Condition Monitoring of Aerospace Hydraulic and Lubrication Systems *via* Filter Debris Analysis

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Abstract:

Evaluation of filter debris as a diagnostic tool to monitor the condition of fluid systems has gained prominence over the last decade, and techniques such as scanning electron microscope coupled with X-ray emission spectroscopy (SEM/EDX), and X-ray fluorescence (XRF) spectroscopy have been employed to determine the chemical composition of engine lube filter debris, necessary for diagnosis of potential lube system component wear modes, and even some modes of fluid degradation. In this paper, the use of a diagnostic filter system, comprised of a diagnostic filter element having a pull-out diagnostic layer, termed the Dirt Alert® diagnostic layer, and a custom designed contaminant analyzer, that allows for convenient on-site analysis of the debris captured on the diagnostic layer, is discussed. The analysis of the chemical composition of filter debris is accomplished *via* X-ray fluorescence spectroscopy, utilizing the contaminant analyzer, currently in the Beta prototype testing stage.

Results from the evaluation of the Beta prototype of the contaminant analyzer with Dirt Alert filter elements loaded with contaminant in the laboratory, with Dirt Alert diagnostic layers from aircraft hydraulic systems, and with filter elements from a helicopter gear box lubrication system, are presented in this paper. The results show that the diagnostic filter system is a viable concept and can be developed to provide a suitable, convenient on-site vehicle for fluid system condition monitoring.

Introduction:

The fluid acts as a repository for component wear debris, fluid break down products, and contaminant ingressed from outside the system. Thus, the evaluation of debris in hydraulic, lubrication, and other fluid systems can provide valuable information about abnormal contaminant ingression, accelerated component wear or impending component failure, and fluid break down. While a number of techniques have been developed over the years for monitoring debris in aircraft engine lubrication systems [1] and aircraft hydraulic systems, filter debris monitoring has gained increasing acceptance over the last decade or so, and numerous studies of evaluation of aircraft engine lube system filter debris, including debris morphology and chemical composition *via* X-ray fluorescence (XRF) spectroscopy or energy dispersive X-ray emission spectroscopy (EDX), have been reported in the literature [2 – 6]. The advantages of the filter element as a diagnostic tool include: the full-flow nature of the filter element, allowing for all debris in the fluid system to pass through the filter element, the coherent surface for capturing fluid system debris efficiently, over time, resulting in a high concentration of debris compared to debris in the fluid or in magnetic plugs/chip detectors, and the fact that debris of all types (metallic and non-metallic) are retained by the filter element.

In current methods for filter debris analysis, the debris is removed from the filter element on to an analysis membrane by back flushing with solvent or solvent air/mixture, ultrasonic removal in a solvent, or by flushing debris off the filter element with a solvent. The debris collected on the analysis membrane is evaluated for amount, size distribution, and morphology, and the chemical elemental composition is determined either by X-ray fluorescence (XRF) spectroscopy or scanning electron microscope/X-ray emission spectroscopy (SEM/EDX), and by infrared spectroscopy (IR) for organic contaminant.

The requirements for an effective debris characterization process include: simple logistics and on-site analysis of the filter debris, minimum operator intervention and 'wet chemistry', reliable instrumentation/techniques, and an expert system for diagnosis/corrective action that allows for decision making at the operating level. In this paper, a diagnostic filter system is discussed that allows for direct evaluation of debris collected on a diagnostic layer built into the filter element, or on the filtration medium. The chemical composition of the collected debris is determined *via* XRF spectroscopy.

Diagnostic Filter System:

The diagnostic filter system is comprised of two components: (1) The Dirt Alert® filter element, which features a pull-out diagnostic layer, and (2) The contaminant analyzer for the evaluation of the chemical composition of the filter debris *via* XRF spectroscopy. Figure 1 depicts a Dirt Alert filter element with the pull-out diagnostic layer.

Figure 1. Dirt Alert® Filter Element with Diagnostic Layer.

The diagnostic layer can be easily removed on-site for convenient visual inspection of the captured debris. The porosity of the diagnostic layer can be adjusted, within the constraints of the regular filtration medium pack, so that the captured debris is appropriate for diagnostics. In the current configuration, the Dirt Alert diagnostic layer exhibits a particle capture efficiency of over 95 % for particles 70 µm, or larger, in size, and an efficiency of about 60 % for particles 30 µm, or larger, in size.

The contaminant analyzer provides semi-quantitative information about key chemical elements of interest, and is designed to be a rugged device for field use. A Beta prototype of the contaminant analyzer, depicted in Figure 2, accepts analysis membranes, sections of Dirt Alert diagnostic layers, and filtration media. No solvents or 'wet chemistry' is required. Since the analysis is non-destructive, additional evaluation of the filter debris may be performed. It should be noted that the Beta prototype was fabricated with existing hardware and does not represent the final envelope/configuration; the final envelope is expected to be significantly smaller.

