FILTER DEBRIS ANALYSIS BY ENERGY DISPERSIVE X-RAY FLUORESCENCE APPLIED TO J52P408 ENGINES

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ABSTRACT

The Joint Oil Analysis Program Technical Support Center (JOAP-TSC) has developed a technique to analyze particles that have been extracted from in-line jet engine oil filters using energy dispersive x-ray fluorescence(EDXRF). The technique is termed filter debris analysis (FDA). Six beta prototype instruments that were capable of performing FDA-EDXRF in an automated mode were manufactured under a U.S. Air Force (AF) Productivity Reliability Availability and Maintainability (PRAM) project. J52P408 (J52) engines were suffering from what appeared to be sudden, catastrophic failures that resulted in the loss of aircraft. The root cause of the failure was lack of lubrication in the 4 ½ bearing area that caused the 4 ½ bearing cage to fracture. The analysis of oil samples by rotrode emission spectroscopy did not indicate a catastrophic bearing failure mode was evolving. FDA-EDXRF was one of the techniques employed to try to discover the onset of 4 ½ bearing failure. An FDA-EDXRF profile of the J52 engine was developed in about 3 weeks. Initially, particulates obtained from J52 filters where FDA indicated that abnormal amounts of bearing wear was present in the engine were sent to Pratt & Whitney Aerospace laboratory to be analyzed by scanning electron microscopy (SEM). The SEM results confirmed the presence of M-50 alloy or bearing wear. Subsequent teardowns of a portion of the engines having abnormal bearing wear indicated by FDA had fractured 4 ½ bearing cages. This paper will outline how FDA technology has kept the J52 fleet flying.

INTRODUCTION

Rotrode atomic emission spectroscopy (RAES) has been used for over a quarter of a century by the U.S. Navy to analyze particulates in oil samples from assets, e.g. jet engines , helicopter gearboxes, etc. AES results are used as an indicator of abnormal wear in U.S. Navy aviation equipment. In general, particulates generated from contact surfaces would be picked up by the lubricant stream. RAES analysis of a sample of the particulates suspended in the lubricant would provide signatures of the elements present in the sample of the oil stream that can then be related back to the alloys liberated from the contact surfaces that may be producing the particulates. RAES would provide early warning of abnormally wearing components and prevent catastrophic failure that could result in the loss of crew and aviation equipment. It is well known and accepted that RAES can not detect particles above 8 microns in size.[1]

U.S. Navy jet engines operate under high speed and load requirements. Due to the structural dynamics of U.S. Navy jet engines, the oil supply circulates close to the engine's hot sections.

The synthetic oil that lubricates these engine systems slightly carbonizes as it passes close to the hot section. The carbonized material gets deposited on and in the pores of the filter element. Over the course of time, the filter element accumulates a sufficient amount of carbon debris that begins to filter out the population of particles that RAES uses for monitoring the condition of jet engines. For example, the F404GE400 engine was placed on RAES monitoring when it was first introduced into the U.S. Navy aviation fleet. F404GE400 filter element was rated as 15 microns absolute and 10 microns nominal. The particle population (8 microns and smaller) that is detected by RAES should easily pass through the filter element. However, bearing failures occurred in the F404GE400 engine that RAES did not detect. Within 2 years of the F404GE400 engine coming into the U.S. Navy fleet and being monitored by RAES, the engine was removed from RAES monitoring. The JOAP-TSC experienced this phenomenon in its oil analysis laboratory when monitoring F404GE400 engines. After an oil and filter element change, the RAES readings for various elements would vary as they normally do. However, after approximately 50 hours following an oil change, the RAES element readings were reduced to zero and one part per million (PPM). The lack of particulates for RAES to effectively monitor the F404GE400 engine was attributed to the deposition of byproducts from the slight carbonization of the synthetic oil as it passes close to the hot sections of the engine. [2,3]

J52 engines were experiencing a high frequency of bearing failures in the 4 ½ bearing assembly and in-flight shutdowns. The bearings in the 4 ½ bearing assembly are roller bearings. During a failure mode, lubrication becomes insufficient in the 4 ½ bearing assembly. The bearing area begins to heat up and begins to carbonize the oil. The carbon material begins to block the holes that feed lubricant into the bearing. The failure process continues with silver plating being liberated from the bearing cage; wearing of the ends of the rollers (bulleting of the roller ends); and finally the simultaneous skidding of all the bearings, causing the roller cage to crack. The complete failure of the bearing assembly and heat buildup can cause the shaft to warp. One of the failures in the 4 ½ bearing assembly resulted in the lubricant being vaporized and a fire occurred in the 4 ½ bearing area.

