

A-RFS CASE HISTORY

Averting Catastrophic Failure of a Main Transmission in a US Army Helicopter

BACKGROUND:

Atomic emission spectroscopy (AES) using a rotating disc electrode (RDE) has been a successful technique applied to condition monitoring (oil analysis) programs for decades. However, in recent years the AES technique has become less effective as an early detection diagnostic technique. The reasons for the reduction in the effectiveness of the AES technique are primarily due to fine filtration and the morphology of particles that are generated at the onset of some types of failures in complex mechanical systems. Rotrode Filter Spectroscopy (RFS) is an analytical technique that has been developed to enhance the sensitivity of the RDE/AES technique in order to overcome these limitations.

Automated rotrode filter spectroscopy (A-RFS) is a sample preparation device designed for the AES that concentrates large and small wear metal debris in a graphite filter electrode. When the graphite filter electrode is analyzed using AES, sensitivity is increased by a factor of 80-100 and particle size detection is improved by a factor of 10. For example, the limit of detection of iron for conventional RDE/AES is 600 parts per billion. This limit of detection is reduced to 6 parts per billion by applying the A-RFS sample preparation technique. When the sample is prepared by the A-RFS device the particle size detection capability of AES is extended from 8-10 micrometers to greater than 70 micrometers.

By concentrating 5 ml of oil sample (fifty times the volume analyzed by conventional RDE/AES analysis), all particle debris (metallic and non-metallic) becomes trapped within the outer circumference of the graphite filter electrode. This process eliminates the major limitations (gravity, oil, resonance time) of conventional RDE/AES analysis. Efficient vaporization of all particles (large and small) is achieved using the total energy produced by the excitation source to reach vaporization temperatures in excess of 5,600 degrees Celsius. This is particularly important when alloy identification (such as M50) is necessary and damaging contaminants, such as silicon containing particles are present. When applied to helicopter engines, transmissions and gearboxes, rotrode filter (RF) analysis can enhance the effectiveness of AES to detect the harmful effects of lubricant contamination and component damage. The A-RFS is shown in operation next to the atomic emission spectrometer in Figure 1.



Figure 1. A-RFS Device in Operation

TEST SITE:

The United States Army Oil Analysis Program (AOAP) has successfully used the AES technique as their primary condition monitoring technique for several decades. To fully understand the capability of rotrode filter spectroscopy, the AOAP initiated a pilot program to apply RFS analysis to helicopter engines, transmissions, and gearboxes. This case history will provide one example of how the RFS technique enhanced the AES capability to identify a failure that was not apparent using conventional RDE/AES or particle counting. For security reasons, the name and location of the Army base, plus the helicopter and component serial numbers have been withheld.

TEST TECHNIQUES:

The location of the A-RFS field evaluation program was chosen by the AOAP based on the availability of rotary aircraft and a fully staffed laboratory with complete analytical capabilities. The site chosen for the RFS field evaluation has an enhanced AES instrument that includes the element vanadium and the A-RFS sample preparation device. The element vanadium is essential in the detection of M50 and M50 NiL bearing alloys.

In addition to RDE/AES and RF/AES capability for wear metal, contaminant and additive analysis, the AOAP laboratories have a LaserNet Fines® particle counter and shape classifier, ferrography to separate ferrous wear debris by particle size for shape analysis, a viscometer, titrators and FT-IR spectrometer to measure the physical properties of the lubricant and water in oil. These instruments provide a comprehensive evaluation of the mechanical integrity of the component as well as the serviceability of the lubricant.

RD/AES ANALYSIS: This section contains the history record for the analysis of the subject component based on conventional rotating disc atomic emission spectroscopy (RD/AES).