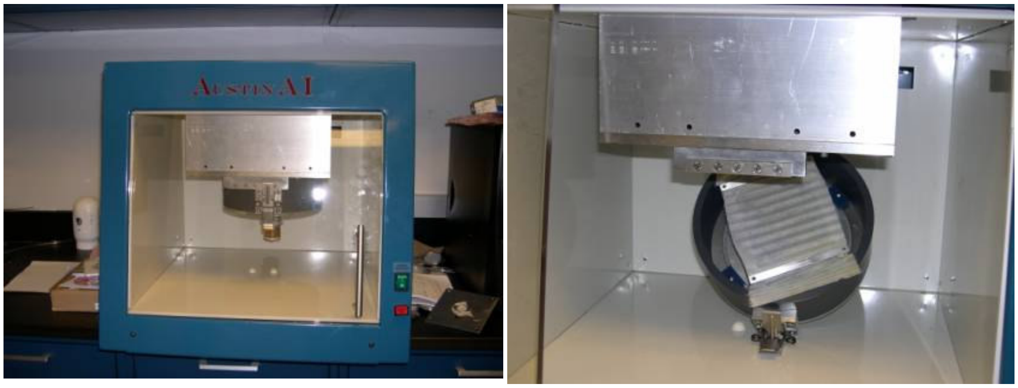


Figure 2. Beta Prototype Of Contaminant Analyzer Showing a Section of Dirt Alert Diagnostic Layer Installed for Analysis(Figure On The Right).

A preliminary evaluation of the Beta prototype was conducted, utilizing Dirt Alert diagnostic layers and filtration media from filter elements from the field, and Dirt Alert filter elements artificially contaminated in the laboratory. The evaluation and results are discussed below.

Calibration Considerations:

Since XRF spectroscopy is sensitive to the size distribution of the analyzed debris as well as matrix effects, the calibration of the XRF analyzer is important from the point of view of semi-quantitative debris analysis. Two types of calibration materials were evaluated in this study:
(1) Micromatter standards, fine uniform solid calibrants, typically used as calibration standards for XRF spectroscopy, and (2) Metal powders, metal oxides, or other chemical compounds, with a broader size distribution that may be more representative of contamination in the field.

Homogeneous suspensions of the calibration materials were prepared in MIL-H-5606 hydraulic fluid at different concentrations, in the range 0.5 mg/l – 20 mg/l, and drawn down through 0.8 µm rated cellulose acetate analysis membranes to provide a uniform dispersion of the calibration material on the analysis membranes. These membranes were then subjected to XRF analysis. The average of the measured XRF intensities in three different regions in each analysis membrane was taken as a representative value for the concentration of the chemical element. Figure 4 shows plots of chemical element concentration (in µg/cm^2) *vs* average intensity for the chemical elements investigated. Also included for comparison are the corresponding plots for the Micromatter standards.

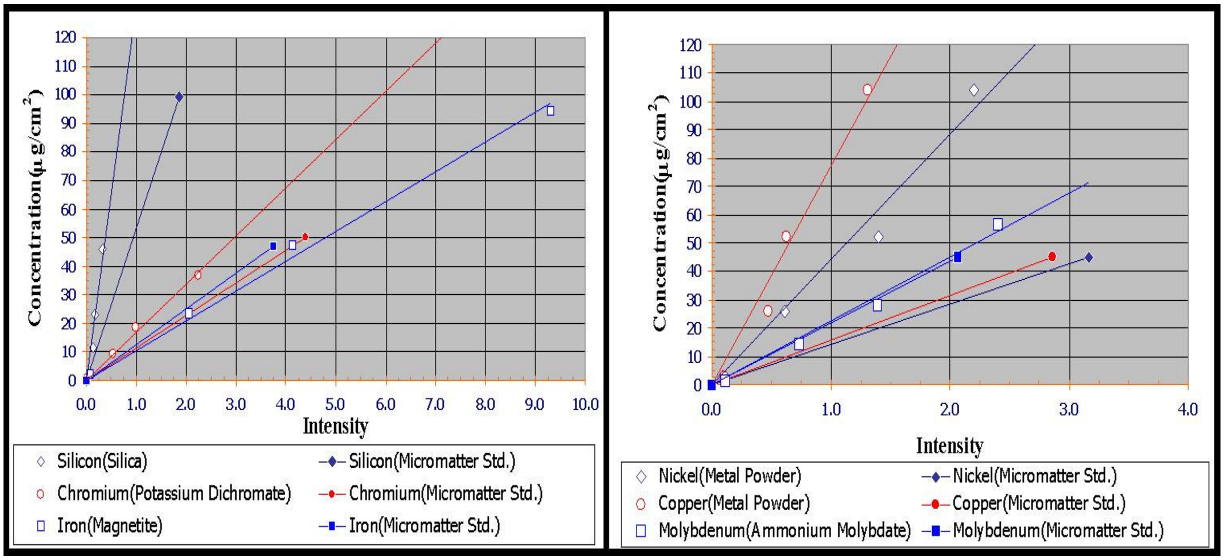


Figure 3. Comparison of the Calibration Based On Micromatter Standards to the Calibration Based on Granular Metal Powders or Oxides, or Other Chemical Compounds.

The calibration curves for iron and molybdenum were similar for both the Micromatter standards and the granular powders, however the calibration curves for the other chemical elements, Figure 3, differed significantly. Thus, the concentrations for these elements would differ considerably, based on the choice of calibration standard. For the present work, it was decided to retain the traditional calibration method employing the Micromatter standards since additional work is required to determine the appropriate calibration for evaluating field samples, and will be undertaken in the future.

Evaluation of Dirt Alert Filter Elements Artificially Contaminated in the Laboratory:

For this phase of the program, Dirt Alert filter elements, corresponding to an engine lube application, with a filtration rating of 30 µm for the filtration medium, were utilized. The four Dirt Alert Filter elements, designated S/N 1 – S/N 4, were loaded with four different mixtures of contaminants (chemical elements), shown in Table I, below.