J52 engines have their oil supply routinely sampled every 10 flight hours. The parts per million (PPM) of 15 elements are simultaneously determined by RAES. Guidelines for acceptable and abnormal parts per million (PPM) concentrations of several elements for J52 engines were previously determined and published in the NAVAIR 17-15-50.3.[4] Iron (Fe) is used to indicate possible bearing wear and silver (Ag) is used to indicate wear from silver plating. However, these RAES element guidelines failed to detect the onset of 4 ½ bearing failure in the J52.

FILTER DEBRIS ANALYSIS

FDA utilizes the approach that an oil filter removes particulates for which it is rated with 99.5% efficiency (absolute rating of a filter.) The lubricating fluid contains particles of alloys from surfaces in an asset that are wearing. The entire volume of lubricant is continuously cycled through the filter element, which is removing wear particles from the lubricant stream. During a filter element's life, a wear history is deposited in the filter element. Sampling and analyzing the particulates deposited in a filter element will provide a comprehensive look at the wear that has occurred during the life of the filter element.

The JOAP-TSC procedure for FDA utilizes a timed series of rinses and washings of a filter element to produce a sample of the particulates in and on a filter element that is suitable for EDXRF analysis. Every filter element is cleaned in exactly the same manner to produce EDXRF samples.

The pore size and the composition of the filter substrate that the particulates are deposited upon are critical to developing a viable FDA database. The FDA profile or database is predicated upon using the same pore size filter substrate for every sample. Also, the filter substrate must not be composed of elements that are considered critical to determining engine wear. For example, if silver (Ag) is critical to engine condition -- a filter substrate composed of Ag could not be used.

To develop an FDA profile for an engine, the following is required:
  1. The metallurgy of the oil system to determine what elements are to be analyzed.
  2. Failure modes being experienced and the components involved.
  3. Random sample of engine population to do an initial FDA profile.
  4. Devise limits through EDXRF analysis of samples.

ENERGY DISPERSIVE X-RAY FLUORESCENCE (EDXRF)

The FDA instrument creates uniform and randomly dispersed populations of particulates for EDXRF analysis. The objective is to create particle dispersions that can be considered thin-films up to films of intermediate thickness for EDXRF analysis. Elements from EDXRF analysis of the particulates extracted from the filter element are reported as percentages and represent the percent of the particulates on the substrate that are composed of a particular element. Elements and combinations of elements are used to identify alloys wearing in the component's system. A database of EDXRF results that statistically identifies the maximum percentages of elements must be developed before predictions about equipment condition can be made. For example, in jet engines, an FDA database has to be developed for each model of engine; this procedure was done for all the models of jet engines monitored by RAES. The data from the sampling of a particular model of engine is statistically analyzed with statistical limits being drawn from the data. The statistically derived element limits are then tested by removing components and inspecting them for damage. The FDA database and statistically derived element limits should be continuously reviewed through analysis of data being added to the FDA database and engineering investigations of equipment removed by FDA.

There is a parallelism between EDXRF analysis of wear particulates from filters and RAES analysis of wear particulates in fluids. Both methods analyze a representative sample of particulate populations. Both methods are based upon the bulk analysis of particulates. A portion of the sample in RAES and EDXRF is analyzed for its composition. Statistical analysis is used to determine the maximum amounts of all elements of interest that are allowed in samples. Removal and disassembling of components demonstrate the effectiveness of the method to detect abnormal wear and how relevant the limits for elements are to actual wear found in the system. The major difference between the two techniques is that RAES is permanently restricted to a ceiling in relation to the size of particulates it can analyze, i.e., 8

microns. If the sampling port for an oil sample is positioned such that the oil is drawn from the system after the oil passes through the filter element then the RAES results are representative of filtered oil. The issue described in the "Background" section above, oil residue in the filter element can interfere with RAES analysis.   If the oil sample is drawn from the system prior to the filter element then the RAES results represent unfiltered oil. In both cases, RAES results represent one cycle of the oil through the system. FDA results represent the wear experienced by the system over the life of the filter element, e.g., a filter element change every 50 hours, the debris extracted and analyzed by FDA represents the wear experienced by the system over 50 hours.