Sample Number	Date Taken	Date Rcvd	Date Analyzed	Oil Chg	Oil Frame	Oil Added	Oil Type	Hot Sample	Reason For Sample	UIC	Lab History Evaluator	Result
0345A	05 Jun 2007	11 Jun 2007	11 Jun 2007	6558H	74H	7424 4H	MIL-L-23689	Hot	ROUTINE			MAINTENANCE
<p>Trans Status: Not in Transfer Status</p> <p>Feedback Required: 1</p> <p>Command: [REDACTED]</p> <p>UIC: [REDACTED]</p> <p>Sort Code: [REDACTED]</p> <p>Tail No: [REDACTED]</p> <p>Sampling Intervals: Hours: 25 Days: N/A</p> <p>Source Oil Type: [REDACTED]</p> <p>Excessive Rubbing Wear, Excessive Cutting Wear, Excessive Sliding Wear, Exceeds NAS1638 Limits, Excessive Spalling/Fatigue Wear, Do not fly, Reference serviceability check from component manual and submit completed 3254-R with resample.</p>												
0475A	10 May 2007	14 May 2007	14 May 2007	5508H	47H	7356 6H	MIL-L-23689	Hot	ROUTINE			NORMAL
1122A	27 Mar 2007	29 Mar 2007	29 Mar 2007	5497H	28H	7375 7H	MIL-L-23689	Hot	ROUTINE			NORMAL
0473A	13 Feb 2007	14 Feb 2007	14 Feb 2007	5470H	9H	7358 6H	MIL-L-23689	Hot	LAB REQUEST			NORMAL
0271A	07 Feb 2007	09 Feb 2007	09 Feb 2007	5461H	0H	7349 9H	MIL-L-23689	Hot	SPECIAL			NORMAL
0177A	05 Feb 2007	07 Feb 2007	07 Feb 2007	5461H	49H	7349 9H	MIL-L-23689	Hot	ROUTINE			SERVICE
<p>Abnormal Findings: Drain and flush component then resample at the end of the next flight day/cycle. Resample.</p>												
0748A	23 Jan 2007	24 Jan 2007	24 Jan 2007	5459H	41H	7341 8H	MIL-L-23689	Hot	SPECIAL			NORMAL
0359A	10 Jan 2007	12 Jan 2007	12 Jan 2007	5436H	24H	7324 5H	MIL-L-23689	Hot	ROUTINE			RESAMPLE
<p>Abnormal Findings: Do Not Fly, Do Not Change Oil, Resample at operating temperature ASAP.</p>												
0492A	12 Dec 2006	13 Dec 2006	14 Dec 2006	5412H	35H	7301H	MIL-L-23689	Hot	POSTMAINT_CHECK			NORMAL
0011A	30 Oct 2006	01 Nov 2006	01 Nov 2006	5366H	22H	7287 5H	MIL-L-23689	Hot	ROUTINE			NORMAL

Samp No	Fe	Ag	Al	Cr	Cu	Mg	Na	Ni	Pb	Si	Sn	Ti	B	Mo	Zn	Ba	P	Ca	Cd	K	V	PPM Guidelines				
																						Fe	Ag	Al	Cr	Cu
0345A	44	1	1	1	1	1	1	1	0	0	6	0	0	0	1	0	0	2768	28	0	0	0				
0475A	36	1	0	0	1	1	0	1	0	2	5	0	0	0	1	0	0	2795	9	0	0	0				
1122A	21	0	0	0	1	1	0	0	0	0	6	0	0	0	1	0	0	2368	19	0	0	0				
0473A	10	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	2620	23	0	0	0				
0271A	1	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2564	15	0	0	0				
0177A	30	2	1	0	1	1	0	0	0	0	6	0	0	0	2	0	0	2475	28	0	0	0				
0748A	28	2	1	1	1	1	0	1	0	1	5	1	0	0	1	0	0	2679	21	0	0	0				
0359A	26	1	1	0	1	1	0	1	0	0	5	0	0	0	1	0	0	2637	8	0	0	0				
0492A	16	0	1	0	0	0	0	0	0	0	6	0	0	0	1	0	0	2543	25	0	0	0				
0011A	11	0	0	0	0	1	0	0	0	0	6	1	0	0	2	0	0	2774	10	0	0	0				

FTIR	Method Number	02	EPWA	WATR	BKON	BKDN2	SOOT	OXID	NITR	AW	GAS	JP	SULF	COOLF	OTHR
Trend	24	2	4	2	3	9	0	0	0	0	0	0	0	0	0
Normal	81	4	14	5	8	32	0	0	24	0	0	0	0	0	0
Marginal	105	5	17	6	9	39	0	0	29	0	0	0	0	0	0
High	123	6	22	7	11	48	0	0	36	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 2. RD/AES History Record for Helicopter Main Transmission-Page 1

