particles are deemed harmful and the elimination of the particles by the fine filter, 3 microns and above, would greatly reduce the secondary wear these particles could induce. The inability of AES to monitor fine filtered lubricant systems and the subsequent removal of weapon systems equipped with fine filtration mean that other techniques, e.g., magnetic chip detectors, physical property analysis, etc., are employed in an attempt to monitor the wear condition of these weapon systems. Magnetic chip detectors are inefficient and are designed to only capture ferromagnetic particles. In the F404 engine, there are numerous alloys that are not ferromagnetic, but are critical to assessing the wear condition of the engine and in detecting the onset failure modes in the F404 engine. The success of a magnetic chip detector depends upon the size of the particle, morphology of the particle, strength of the magnetic field and the location of the chip detector.[3] Another approach to reducing failures is to change out components, modules, etc. based solely upon the amount of time the component or module is in operation. This can be an effective technique to reduce the number of failures. Even though all of these techniques are used to directly or indirectly monitor the condition of fine filtered systems - magnetic chip detectors and physical property analysis in conjunction with the removal of components or modules based upon the time they are in operation - a fine filtered lubricant system like the F404 engine still experiences failures.[4]

Table 1 depicts a few examples of weapon systems or components that had been monitored by AES, but were removed from monitoring due to fine filtration or because AES is ineffective in predicting the abnormal wear and onset of the failure modes of the weapon system. The F404 engine used in the F-18 aircraft is the focus of this study. The F404 is equipped with three separate lubricant systems - Airframe Mounted Accessory Drive (AMAD), engine lubricant system and Variable Engine Nozzle (VEN). Each system is lubricated with MIL-L-23699 synthetic oil and has an oil filter. The subject of the EDXRF study is the debris extracted from the engine oil filter.

SERVICE	EQUIPMENT MODEL	AIRCRAFT MODEL	ENGINE/ GEARBOX	REASON FOR REMOVAL FROM DoD OIL ANALYSIS PROGRAM
US NAVY	F404-GE-400	F-18 (JET)	ENGINE	AES NOT EFFECTIVE IN DETECTING FAILURES
US NAVY	T700-GE-401/401C	SH-60 (HELICOPTER) T700-GE-401/401C	ENGINE	3 MICRON FILTRATION
US ARMY		UH-60 (HELICOPTER)	ENGINE AND GEARBOXES	3 MICRON FILTRATION
US ARMY	T400-CP-400	AH-1 (HELICOPTER)	ENGINE	3 MICRON FILTRATION
US AIR FORCE	T56-A-14/16/425/427	C-130 (TURBOPROP)	ENGINE	AES NOT EFFECTIVE IN DETECTING FAILURES
US AIR FORCE	F404-GE-F1D2	F-117 (JET)	ENGINE	3 MICRON FILTRATION

Table 1. Components of Weapon Systems Removed from AES Surveillance.

Theory: An oil sample taken from a lubricant system is a "grab" sample. The analysis of an oil sample by AES represents the condition of the lubricant system at the time the oil sample is taken. The optimum choice for spacing of the oil samples is dependent upon the type of failures experienced in the past by the system being sampled. The assumption is that the wear condition of the machine in the intervals between samples is predicted by the oil samples taken at specific intervals. Ideally, oil sampling intervals are adjusted to reflect the findings of the failure analyses for the weapon system and to detect the onset of abnormal wear and the onset of failure modes. The oil sampling intervals must be close. This is why a high frequency of sampling must be done to monitor a machine with AES.

The debris extracted from an oil filter represents an accumulation of information about the lubricant system for a period of time; e.g., F404 engine oil filters are removed every 200 hours of operation. The debris accumulated by the filter represents 200 hours of wear. No assumptions need to be made about the wear condition of the engine in the 200 hour interval between filter removals. The wear history has been accumulated by the engine oil filter. The filter in the lubricant system of the F404 engine is a 10 micron nominal, 15 micron absolute filter. This does not qualify it as a fine filter. However, the MIL-L-23699 synthetic oil becomes slightly carbonized by the hot sections of the engine. The slightly carbonized oil coats the oil filter and transforms it into an extremely fine filtering device. Particles as small as 0.3 micron are captured by the filter.