PRAM BETA PROTOTYPES

Initially, the task of extracting debris from oil filters was performed manually. The USAF productivity, reliability, availability and maintainability (PRAM) program provided funding to the JOAP-TSC to construct an alpha prototype & six beta prototype units that incorporated a miniature EDXRF system. The six beta prototype units were designed to automatically extract debris from oil filters, prepare patches for EDXRF analysis using vacuum assisted filtration, perform EDXRF analysis on the particulates, report particle counts and report the results of the EDXRF analysis.

Particulates are extracted from filter elements by a timed sequence of events that are controlled by a computer that involves the use of a solvent. Particles that are liberated by the sampling cycle of the PRAM beta prototype instrument pass through a particle counter, MetalSCAN. Ferrous and nonferrous particles are counted. The particles then are captured on a 20 micron filter patch substrate surface and held on the substrate by vacuum.

EDXRF analysis of the particulates that make up the debris extracted from filter elements is the heart of FDA analysis. Elements are chosen for inclusion for the EDXRF analysis based upon failure modes and metallurgy of the system's components. Elements and combinations of elements lead to identification of alloys that comprise the assets oil system. The capability of FDA to identify abnormally wearing components is directly related to the particle population that is analyzed. In the manual FDA method, 1 micron substrates were used to capture particles. However, 1 micron pore size substrates produced very thick samples and long filtration times. To automate the procedure to produce a substrate suitable for EDXRF analysis, the maximum substrate pore size had to be found where EDXRF element percentages correlated with the EDXRF element percentages obtained at 1 micron. A 20 micron pore size was determined to be the maximum pore size that could be used and preserve the FDA profile.

In the case of the J52 engine, 20 microns was chosen as the pore size for the substrate. The capture of the debris extracted from the filter element in a uniform and totally random fashion is necessary to obtain valid EDXRF results. A filter patch with debris on it is then analyzed by energy dispersive x-ray fluorescence (EDXRF) and the percentages reported by fundamental parameters (FP). Excessive loading of debris on a filter patch can interfere with the EDXRF measurement of the elements, produce high deadtime in the x-ray measurement and cause spectral shift which will cause the software to report erroneous results for the percentages of each element.   The percentages reported by fundamental parameters for each element are placed

in a spreadsheet and the limits for each element are defined statistically.

PROPOSED AND IMPLEMENTED SOLUTIONS FOR J52 ENGINES

A decision was made to investigate the historical record of RAES results on J52 engines. Particular attention was paid to the engines that had confirmed 4 ½ bearing failures. In analyzing oil samples by RAES, Fe is the major element used to indicate abnormal bearing wear. Ag represents silver plating that is used to plate bearing cages and other components in the oil system of the J52 engine. However, research of RAES results from J52 engines that had failed 4 ½ bearings had PPM levels of Fe and Ag that were much lower than previously published PPM limits for those elements. Some 4 ½ bearing failures had no Fe in the oil sample before failure. In January 2002, the following condition monitoring tools were added to monitor the J52 engine:

1.   Based upon the RAES data, Fe and Ag PPM limits were reduced --7 PPM for Fe and 1 PPM for Ag in an attempt to capture impending 4 ½ bearing failures. The result was that 30 engines fell immediately into the 7 PPM Fe and 1 PPM Ag categories and were candidates for removal. Further, if one took all the RAES results on J52 engines that had 7 PPM Fe or 1 PPM Ag in their oil analysis history, an additional 100 engines fell into that category. The frequency of sampling oil was doubled, i.e, from taking an oil sample every 10 hours to taking a sample every 5 hours.

2.   A field test was devised for the J52 engine and termed the coffee filter test. Whenever an oil filter is removed, the coffee filter test would be performed as follows: A ½ inch diameter circle is drawn on the coffee filter. The J52 filter element is placed into a plastic bowl with solvent and vigorously shaken. The filter element is removed and the debris is filtered through the coffee filter. The debris is scraped into the ½ inch diameter circle. If the debris fills the ½ inch circle, then the aircraft is down until an oil sample is analyzed by RAES.

3.   A chip collector was installed in the oil tank. The chip collector was to be examined for chips every 10 flight hours.