A test set up that allows for a recirculating flow of MIL-PRF-23699 fluid at 100 °F and a flow rate of 34 GPM, designed to simulate the engine lube system parameters, was utilized for loading the four filter elements. Figure 4 depicts a schematic of the test set-up for contaminant loading of the filter elements. Each contaminant was added, sequentially, to the reservoir, in solid form, and allowed to recirculate through the filter element for about 20 minutes. Two regular filter elements, i.e., without Dirt Alert diagnostic layers but otherwise identical in construction, were loaded with contaminant mixtures corresponding to S/N 1 and S/N 4, respectively, as a control (see below).

Subsequent to the contaminant loading, the Dirt Alert diagnostic layers from the four filter elements were removed (pulled out), and three sections (beginning, middle, and end) were evaluated with the XRF contaminant analyzer. Three areas in each section were evaluated. For comparison, SEM/EDX evaluation of the three sections of each diagnostic layer was also performed.

Table I. Composition of Contaminant Mixtures Used to Contaminate Dirt Alert Filter Elements

Contaminant (Chemical Element)	**Contaminant Mass (g)**			
	Filter Element S/N 1	**Filter Element S/N 2**	**Filter Element S/N 3**	**Filter Element S/N 4**
Aluminum oxide (Al)	0.400	1.600	1.000	0.500
Chromium powder (Cr)	0.100	0.400	0.025	0.750
Copper powder (Cu)	0.100	0.400	0.050	0.950
Magnetite (Fe)	0.400	1.600	0.750	1.000
Magnesium powder (Mg)	0.200	0.800	0.250	0.450
Molybdenum powder (Mo)	0.020	0.080	0.000	0.200
Nickel oxide (Ni)	0.100	0.400	0.125	1.200
ISO Fine Test Dust (Si)	0.100	0.400	0.060	0.100
Zinc powder (Zn)	0.100	0.400	0.025	0.250

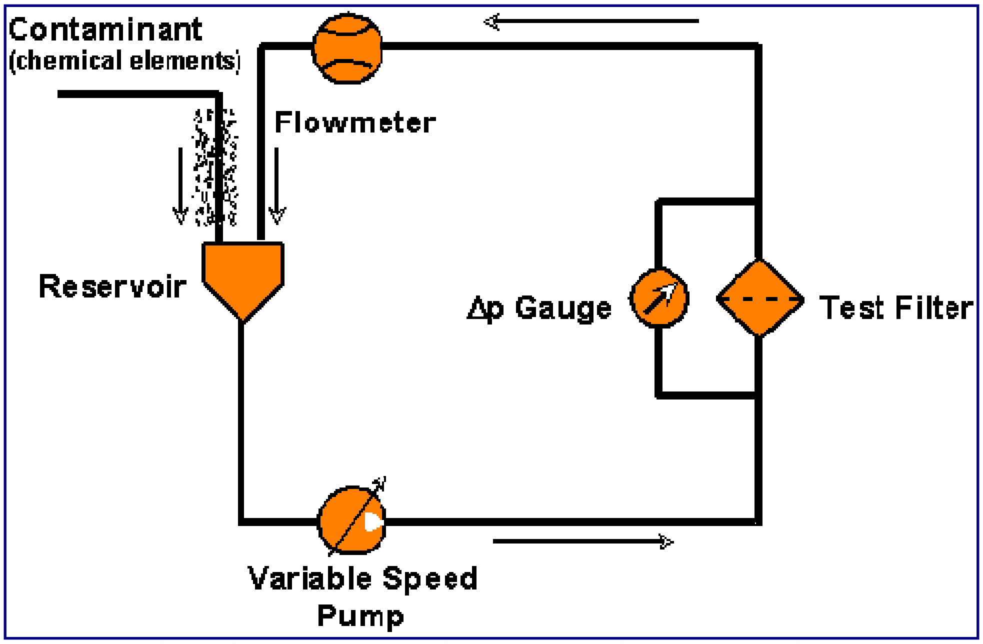


Figure 4. Simplified Schematic of Test Set-up for Loading Dirt Alert Filter Elements with Contaminant Mixtures.

Contaminant was flushed off the two filter elements, without the Dirt Alert diagnostic layers, henceforth designated as Filter Rinse #1 and Filter Rinse #4, on to 0.8 µm analysis membranes. The analysis membranes were evaluated with the XRF contaminant analyzer. Three areas in each membrane were evaluated. SEM/EDX evaluation was also performed on each membrane. Figure 5 depicts the Dirt Alert diagnostic layer of filter element S/N 4, along with photomicrographs (~ 100X magnification) depicting the contaminant on the diagnostic layer and the contaminant on the analysis membrane corresponding to Filter Rinse #4 (see above).