Fine filtered systems present no problems for analysis by the EDXRF-FDA method. EDXRF is the type of x-ray measurement made in this study. EDXRF spectroscopy is a non-destructive determination of elemental composition and provides simultaneous analysis for elements in a sample. A sample is exposed to x-ray photons emitted from an x-ray tube. The sample absorbs some of the x-rays and then emits x-rays of its own in a process called fluorescence. The resulting fluorescent x-rays are characteristic of the elements in the sample. The EDXRF instrument used in this study incorporates a lithium drifted silicon detector to detect the fluorescent x-ray photons emitted from the elements in the sample. The detector absorbs the x-rays individually and produces a pulse with a voltage proportional to the x-ray energy of the photon. Electronic separation of the pulses according to their height yields a photon energy spectrum,[5] a process known as energy dispersion. This spectrum contains the information identifying which elements are present in the sample and the quantity of each element in the sample.

The basic atomic mechanism for producing x-ray fluorescence may be understood by considering the interaction of the incoming x-ray with the atomic electrons. Electrons are oriented around elements in energy shells. The electrons of interest in EDXRF analysis are in the K, L and M inner energy shells.[6] The K electrons are in the energy shell closest to the nucleus and are the most tightly bound electrons in the atom. An x-ray photon emitted from the source, an x-ray tube, can impinge upon an element's electron and cause the ejection of the electron, leaving behind an orbital vacancy. An electron from another energy shell can move into this vacancy with the emission of an x-ray photon, a process called fluorescence. The emitted x-ray photon carries an energy equal to the difference in the binding energies of the two energy shells, e.g. the more loosely bound outer shell binding energy is subtracted from the binding energy of the more tightly bound inner shell.[6] The value of the emitted x-ray photon's energy is characteristic of the element. This is a simplified explanation of the process and omits other possible interactions, but is quite sufficient for a basic understanding of the relevant processes.

The EDXRF analysis of a large piece, an inch or more in diameter, of metal alloy with a specific composition of elements is straightforward. Thickness is the important dimension for macroscopic samples, all dimensions are important for small particles less than approximately 100 microns. The percentages reported by an EDXRF spectrometer analysis can be related to the concentration of each element in the alloy. However, the debris from oil filters is composed of metal particles from many different alloys. The percentage of a given element in this mixture of several alloys does not have the same meaning as the percentage of the element in a single alloy and is not directly related to the elemental concentrations in any of the individual particles. The elemental analysis of wear particulates by EDXRF, for the purposes of condition monitoring, can be carried out quite effectively by a statistical analysis of the percentages alone without addressing the theoretically complicated issue of concentration for these particulates.

The particulate sample is also different from the bulk sample. A sufficiently thin sample will produce fewer total fluorescent x-rays, although the average number of fluorescent x-rays per atom will be greater than for a bulk sample. The x-ray spectral data was analyzed by an approach called thin film analysis. Thin film analysis applies where all of the atoms that compose the film transmit essentially all the fluorescent x-rays, which occurs for films and debris samples having a maximum thickness of about 1 micron. [7] The real samples of wear particulates prepared in this application are a mixture of infinitely thin films and intermediate thickness films (that fall between thick films and infinitely thin films). Such thickness effects, when discussed in terms of particulate samples, are often referred to as particle size effects. Fortunately, the effect of particle size is to increase the measurement sensitivity for smaller particles and is accounted for in the statistical analysis of the data.

Intermediate thickness films, large particles, and bulk samples of alloys can exhibit matrix effects, where the fluorescent intensity radiated, per atom of a given element, depends upon the alloy composition. This complication can be handled with a Fundamental Parameters (FP) calculation. The FP calculation produces the matrix correction factors (alphas) and the estimate of sample thickness. The FP calculation estimates the thickness by comparing measured x-ray intensities to theoretical x-ray intensities expected from a sample of a given thickness. The FP calculation goes through iterations until the program finds the thickness which matches the theoretical x-ray intensities with the measured x-ray intensities. Once the thickness is found, the matrix correction factors (alphas) are calculated for the unknown sample.[7] Once the FP analysis is complete, the corrected data may be analyzed and compared with the engine history.

Application: The F404 engine is a modular engine. The debris extracted from the F404 oil filter is deposited on a 1 micron polycarbonate filter. The procedure is too detailed to present here. [8] The debris is analyzed on a Spectrace 6000 EDXRF spectrometer. In this study, 189 filters were analyzed. For each filter, EDXRF index values were calculated for each of the 18 elements analyzed by the spectrometer. Two index values were calculated for use in comparing filter content with engine condition.