PPT's	Fuel Dil	Viscosity	Temp	Total	Blotter Spot	Coolant/Dispers	Crackle	Alkalin	Water				Unit	Index
									390 PPM	354 PPM	406.4 PPM	300.8 PPM		
0345A									390	354	406.4	300.8		
0475A									216.4	196.4	277.6	295.6		
1122A									503.6	354.8				
0473A														
0271A														
0177A														
0748A														
0359A														
0492A														
0011A														

Lasernet Fines	NAS (Particles per 100ml)				ISO4406 (Particles per 1ml)			
	5-15um	15-25um	25-50um	50-100um	>4um	>6um	>14um	>14um
Samp No	NAS				ISO4406			
0345A	9	1,228,876	28,676	3,001	23 / 21 / 16	61,620	12,609	320
0475A	12	66,308	5,669	1,334	20 / 17 / 13	6,702	756	73
1122A	11	640,163	29,046	1,689				
0473A	10	471,364	24,007	4,002				
0271A	11	134,806	12,337	2,667				
0177A	12	416,947	22,009	3,335				
0748A	12	629,897	17,873	2,668				
0359A	12	812,584	33,690	8,338				
0492A	12	706,796	31,014	2,667				
0011A	+	548,640	21,700	2,337				

Ferroggraphy	Ferrous				Non-Ferrous				Contaminants								
	NR	SS	Cut	GR	NR	SS	Cut	GR	BO	RO	Co	Sp	Dg	SD	Fib	CS	Oth
0345A																	
0475A																	
1122A																	
0473A																	
0271A																	
0177A																	
0748A																	
0359A																	
0492A																	
0011A																	

Sample No	Tracking	Sample Remarks	Analysis Remarks	
				MONITOR
0475A				
0271A				
0177A				
0748A				
0359A				

Figure 3. RD/AES History Record for Helicopter Main Transmission-Page 2

This history record consists of two pages. Page 1 shown in Figure 2, has a header containing all information specific to the component, the aircraft serial number where the component is installed and where it is located. This information has been blocked out for security reasons.

The next section of Figure 2 contains the laboratory sample number and all information pertaining to each sample, such as hours since overhaul and hours since oil change plus comments and recommendations. The middle section of Figure 2 contains the results produced by the rotating disc atomic emission spectrometric (RD/AES) technique. The analytical results appearing below the element symbols are for the most current sample analyzed. The bottom section of Figure 2 contains PPM Guidelines for the type of component being analyzed.

Page 2 shown in Figure 3 consists of three sections. The top section contains the results for the physical properties tests (PPT's) which include fuel dilution, viscosity, water, and acid/base number, etc. The middle section contains the LaserNet Fines® particle count and International Standards Organization (ISO) particle size classification codes. The bottom section contains the Ferrography results categorized into Ferrous, Non-Ferrous and Contaminant debris.

Interpreting the RDE/AES data in Figure 2, it is apparent iron was increasing from an initial concentration of 11 ppm to a concentration of 30 ppm for sample number 0177A. After a review of sample 0177A, an oil drain and flush were recommended. Continued review of the main transmission after the drain and flush recommendation indicated an accelerating concentration of the element iron only. The concentration of iron, however, remained within the "NORMAL" guideline of < 81 ppm and the trend never exceeded the limit of > 24 ppm in 10 hours of operation. In accordance with RDE/AES analysis alone, the main transmission of this helicopter was operating within technical order guidelines.

Interpreting the LaserNet Fines® particle count data in Figure 3 produced an ambiguous assessment of the condition of this component. The particle count was elevated and contained particles in excess of the filtration rating, but did not exceed ISO classification to warrant component removal. A significant reduction in NAS and ISO classifications can be observed after the drain and flush maintenance recommendation based on the analysis of sample 0177A. Continued particle count analysis of this component never exceeded the ISO classification code necessary to support removal from service.