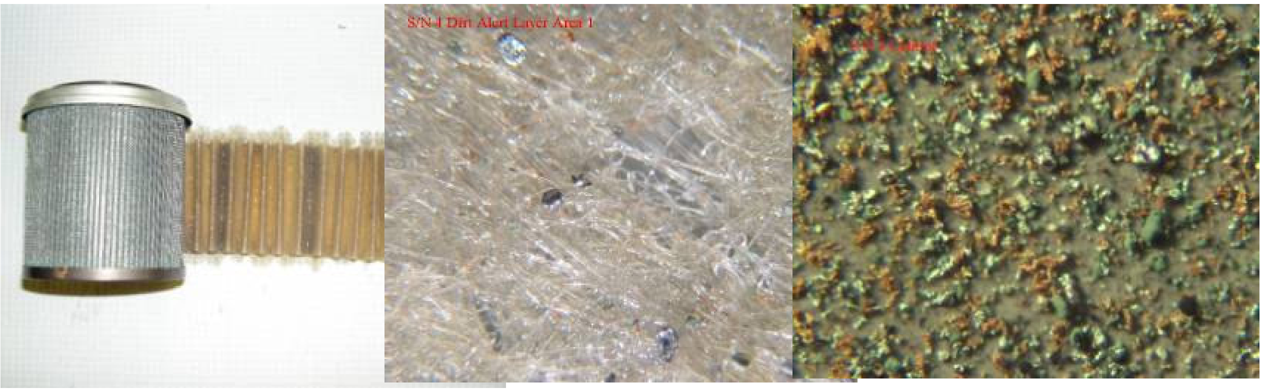


Figure 5. Dirt Alert S/N 4 Diagnostic Layer S/N 4 Filter Rinse #4

The results of the analyses are tabulated in Table II, showing the concentrations of the chemical elements, determined from the XRF analysis of the diagnostic layers, for Dirt Alert filter elements S/N 1 and S/N 4, along with the corresponding Filter Rinse #1 and Filter Rinse #4. For brevity, the results for Dirt Alert filter elements S/N 2 and S/N 3 are omitted. The trend of the results for these filter elements was similar to that for S/N 1 and S/N 4. The average concentrations (averaged over the evaluated areas of the diagnostic layers or analysis membranes; see above) and corresponding standard deviations are tabulated.

Table II. Estimated Concentrations of Chemical Elements Based on XRF Analysis

Chemical Element	Chemical Element Concentration(~ Micrograms/square centimeter)							
	Dirt Alert Filter S/N 1		Filter Rinse #1		Dirt Alert Filter S/N 4		Filter Rinse, #4	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
Mg	3.19	1.01	0.00	n/a	0.47	0.52	0.09	0.37
Al	2.99	1.14	3.54	0.22	0.79	0.57	0.40	0.31
Si	2.34	0.76	0.00	n/a	0.77	0.59	0.47	0.27
Cr	3.40	4.17	2.79	0.73	7.63	7.56	11.27	9.11
Fe	2.60	1.31	11.05	0.07	4.89	3.01	6.96	4.91
Ni	7.08	6.24	27.05	2.17	34.15	25.80	63.26	45.49
Cu	12.35	7.69	54.65	4.80	59.74	40.75	140.10	98.43
Zn	2.93	4.42	13.03	0.43	3.40	4.27	0.00	n/a
Mo	4.31	3.65	4.30	1.34	5.31	5.75	5.63	5.07

Notes: 1. Dirt Alert layer averages are over three sections: beginning, middle, and end; three areas in each section. Filter Rinse averages are over three areas of membrane.

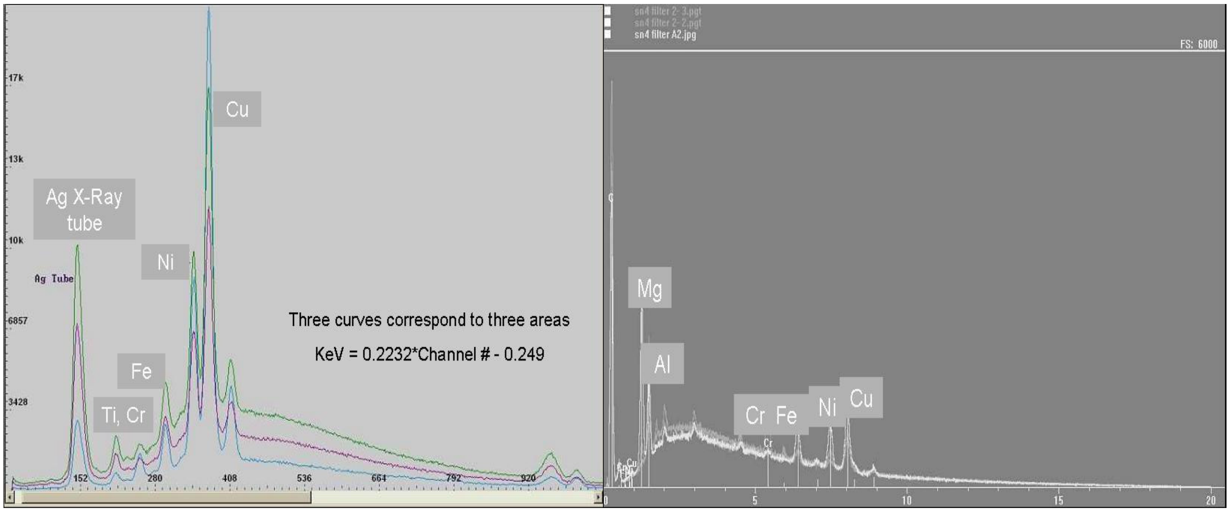


Figure 6. Dirt Alert S/N #4 XRF Spectrum Dirt Alert S/N #4 SEM/EDX Spectrum

Figures 6 and 7 show the XRF and SEM/EDX spectra of the contaminant on the Dirt Alert diagnostic layer S/N 4 and of the contaminant on the analysis membrane corresponding to Filter Rinse #4, respectively. In each case, three spectra, one from each section of diagnostic layer or from three areas of the analysis membrane, are shown