To calculate the Element Percent Index (EPI), the fluorescent x-ray counts (intensity) recorded by the spectrometer for each element are divided by the total counts measured during the time of the analysis of the sample. The readout for each element is expressed as a percentage. This percentage is normalized to 100%. In this study, the percent of each of the elements reported is treated only as a percent of the total counts for all elements accumulated for that filter during the period of analysis. The levels of significance were set by a statistical analysis of the entire set of normalized percentage data, for that element, from all available filters. Each element has 189 normalized percentage results, one per filter. The mean and standard deviation for each element's normalized percentage is calculated. A percentage exceeding the value of the mean plus three standard deviations is considered an outlier. Percentages that are outliers are labeled with a 5 level of significance. The outlier values represent the highest percentage values of an element in the oil filter debris. The mean and standard deviation are recalculated omitting the outliers. Levels of significance are assigned to each recalculated percentage. If the percent of the element is less than or equal to the (recalculated) mean plus one (recalculated) standard deviation, the percent for the element is assigned a level of significance of 1. If the percent for the element is greater than the mean plus 1 standard deviation and less than or equal to the mean plus 2 standard deviations, the percent for the element is assigned a level of significance of 2. If the percent for the element is greater than the mean plus 2 standard deviations and less than or equal to 3 standard deviations, the percent for the element is assigned a level of significance of 3. If the percent for the element is greater than the mean plus 3 standard deviations, the percent for the element is assigned a level of significance of 4. The level of significance values just described are defined as the EPI.

In this way, the statistical levels of significance for each sample's elements are derived from the EDXRF spectrometer's normalized reported percentages. The more an element's normalized percentage deviates positively from the mean, the higher the level of significance assigned to the element's percentage, e.g. 1, 2, 3, 4 or 5. A level of significance for an element of 1 or less is considered "Normal" wear. A level of significance of 4 or 5 signifies an element's percentage had a very large positive deviation from the mean, suggesting advanced, detrimental wear.

The Element Thickness Index (ETI) is calculated in the same fashion as the EPI, but the normalized percentages are first all multiplied by the thickness value obtained from the FP calculation for that filter sample. The ETI was developed to take into account the total amount of material in the sample, while also characterizing the significance of the element's presence in a sample. Again, levels of significance are attached to each element's thickness index. The levels of significance of each element's thickness index are derived by the same process as the EPI levels of significance.

This empirical approach to developing a set of indexes allows for the identification of the elements present and the calculation of statistical levels of significance for each element. The mere presence of an element is not enough to indicate a problem, unless the EPI or ETI for that element is abnormally large.

A shorthand notation was developed for use in tabulating the index values. The EPI notation is composed of the element's chemical symbol and a numerical designation of 2, 3, 4 or 5 followed by a "P", e.g. Ti-5P for titanium with a significance level of 5. The ETI notation has the element's chemical symbol and a numerical designation of 2, 3, 4 or 5 followed by a "T", e.g. Ti-5T.

The EPI and ETI values for all 189 filters were computed. EDXRF guidelines were developed after a detailed consideration of comparisons between the EDXRF results and the metallurgy of the F404 engine. The EPI and ETI values which satisfy the guidelines are then used to identify the engine modules which are producing the wear particles. The F404 is a modular engine. Data tested by the above guidelines are then used to identify the source(s) of the analyzed wear particulates, Table 2, modules and and certain components within the module.

Elements	Level	Oil Pump	Oil Tank	AGB	F	HPC	HPT	LPT
Al	3,4,5	YES	YES	YES	YES	NO	NO	NO
Cu+Pb+Zn	2,3,4,5	YES	NO	NO	NO	NO	NO	NO
Fe	2,3,4,5	NO	NO	YES	YES	YES	YES	YES
Fe+V	2,3,4,5	NO	NO	YES	YES	YES	YES	YES
Ti	2,3,4,5	NO	NO	YES	YES	YES	NO	NO
Ti+V	2,3,4,5	NO	NO	YES	YES	YES	NO	NO
Ti+Sn	2,3,4,5	NO	NO	NO	YES	YES	NO	NO
Ti+Sn+V	2,3,4,5	NO	NO	NO	YES	YES	NO	NO
Ni	2,3,4,5	NO	NO	NO	YES	YES	NO	YES
Ni+Nb	2,3,4,5	NO	NO	YES	YES	YES	YES	YES
Co+Mo	2,3,4,5	NO	NO	NO	YES	YES	NO	NO
Cd*	2,3,4,5	NO	NO	NO	NO	YES	NO	YES
W*	2,3,4,5	NO	NO	NO	NO	YES	YES	YES
Ag*	2,3,4,5	NO	NO	YES	YES	YES	YES	YES
Si	3,4,5		DIRT	CON	TA	MIN	ATI	ON

*Elements considered if Fe, Ni and/or Ti are present.