Due to the labor intensive nature of ferrography, the production and analysis of a ferrogram would not normally be ordered by the data analyst without some evidence of an abnormal condition from at least one of the primary analytical instruments. The laboratory recommendation to perform a ferrogram is generally based on an abnormal indication from one or more other analytical instruments or visual debris suspended in the sample bottle. In this case history, both the RDE/AES and LaserNet Fines® produced results that were interesting, but not outside of normal operating guidelines. Fortunately, this helicopter was located within the geographical area covered by the AOAP laboratory where rotrode filter spectroscopy was being field tested.

RF/AES ANALYSIS: This section of the case history contains the rotrode filter spectroscopic analysis of the same helicopter main transmission. Figure 4 below is the RFS component history record and consists of a single page record because all other analytical data is stored on the RD/AES component history record.

CONUS - Fort		Component Model: MAIN XMSN		Command:		Feedback Required: 0																
Component S/N:		End-Item Model:		UIC:		Sampling Intervals																
End-Item S/N:		Source Oil Type:		Sort Code:		Hours: 25																
		Tail No:		Days: N/A																		
		Trans Status: Not in Transfer Status																				
Samp No	Date Taken	Date Rcvd	Date Analyzed	Since Ovhl	Since Chg	Oil Air Frame Hours	Oil Added	Type Sample	Hot Sample	Reason For Sample	UIC	Lab History Evaluator	Result									
0R345	05 Jun 2007	11 Jun 2007	11 Jun 2007	5535H	74H	7424.4H	0	MIL-L-23689	Hot	ROUTINE			OTHER									
0R475	10 May 2007	14 May 2007	14 May 2007	5509H	47H	7396.6H	0	MIL-L-23689	Hot	ROUTINE			OTHER									
R1122	27 Mar 2007	29 Mar 2007	29 Mar 2007	5487H	26H	7375.7H	0	MIL-L-23689	Hot	ROUTINE			OTHER									
Abnormal Findings. Test results and findings are provided as-is and no recommendation is made.																						
0R473	13 Feb 2007	14 Feb 2007	14 Feb 2007	5470H	9H	7358.6H	0	MIL-L-23689	Hot	LAB REQUEST			OTHER									
Abnormal Findings. Test results and findings are provided as-is and no recommendation is made.																						
0R271	07 Feb 2007	09 Feb 2007	09 Feb 2007	5461H	0H	7349.9H	0	MIL-L-23689	Hot	SPECIAL			OTHER									
Abnormal Findings. Test results and findings are provided as-is and no recommendation is made.																						
0R177	05 Feb 2007	07 Feb 2007	07 Feb 2007	5461H	49H	7349.9H	0	MIL-L-23689	Hot	ROUTINE			OTHER									
Abnormal Findings. Test results and findings are provided as-is and no recommendation is made.																						
0R748	23 Jan 2007	24 Jan 2007	24 Jan 2007	5453H	41H	7341.8H	0	MIL-L-23689	Hot	SPECIAL			OTHER									
Abnormal Findings. Test results and findings are provided as-is and no recommendation is made.																						
0R359	10 Jan 2007	12 Jan 2007	12 Jan 2007	5436H	24H	7324.5H	0	MIL-L-23689	Hot	ROUTINE			OTHER									
Abnormal Findings. Test results and findings are provided as-is and no recommendation is made.																						
0R492	12 Dec 2006	13 Dec 2006	14 Dec 2006	5412H	35H	7301H	0	MIL-L-23689	Hot	POST MAINT. CHECK			OTHER									
Abnormal Findings. Test results and findings are provided as-is and no recommendation is made.																						
00R11	30 Oct 2006	01 Nov 2006	01 Nov 2006	5399H	22H	7287.5H	0	MIL-L-23689	Hot	ROUTINE			OTHER									
Abnormal Findings. Test results and findings are provided as-is and no recommendation is made.																						
RF/AES																						
Samp No	Fe	Ag	Al	Cr	Cu	Mg	Na	Ni	Pb	Si	Sn	Ti	B	Mo	Zn	Ba	P	Ca	Cd	K	V	
0R345	6485	126	118	74	175	194	19	341	29	144	20	6	1	35	254	0	2458	33	48	7	0	0
0R475	2687	49	40	21	50	64	4	94	2	42	13	1	0	16	101	0	2131	1	10	1	0	0
R1122	376	7	14	3	6	9	0	11	0	2	54	0	0	56	8	4	8544	9	0	0	2	0
0R473	614	6	23	3	7	10	3	19	0	15	0	1	0	1	35	0	42	2	1	0	0	0
0R271	64	1	5	1	2	4	1	3	1	5	2	1	0	2	19	0	193	2	0	0	0	0
0R177	2654	74	37	16	51	41	2	91	1	29	3	1	0	8	89	0	602	0	8	2	0	0
0R748	1337	59	36	12	33	32	0	45	1	23	18	4	0	17	46	3	2569	15	3	0	1	0
0R359	2342	59	49	17	42	32	5	92	6	49	3	5	1	6	119	2	122	17	10	3	0	0
0R492	18	2	2	0	3	4	4	1	0	16	0	8	0	0	32	0	19	11	0	4	0	0
00R11	302	6	16	2	6	9	3	8	0	25	1	2	0	2	8	0	143	14	3	5	0	0
PPM Guidelines																						
Row No	92																					
Trend	24	4	2	3	9	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0
Normal	81	4	14	5	8	32	0	0	0	24	0	0	0	0	0	0	0	0	0	0	0	0
Marginal	105	5	17	6	9	39	0	0	0	29	0	0	0	0	0	0	0	0	0	0	0	0
High	123	6	22	7	11	48	0	0	0	36	0	0	0	0	0	0	0	0	0	0	0	0
Average	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 4. RF/AES History Record for Helicopter Main Transmission