Comparison of the concentrations of the chemical elements in Table II with the concentrations used to load the filter elements in Table I, shows that, in general, the trend of concentrations is reproduced for the higher atomic number chemical elements (Cr and above), but the concentrations are under estimated for the lighter chemical elements (Al, Mg, and Si). It should be noted that a more quantitative agreement is precluded by the fact that the porosity of the diagnostic layer would permit a significant fraction of the contaminant to pass through, depending on the size distribution, and be collected in the filtration medium of the filter element. Additional factors for the lighter elements include the lower sensitivity of the current Beta prototype of the contaminant analyzer for lighter chemical elements, the calibration standards used, and matrix effects. This is also evident in the comparison of the XRF and SEM/EDX spectra (Figure 6 – 7), where significant peaks are observed for aluminum and magnesium in the

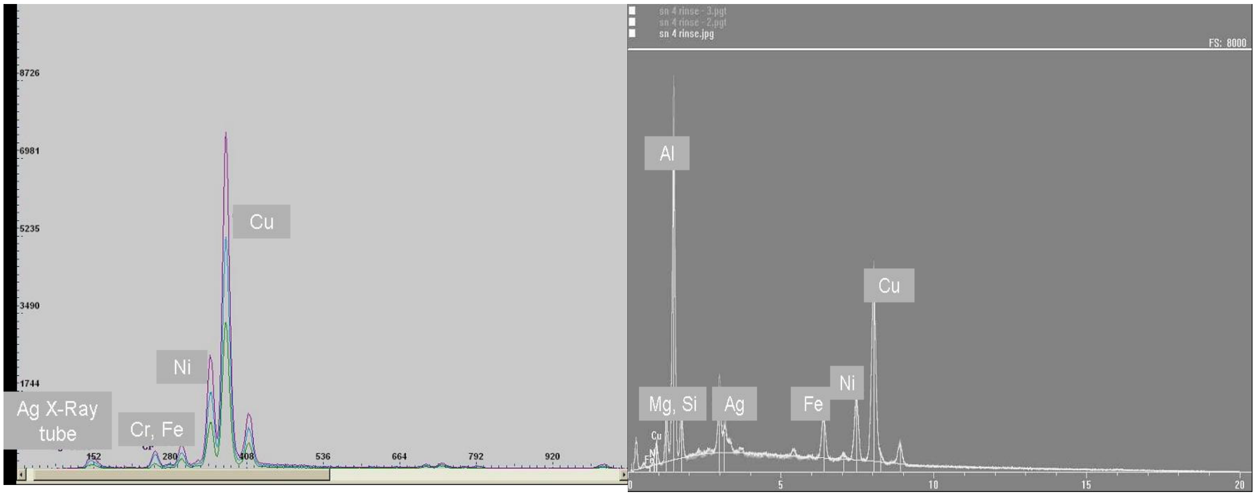


Figure 7. Filter Rinse #4 XRF Spectrum Filter Rinse #4 SEM/EDX Spectrum

SEM/EDX spectra. With the exception of the lighter chemical elements, there is general agreement between the XRF and SEM/EDX spectra. It should also be noted that the use of a silver X-ray tube in the Beta Prototype of the XRF contaminant analyzer precluded measurement of silver; this will be rectified in the production design by using a different X-ray tube.

Since the analysis membranes for Filter Rinse #1 and #4 were prepared by rinsing off contaminant from the filter elements, the results would be similar to those obtained by the current methods used to evaluate filter debris. In general, the chemical element concentrations trend in a similar manner to those for Dirt Alert diagnostic layers S/N 1 and S/N 4. A noteworthy observation is the large standard deviations in the estimated chemical element concentrations for the contaminant on the Dirt Alert diagnostic layers S/N 1 and S/N 4, Table II, about the same magnitude as the concentration values at the lower concentrations. This is also evident in the three XRF spectra from three different sections of the diagnostic layer S/N 4 (Figures 6). A primary factor contributing to this would be the non-uniformity of contaminant distribution on the diagnostic layers (visible in the Dirt Alert diagnostic layer S/N 4 shown in Figure 5) due to non-homogeneous flow characteristics; the flow inlet/outlet configuration for the Dirt Alert filter element housing results in the flow impinging on one side of the filtration medium and then exiting the filter at right angles to the inlet.

Visual inspection of the diagnostic layer S/N 4 showed that the lack of homogeneity in contaminant distribution was primarily along the length of the diagnostic layer. Thus, increasing the sampling along the length of the diagnostic layer would alleviate the effects of the non-uniform contaminant distribution. The standard deviations in the estimated chemical element concentrations for Filter Rinse #4 were also large, indicating that a similar, inhomogeneous contaminant distribution may also be an issue in preparing analysis membranes by flushing filter debris from filter elements. Again, increasing the sampling area would reduce concentration errors associated with inhomogeneous contaminant distribution.

Evaluation of Dirt Alert Diagnostic Layers From the 'Green Run' Testing of Aircraft Hydraulic Systems:

Dirt Alert diagnostic layers, from the 'Green Run' testing of hydraulic systems on an aircraft model, were supplied by the aircraft manufacturer (OEM) for the evaluation. Figure 8 depicts a typical Dirt Alert diagnostic layer.