Table 2. EDXRF-FDA Decision Matrix for Sources of Elements.

The EDXRF decision scheme can be easily adapted to the existing US Navy and Army oil analysis software, Oil Analysis Standard Interservice System (OASIS). This will provide an evaluation platform already familiar to field personnel.

Discussion of Results: To determine the critical metals in the F404 engine, a complete breakdown of the engine oil system components and alloy composition is required. From this information, a clear understanding is obtained for the probable sources of the elements. In parallel, the elements found by AES analysis of oil samples must also use the metallurgical composition of the components in an oil system to deduce the probable sources of the elements. The US Navy Aircraft Engine Maintenance System (AEMS) provides information about F404 engine maintenance. AEMS provides information about when maintenance was performed on an engine, the reason for the maintenance and the module or modules that were replaced. Using the AEMS information as a "standard" for correlating EDXRF-FDA results to AEMS data, a comparison was made between the EDXRF-FDA results and the AEMS information. The true measure of a condition monitoring technique and technology is its capability to give ample warning of an impending failure. Remarkably, this EDXRF-FDA technique predicted engine failure in every case that engine failure occurred. In this study, 27 oil filters representing 24 engines experienced failures of engine modules associated with the engine oil system. Twelve oil filters were removed prior to engine failure. Fifteen oil filters represent engine failures that coincided with the removal of the filter. In each case, this EDXRF-FDA technique:

(1) detected that advanced, detrimental wear was occurring,
(2) identified the elements in the wear debris, and
(3) correlated those elements with the module that failed.

The metallurgy of the F404 engine frequently eliminates some modules from consideration, while narrowing the scope to a few modules or even to a single module. This capability of the EDXRF-FDA method, to indicate the F404 module or modules that are the sources of the elements, is an additional feature above what is required of a condition monitoring method -- predicting impending failure.

An example will demonstrate the capability of the EDXRF-FDA method. Two oil filters, samples 1 and 2 respectively, were removed from F404 engine serial number 310656 at different times. Sample 1 engine oil filter was removed at 2418 Hours Since New (HSN). The elements of concern and their respective levels of significance are; Ti-4P, Ti-2T, V-4P, W-2P, Al-3P. This combination of metals, Ti, V and W, can originate from the HPC. Sample 2 engine oil filter was removed at 2515 HSN. The elements of concern and their respective levels of significance are; Ti-4P, V-4P, Sn-4P and Al-5P. Sample 2 indicates large and abnormal amounts of Ti, V and Sn being generated. The Ti, V and Sn indicate the wearing of Ti alloys. The abnormal amount of Al indicates a housing could be involved or severe corrosion exists. At 2660 HSN, AEMS indicated that engine serial number 310656 experienced an HPC failure. Sample 1 at 2418 HSN, indicated the HPC could be the source of the elements. The subsequent sample also confirmed the HPC was the source of the elements. This EDXRF-FDA method indicated the HPC was the source of the elevated wear debris 142 operating hours before the HPC failed.

Deployable Filter Debris Analysis (DFDA): The Canadian Forces (CF) at Trenton in conjunction with GasTops LTD have developed and tested a prototype Deployable Filter Debris Analysis (DFDA) machine that automatically cleans F-18 engine oil filters. The instrument also segregates particles according to their size and ferromagnetic properties. Four filters for the particles extracted from each F404 lubricant filter were prepared by the DFDA as follows:

-- a filter with ferromagnetic particles 20 micron to <200 micron (20 micron F),
-- a filter with ferromagnetic particles 200 micron and greater (200 micron F),
-- a filter with nonferromagnetic particles 20 to <200 microns (20 micron NF),
-- and a filter with nonferromagnetic particles 200 microns and greater (200 micron NF).

The filters were analyzed by CF Trenton using ferrography terminology to identify the type of wear.[1] Ferrography is a method that separates particles from the oil by passing an oil stream down a glass substrate that is placed in a magnetic field. The size, morphology and color of the particles can be observed with the aid of a microscope. The information gathered from this analysis yields a concept of the type of wear occurring in the system. The pore size of the filters that captured the particles in the DFDA machine are not the same as the pore size, 1 micron, used to develop the EDXRF-FDA method. A new EDXRF-FDA database had to be developed to characterize the significance of the wear. The number of samples are limited, however some examples will demonstrate the correlation between the CF Trenton analysis of the DFDA filters and EDXRF-FDA method. EDXRF-FDA method will also yield considerably more detail about the composition of the particles on the DFDA filters and their relative significance. No maintenance data or pertinent information was available about the engines, therefore a correlation between actual maintenance performed on an engine and the EDXRF-FDA method and the CF Trenton filter analysis method could not be done.