4.   Remove all J52 engine oil filter elements and send to the JOAP-TSC for FDA. Previously, J52 engine oil filters had no requirement to be removed based upon flight hours. Filter elements were left in the J52 engine for undetermined lengths of time.

J52P408 FDA/EDXRF ANALYSIS

PRAM beta prototype units and a Spectrace Quanx EDXRF unit were used to develop the EDXRF database for the elements associated with the J52. During this phase, the metallurgy of the engine oil system was not available, so we concentrated on defining the indication of excessive amounts of bearing material (M-50) in the engine system that would trigger a removal recommendation.

The initial filters removed from J52 engines were heavily loaded with debris and partially carbonized oil. To prepare substrates for EDXRF analysis and account for all debris that was

removed from the filter, the debris from the coffee filter test was washed onto the 20 micron filter substrate and combined with the debris extracted from the engine filter element to produce a sample for EDXRF analysis.

In numerous cases the debris deposit for the EDXRF sample was so heavy that it had to be manually removed from the initial 20 micron filter patch, re-suspended in solvent and a portion of the slurry deposited on a 20 micron substrate. The heavy amounts of carbon debris in the oil filter lead to the conclusion that the effectiveness of RAES analysis to detect abnormal wear in the oil system of the J52 would be greatly diminished as it was for the F404GE400 engine. The initial FDA profile and statistical limits were established for the J52 engine in about 3 weeks.

The principal components of M-50 are iron (Fe), chromium (Cr), molybdenum (Mo) & vanadium (V). [5]   The elements Fe and Cr were not good indicators of the presence or absence of M-50 because they are present in a multitude of metallurgies throughout the engine. The combination of V and Mo indicates M-50. The allowable amount of M-50 in the J52 engine was limited to the trim mean plus one standard deviation for the percentages of V and Mo.   M-50 is also present in the number 2, 3, 4, 5 and 6 bearing assemblies. The indication of M-50 can be from other bearing assemblies, however, because the 4 ½ bearing assembly is a known failure mode that can lead to loss of plane and/or life, that area of the engine is always looked at for the source of M-50. FDA successfully diagnosed six 4 ½ bearing failures for which RAES had no indication of abnormal levels of Fe or Ag. (see Figure 1) After the discovery of the six, 4 ½ bearing assembly failures, it was decided by the J52 engineers to change engine oil filter elements every 50 hours. Once the 50 hour cycle for an oil filter change began throughout the J52 fleet, RAES analyses began to get meaningful indications of Fe and Ag along with other elements.

Early in the J52 FDA program, a J52 engine was determined by inspection to have a failed 4 ½ bearing assembly, but the FDA previous to the discovery of the failed 4 ½ bearing assembly did not have an indication of M-50 and RAES values for Fe and Ag were in the normal range. The oil filter from the J52 engine with a failed 4 ½ bearing had excessive M-50. Why was there no indication of M-50 in the filter before the failure? The number of FDA analyses on each J52 engine at this point in time was very small, two or possibly three analyses per engine so, we concluded that the failure mode had a precursor that we had not identified. Examination of the FDA history on the engine showed a large amount of Ag in the previous FDA, well above the normal level for Ag. Silver is used as plating on J52 bearing cages. Now, the failure mode on the 4 ½ bearing became more defined. The conclusion was reached that percentages of Ag above the normal range could be a precursor to the failure of a 4 ½ bearing. If Ag was detected above the normal range by FDA, the engine's oil filter would be removed in 25 hours instead of 50 hours. The reason in reducing the sample cycle was to detect the impending failure of the 4 ½ bearing as soon as possible. A subsequent FDA could have Ag in the normal range and have excessive V and Mo percentages in the debris extracted from the filter, indicating excessive M-50 in the system and the engine would be removed. The particular scenario just described did occur. In fact, an engine out of overhaul had this exact situation happen-- it displayed excessive Ag at its first 50 hour FDA, it was placed on 25 hour filter removal cycle and the 25 hour filter had excessive Mo and V in it! The engine was removed from service and a subsequent