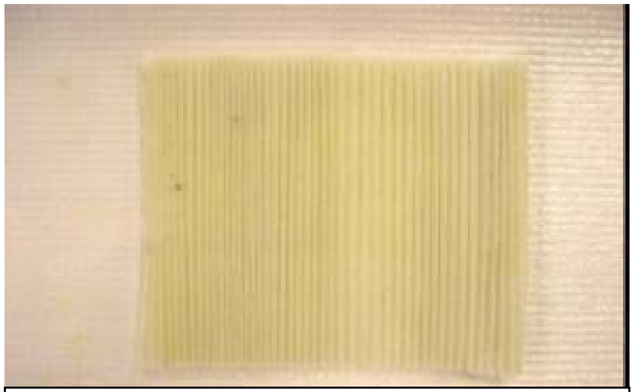


Figure 8. Typical Dirt Alert Diagnostic Layer from Aircraft Hydraulic System

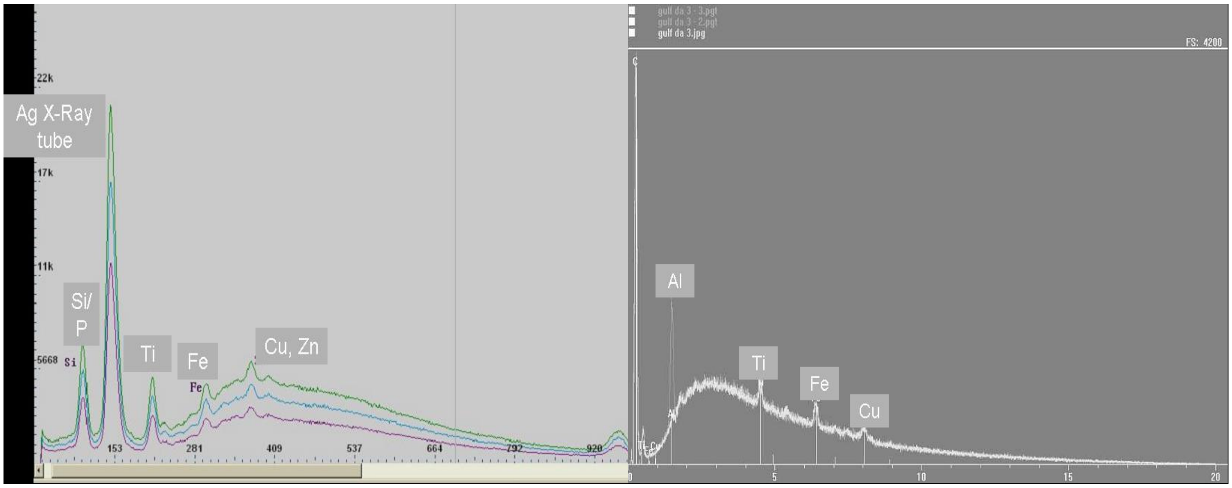


Figure 9. Diagnostic Layer #3, XRF Spectrum Diagnostic Layer #3, SEM/EDX Spectrum

Visual inspection of the diagnostic layers showed the presence of some metallic debris, but the overall concentration of visible contaminant was low. Three sections of each diagnostic layer (beginning, middle, and end) were sampled for XRF and SEM/EDX analyses; one area in each section. Figure 9 depicts the XRF and SEM/EDX spectra for diagnostic layer #3. The three different spectra, in each case, represent the three sections sampled. As stated previously, the SEM/EDX analysis was effective in detecting the lighter chemical elements, such as aluminum, Figure 9. Table III tabulates the estimated concentrations of the chemical elements determined from the XRF analysis. The concentrations of most of the chemical elements were low.

Table III. Estimated Concentrations of Chemical Elements Based on XRF Analysis.

Chemical Element	Concentration(~ Micrograms/square centimeter)					
	Dirt Alert Layer #1		Dirt Alert Layer #2		Dirt Alert Layer #3	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
Mg	1.32	0.55	2.03	0.69	1.27	0.54
Al	0.57	0.41	1.00	0.14	0.19	0.52
Si	0.63	0.59	1.54	0.06	0.41	0.26
Cr	0.75	0.20	0.16	0.02	0.19	0.02
Fe	1.35	0.11	0.87	0.01	0.66	0.02
Ni	0.17	0.07	0.15	0.03	0.20	0.06
Cu	0.84	0.08	0.69	0.02	0.66	0.04
Zn	1.35	0.33	0.82	0.07	0.86	0.03
Mo	0.34	0.08	0.14	0.0	0.17	0.2

Notes: **1.** Dirt Alert layer averages are over three sections: beginning, middle, and end; one area in each section.

The standard deviations for the chemical element concentrations were significantly lower for the heavier chemical elements (chromium and higher), compared to those obtained in the evaluation of the Dirt Alert filter elements described in the previous section. This may be rationalized by the flow distribution in the hydraulic filter housing resulting in a more homogeneous deposition of contaminant on the Dirt Alert diagnostic layers. The higher deviations in the lighter chemical element (Al, Si, and Mg) concentrations is likely due to the lower contaminant analyzer sensitivity for the lighter chemical elements, the calibration standards used, and matrix effects.