An engine oil filter was taken from a U.S. F-18, F404 engine and labeled F20 USA. The DFDA machine produced a filter labeled F20 USA21 NF. The EDXRF-FDA elements and levels of significance and the CF Trenton filter evaluation are as follows:

SAMPLE NAME	ELEMENTS AND LEVEL OF SIGNIFICANCE	MODULES INDICATED	CF TRENTON DFDA FILTER ANALYSIS
F20 USA21NF	Fe-2P, Ag-3P, Al-5T, Ti-5T, Cr-2T, Fe-5T, Zn-3T, Cu-4T, Mo-5T, Ag-5T, Sn-2T	Ag Plating, Bearing Wear and Ti with Sn Alloy - F,HPC; High Al - Oil Tank, Oil Pump, AGB, F.	Heavy amounts of Al cutting and gear wear and what appears to be carbon particles.

The CF Trenton filter analysis of the nonferrous debris captured on the 20 micron filter states that they observed heavy amounts of Al cutting and gear wear. The elements and levels of significance that are important to the evaluation of the condition of the engine in this EDXRF-FDA method are: Fe-2P, Ag-3P, Al-5T, Ti-5T, Fe-5T, Ag-5T and Sn-2T. The EDXRF-FDA method agrees that there is a very significant amount of particles or loading of debris composed of Al on the filter as designated by Al-5T. The 5 level of significance is the highest level signifying an extraordinary value, an outlier, in the analysis of the data. The "T" means that this value is taken from the loading of the filter. The heavy amount of gear wear particles observed by CF Trenton signifies Fe and the EDXRF-FDA method agrees about the significance of the presence of Fe by the Fe-2P and Fe-5T ratings. The EDXRF-FDA method also detects significant levels of Ti alloy that was not observed by the CF Trenton analysis of the filter. Ti is one of the three primary metals that the EDXRF-FDA evaluation of the F404 engine oil filter debris is based upon. Another metal, Ag is seen by the EDXRF-FDA method, but is not observed in the CF Trenton evaluation. Also, a key indicator element that could not be observed by the CF Trenton analysis, Sn, is present. The modules indicated by the elements detected by the EDXRF-FDA method, Fe-2P, Ag-3P, Al-5T, Ti-5T, Fe-5T, Ag-5T and Sn-2T, indicate that the Fan and High Pressure Compressor can be the sources of this combination of elements. The presence of the Al indicates the Oil Tank, Oil Pump, Accessory Gearbox, Fan could be the source of the Al. The presence of Al must be treated as a unique case. A failure mode in the F404 engine is initiated by the introduction of moisture through an intake vent. The moisture reacts with the synthetic oil, MIL-L-23699, and causes the synthetic oil to dissociate or chemically convert to the reactants that produce the synthetic oil, organic acids and the organic polyol. The acids can easily corrode the Al alloys present in the Oil Tank, Oil Pump, Accessory Gearbox, and Fan sections of the engine. Corrosion induced by the intrusion of water into the F404 engine oil system has been attributed as one of the mechanisms to induce bearing failure in the accessory gearbox.[9] The possibility of Al being generated by corrosion resulted in the level of significance for Al being 3, 4, or 5 to be considered in an evaluation. However, damage to a housing must be considered at a level of significance for Al of 4 or 5. The EDXRF-FDA method offers areas of the engine as sources for the elements whereas the CF Trenton filter analysis method can not.

The second 20 micron filter prepared from the debris extracted from the F20 engine oil filter is labeled F20 USA 21F. The EDXRF-FDA elements and levels of significance and the CF Trenton filter evaluation are as follows:

SAMPLE NAME	ELEMENTS AND LEVEL OF SIGNIFICANCE	MODULES INDICATED	CF TRENTON DFDA FILTER ANALYSIS
F20 USA 21F	V-2P, Fe-3P, Mo-3P, V-5T, Cr-3T, Fe-4T, Ag-2T, Mo-5T	Ag Plating, Bearing Wear - AGB, F, HPC, HPT, LPT.	Heavy amounts of Fe laminar, sliding and gear wear and what appears to be carbon particles.