Comparing the RF/AES data in Figure 4 to the RDE/AES data in Figure 2 reveals the true magnitude and rate of the wear being generated within this component. Iron, which is the dominant wear metal element in most oil wetted components, was producing elevated concentrations almost from the beginning of this history record. This element continued to increase rapidly above the baseline especially after the drain and flush recommendation is given for sample OR177. As the malfunction progressed, producing higher concentrations of wear particles, the lower percentage alloying elements such as chromium and nickel appeared and increased with the severity of wear. Elements such as silver, aluminum, copper and magnesium appeared and increased as the assembly experienced additional stresses.

The difference in the wear metal concentration between the RD/AES measurement and RF/AES measurement is due to three factors. RF/AES analyzes a larger sample volume which increases its sensitivity. It eliminates the negative effect gravity has on transporting large particles to the excitation source and it produces higher excitation temperatures for greater particle size vaporization efficiency. Therefore, the RF/AES is significantly more capable of detecting the development of an abnormal mechanical condition

LABORATORY ACTION: As a result of the wear metal concentration and rate of increase in several of the wear metal elements that appeared in the RF/AES analysis, the laboratory ordered that a ferrogram be prepared and analyzed.

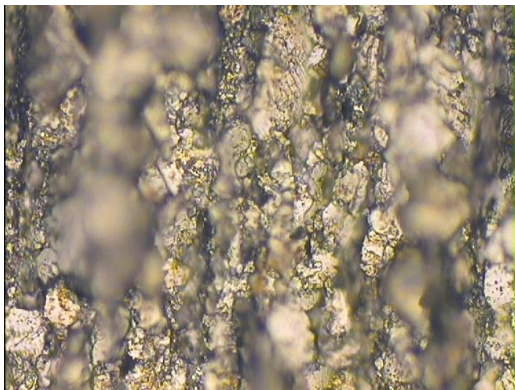


Figure 5. Ferrogram Slide #1



Figure 5. Ferrogram Slide #2

A ferrogram is made by diluting an oil sample to reduce its viscosity. The sample then flows from one end of a special microscope slide to the opposite end while being subjected to a powerful magnetic field. The larger wear particles become trapped quickly whereas the smaller particles, with less mass, travel further along the slide before they are trapped by the magnetic field. As a result, the ferrous debris becomes separated by particle size thus allowing microscopic inspection to be performed. Figures 5 and 6 are ferrogram screen images of the wear metal debris from sample number 0534A.