Evaluation of Helicopter Main Transmission Gear Box Lubricant Filter Elements, Debris Collected from the Gearbox, and a Sample of Gearbox Lubricant:

Two main transmission gearbox (MGB) lube filter elements, along with an analysis membrane with debris from the MGB filter bowl and a sample of MGB lubricant, obtained during testing of a military helicopter MGB, were provided by the helicopter manufacturer for the evaluation. The filter elements, designated MGB Filter Elements #1 and #2, were not equipped with diagnostic layers, and the evaluation was conducted on the filtration media, removed from the filter elements. The filtration media and analysis membrane with debris from the MGB filter bowl, henceforth designated MGB Oil Debris, were subjected to XRF and SEM/EDX evaluation (four areas in each sample). The sample of MGB oil was evaluated *via* Spectrometric Oil Analysis (SOA) for comparison of SOA and filter debris evaluation results.

Figure 10 depicts representative contaminant rinsed off MGB Filter Element #2 and representative contaminant on the analysis membrane containing the MGB Oil Debris. A variety of metallic and oxidized metallic debris were present, along with some nonmetallic debris.

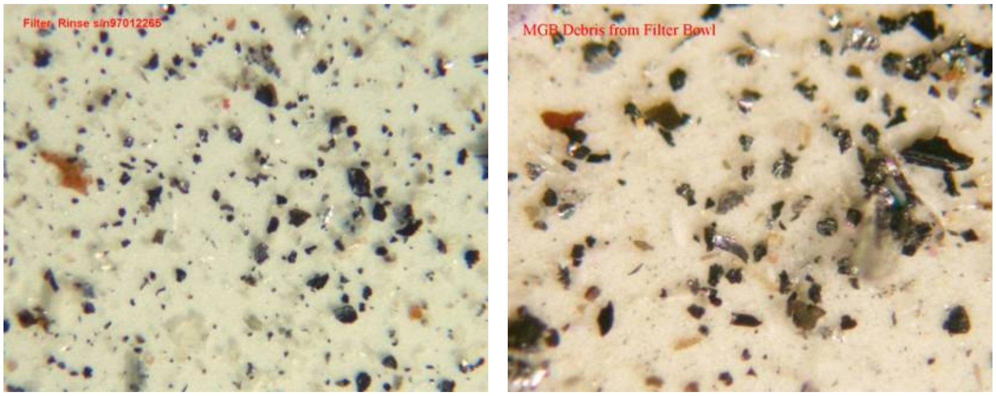


Figure 10. Contaminant from MGB Filter Element #2

Contaminant from MGB Filter Bowl

Table IV tabulates the estimated chemical element concentrations determined from the XRF evaluation. Figure 11 depicts the XRF and SEM/EDX spectra for the filtration medium of MGB

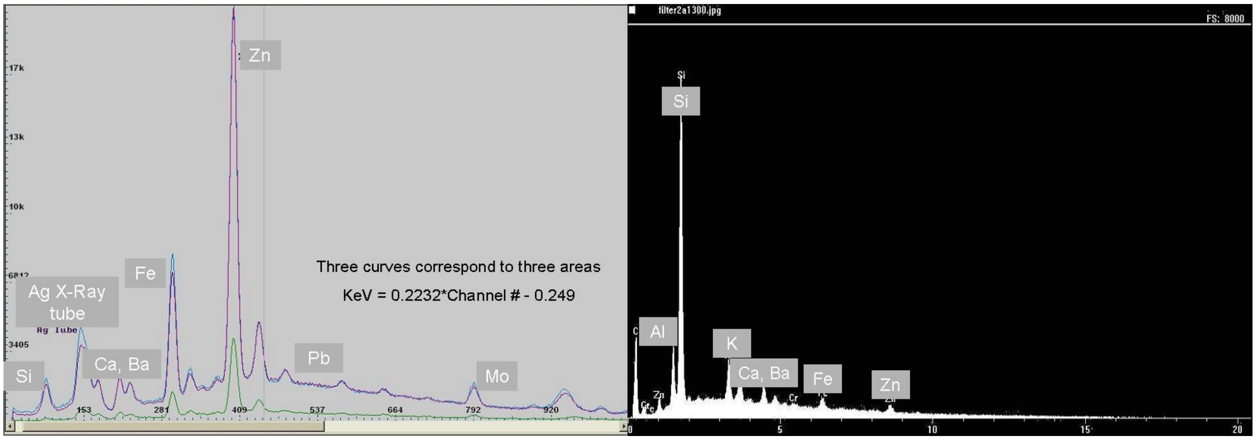
Table IV. Estimated Concentrations of Chemical Elements Based on XRF Analysis.

Chemical Element	Concentration(~ Micrograms/square centimeter)					
	MGB Filter Elt. #1		MGB Filter Elt. #2		MGB Oil Debris	
	Average	Std. Dev.	Average	Std. Dev.	Average	Std. Dev.
Mg	0.00	n/a	0.00	n/a	2.59	0.36
Al	0.00	n/a	0.00	n/a	8.61	3.70
Si	4.80	2.72	9.56	5.73	4.06	1.30
Cr	0.00	0.07	0.02	0.04	0.91	0.07
Fe	9.52	6.26	7.16	3.48	19.67	1.09
Ni	0.38	0.28	0.22	0.11	0.79	0.11
Cu	0.79	0.51	0.76	0.57	0.94	0.04
Zn	83.73	48.77	87.89	46.46	15.03	0.78
Mo	0.90	0.49	8.45	3.69	3.58	0.39

Notes: **1.** Averages are over four areas of filtration media or debris on analysis membrane (MGB Oil Debris).