The CF Trenton filter analysis of the ferrous debris captured on the 20 micron filter states that they observed heavy amounts of Fe laminar, sliding and gear wear. The EDXRF-FDA method agrees that there are heavy amounts of Fe wear particles represented by the Fe-3P and Fe-4T levels. The CF Trenton filter analysis did not observe the Ag present on the filter. The presence of Fe can be attributed to the Accessory Gearbox, Fan, High Pressure Compressor, High Pressure Turbine and Low Pressure Turbine. The EDXRF-FDA method offers sources for the elements whereas the CF Trenton filter analysis method can not.

In the above examples, empirical agreement exists between the CF Trenton filter analysis method and the EDXRF-FDA method about the elements seen on a filter. However, differences between the methods will result because of the ability of the EDXRF-FDA method to discern the elements present in the particles on the filter. It can not be expected that microscopic observation of the color of particles alone is sufficiently sensitive to discern all the elements present on the filter. Several types of alloys have identical colors, i.e., Ag, Al, Mg, and increase the possibility of mistaking one type of alloy for the other unless lengthy, time consuming assays are done on each particle. Two elements, Ti and Ni, are not mentioned in any of the CF Trenton filter evaluations, but the EDXRF-FDA method definitely discerned significant levels of Ti and Ni in various samples. The observation of particles on filters by microscopic examination has advantages, but it is well beyond the scope of the method to be able to identify the elements composing the particles. The EDXRF-FDA method can discern the relative abundances of the elements composing the particles, assess the significance of the elements and indicate the possible sources of the wear in the engine based upon the combination of the elements from the metallurgy of the engine oil system.

The particles present on the 20 micron filters could not be easily analyzed by AES. Simply suspending the particles in oil would not suffice for AES analysis. The particles can be dissolved by strong acids and can be analyzed by Atomic Absorption.[2] Atomic Absorption was phased out of the DoD oil analysis program as a field instrument and is not used in the field in the CF. The particles can be dissolved by strong acids and resuspended in a medium suitable for analysis by AES, e.g., mineral oil.[10] This procedure for using AES to measure particulate debris from F404 engine oil filters was deemed unsuitable for use in the field by CF military personnel.[1]

Conclusions: In the DoD and CF, F404 engine oil filters are changed every 200 hours. The oil filter that is removed is simply discarded. The analysis of debris from in-line oil filters yields a cumulative history of the wear the engine is experiencing. The EDXRF-FDA method described in this paper yields the relative abundances of each element, builds a database, statistically analyzes the database and sets limits based upon the database.

The other methods AES, particle counting and ferrography depend upon frequent grab samples to detect the particles that will indicate the onset of abnormal wear and/or failure. The grab sample only indicates the condition of the machine when the sample is taken. The frequency of sampling is dictated by the types of failures that are occurring in the machine. In the case of AES, it is assumed that the failure modes will generate sufficient quantities of particles in the size range that AES can detect within the frequency of sampling. This is why sampling for AES analysis requires small intervals between samples and the sampling frequency must be high.

Fine filters severely limit the use of AES, particle counting and conventional ferrography to monitor the wear condition of the machine. Numerous weapon systems have been removed from AES monitoring because of fine filtration and the inability of AES to detect abnormal wear and/or failures in weapon systems. In the case of the F404 engine, the effective ultra fine filtration of the engine oil system eliminates the use of AES in monitoring the wear condition of the machine. Monitoring of the wear condition of the F404 engine oil system is relegated to magnetic chip detectors and replacement of components/modules in the lubricant system based upon the hours of operation. However, F404 engines still experience failures. The EDXRF-FDA method represents the condition monitoring capability required to detect the onset of abnormal wear and the onset of failure modes in the F404 engine.

The EDXRF-FDA method is a common sense approach to monitoring the wear condition of the F404 engine and would give the DOD and CF a cutting edge, nondestructive technology that field personnel can easily use. The long lead times given by the EDXRF-FDA method before a failure occurs would allow for a significant reduction in the frequency of sampling a machine. Typically, for a jet turbine engine an oil sample is taken every 10 operating hours. For example, if the engine oil filter for the EDXRF-FDA method is taken every 200 operating hours then 20 oil samples would have to be taken in the same interval. In this example, the EDXRF-FDA method offers a reduction of 19 samples.

The DFDA machine demonstrates great potential in automating the preparation of samples for EDXRF analysis. However, more F404 engine oil filters need to be cleaned and analyzed by the EDXRF-FDA method to demonstrate the potential application to the EDXRF-FDA condition monitoring process.

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