As a result of a thorough multiple analytical assay of sample 0345A, the laboratory submitted the following maintenance recommendation:

Excessive Rubbing Wear
Excessive Cutting Wear
Excessive Sliding Wear
Exceeds NAS1638 Limits
Excessive Spalling Fatigue Wear
DO NOT FLY

Reference serviceability check from component manual and submit completed 3254-R with resample.

POST RECOMMENDATION ASSESSMENT: Maintenance action was performed on this component in accordance with the laboratory recommendation. Post maintenance feedback assessed the condition as follows.

Both magnetic chip detectors in the main transmission of this helicopter were defective and did not indicate imminent failure of the component. In addition, the warning lights never illuminated to show that the chip detectors had failed. This combination of diagnostic monitoring failures placed the main transmission in an unmonitored condition whereby component degradation and catastrophic failure were undetectable.

The main transmission was removed from service and sent to depot maintenance for teardown inspection and overhaul. Post teardown and inspection records from the overhaul maintenance depot are on request.

Figures 7 and 8 are photographs of the magnetic chip detectors removed from the defective main transmission illustrating the severity of wear debris generated by this malfunction.



Figure 7. Defective Magnetic Chip Detectors (MCD)



Figure 8. MCD with Wear Metal Debris

SUMMARY:

The US Army has successfully applied the Rotating Disc Electrode Atomic Emission Spectrometer (RDE/AES) in their condition monitoring oil analysis program for several decades. Due to design changes in modern engines, improved filtration efficiency and the use of magnetic chip detectors (MCD's) plus advances in metallurgy have all contributed to a decline in the efficiency of the conventional RDE/AES technique.

To enhance the sensitivity and particle size detection capability of the AES, rotrode filter spectroscopy has been applied to helicopter engines, transmissions and gearboxes. The AOAP has piloted a field evaluation program where RF/AES analysis is being performed simultaneously with RDE/AES analysis in one of their laboratories analyzing helicopter platforms. RF/AES analytical data is being generated on a routine basis and this data is compared to conventional RDE/AES and complimentary analytical techniques such as particle counting and ferrography to evaluate its potential to enhance the analytical capability of the AOAP.

This case history is from the AOAP laboratory where RF/AES analysis is routinely being performed. This laboratory experienced an abnormal condition where RF/AES analysis detected elevated levels of several wear metals appearing at increasing rates of production. RDE/AES analysis of the same oil samples revealed minimal elevated presence of just one wear metal, iron. Based on RF/AES analysis a ferrogram was produced and analyzed that confirmed the presence of an abnormal concentration of large rubbing, cutting, and sliding ferrous wear metal debris. A laboratory maintenance recommendation was issued that resulted in the removal of the main transmission from the helicopter.

Post maintenance records indicate that both magnetic chip detectors had failed rendering the onboard diagnostic monitoring capability incapable to warning of imminent failure.

CONCLUSION:

The A-RFS is an accessory for existing atomic emission spectrometers which aids in efficiently vaporizing all wear metals and contaminants in an oil sample from any helicopter engine, transmission or gearbox. Concentrating all debris contained in this sample is equivalent to analyzing 50 times the sample volume analyzed by conventional RDE/AES. The benefit gained by concentrating the debris is significant. It provides better statistical representation of the total lubricant contamination in the engine and it elevates fine filtered debris to a concentration that is detectable. Direct deposition of all debris in the pores of the graphite filter electrode results in more efficient sample introduction into the excitation source. Removal of the lubricant in the A-RFS process results in higher excitation energy for vaporization of larger particles and higher temperatures necessary to vaporize alloy elements such as vanadium and contamination in the form of silicon particles.

This case history provides evidence that the application of RFS in routine oil analysis of helicopter platforms enhances the capability of conventional atomic emission spectrometers. The enhanced sensitivity and higher vaporization temperatures can result in early detection of component failure and when used in conjunction with complimentary analytical instrumentation can enhance the effectiveness of a condition monitoring program. The A-RFS sample preparation accessory for AES instruments is an improvement to any condition monitoring oil analysis program.