Filter Element #2, and Figure 12 depicts the XRF and SEM/EDX spectra for the MGB Oil Debris.

The chemical element concentrations in Table IV show high concentrations of zinc for the two MGB filter elements and a much lower concentration for the MGB Oil Debris. The filtration medium is comprised of glass fiber and contains both silicon and zinc, which would contribute to the high concentrations of zinc observed. This is also evident in the XRF spectrum of MGB Filter Element #2 in Figure 11, where zinc is a major peak, compared to the corresponding SEM/EDX spectrum, where silicon is a major peak. As stated previously this is due to the lower sensitivity of the current XRF analyzer for the lighter chemical elements, including silicon, the calibration standards used, and matrix effects. There is overall, qualitative agreement between the XRF and SEM/EDX spectra for both the MGB filter elements and the MGB Oil Debris for the higher atomic number chemical elements (except for zinc as noted above). The standard deviations for the chemical element concentrations are significant, about 50 % of the concentrations, for the two MGB filter elements, but significantly lower for the MGB Oil Debris sample on the analysis membrane. As stated previously, a more comprehensive sampling of the filtration medium is required to alleviate this.



Three curves correspond to three areas

KeV = 0.2232*Channel # - 0.249

Figure 11. MGB Filter #2 XRF Spectrum MGB Filter #2 SEM/EDX Spectrum

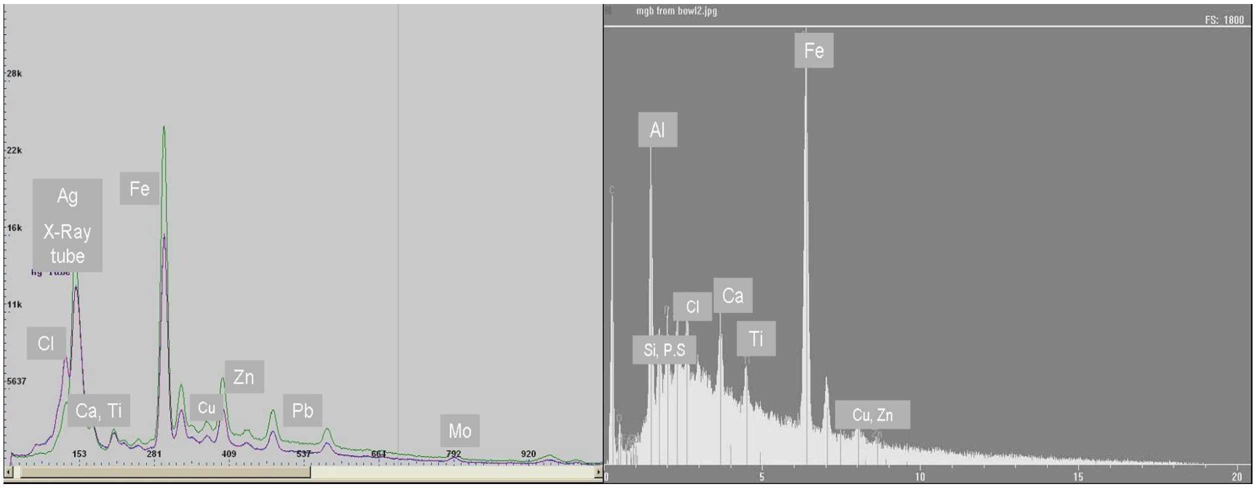


Figure 12. MGB Oil Debris XRF Spectrum MGB Oil Debris SEM/EDX Spectrum.

Table V summarizes the results of the Spectrometric Oil Analysis (SOA) of the MGB lubricant sample. The analysis only detected the presence of silicon (18 ppm) and zinc (1 ppm).

Table V. Results of Spectrometric Oil Analysis of MGB Lubricant Sample.

Chemical Element	**Concentration (ppm)**
Iron (Fe)	0
Chromium (Cr)	0
Molybdenum(Mo)	0
Aluminum(Al)	0
Copper (Cu)	0
Nickel (Ni)	0
Silicon (Si)	18
Magnesium (Mg)	0
Zinc (Zn)	1

The limitations of SOA with respect to particle size, if no acid digestion techniques are employed, is well known, and, in the present case, both the amount of debris present in the MGB filter elements and in the filter bowl (MGB Oil Debris) clearly illustrates the advantage of filter debris analysis.

Conclusions and Future Development:

The intent of the present work was to evaluate the concept of the diagnostic filter system: the Dirt Alert diagnostic layer in conjunction with the XRF based contaminant analyzer, for hydraulic and lubricant system condition monitoring, specifically the direct evaluation of the chemical composition of debris collected on a diagnostic layer of the filter element (or the filtration medium) *via* XRF analysis. The results of the evaluation of Dirt Alert diagnostic layers prepared in the laboratory, and diagnostic layers and filter elements from the field, discussed in this paper, show that the diagnostic filter system is viable, and can be developed to provide a suitable, convenient on-site vehicle for fluid system condition monitoring.

Future development efforts will focus on:

- Improving the semi-quantitative correlation of chemical element concentrations (calibration standards, diagnostic layer sampling protocol, improved algorithms for data analysis, etc.).

- Improving the detection of low Atomic Number elements.

- Incorporating filter loading with time into the diagnostic algorithms.

- Commencing development of an expert system.

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