engineering investigation discovered a failed 4½ bearing assembly (see Figure 1.) RAES did not indicate abnormal wear and neither did the chip collector.
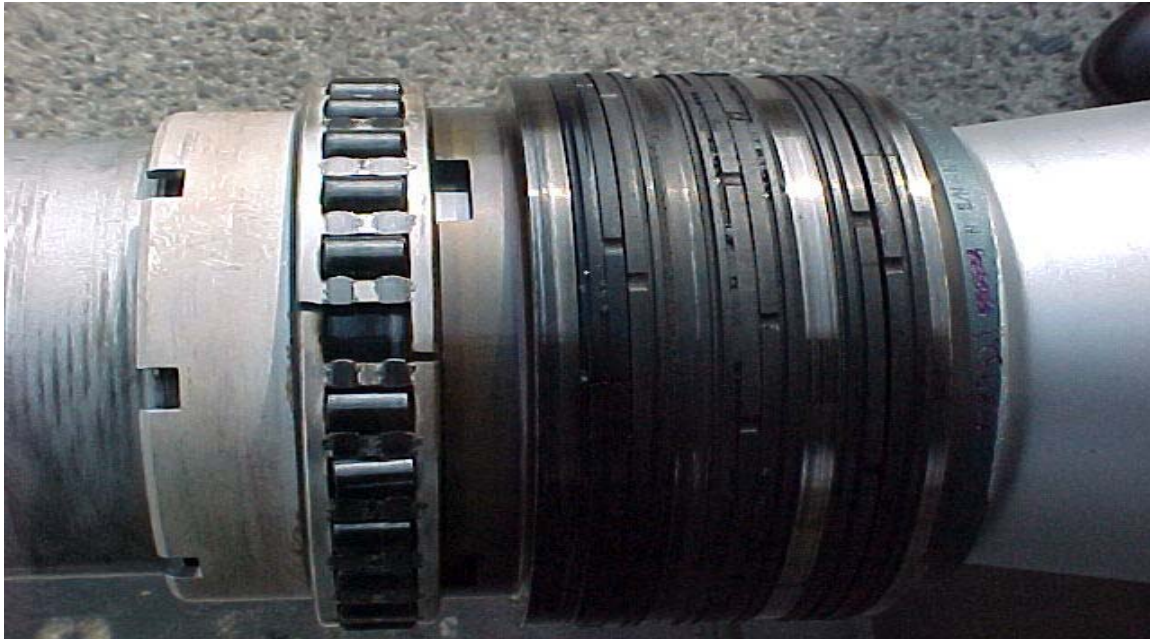
Figure 1. Broken 4 ½ bearing cage detected by FDA.

FDA EFFECTIVENESS OF FINDING 4 ½ BEARING FAILURES

When an engine is removed due to FDA finding excessive M-50 in the filter debris, the 4½ bearing assembly is automatically replaced. A contractor, Wyle Laboratories, was contracted by the J52 engineers to compile and analyze the FDA data. Wyle Laboratories devised a method to visually rate the condition of the 4 ½ bearing assembly. The rating system was as follows:
1 - pristine condition,
2 - silver plowing, roller end wear,
3 - bearing cage cracked,
4 - cage cracked -and rollers liberated and
5 - severely damaged. [6]

This type of inspection was based upon one individual's evaluation of the condition of all J52 4 ½ bearings. Pratt & Whitney manufactures the J52 engine for the U.S. Navy. Pratt & Whitney's bearing engineer's viewpoint was that the 4 ½ bearing assembly had failed at stage 2, silver plowing and/or roller end wear. The U.S. Navy's J52 engineers decided for their evaluation of FDA that stage 3 was a functional failure and the 4 ½ bearing had to be removed; at stage 2, the 4 ½ bearing assembly could still function even though the bearing assembly exhibited wear characteristics that were beyond allowable limits.

At NADEP Cherry Point, the J52 engineer's practices illustrate that the other sources of M-50 alloy in the J52 engine are experiencing wear/damage. If the 4 ½ bearing assembly is failed or intact, they examine all the bearings for the source of M-50 alloy. Some examples where the 4.5

bearing is in good condition, but excessive wear/damage is found in other areas are:

Engine serial number (ESN) - 711663, #4.5 good condition, replaced #3 thru #6 bearings
ESN - 678600, #4.5 in good condition, replaced #5, #6 bearing.
ESN - 711642, #4.5 in good condition, replaced #6 bearing.
ESN - 711673, #4.5 in good condition, replaced #5 bearing.

These few examples demonstrate that M-50 was being generated by other bearing assemblies and that these assemblies were worn to the point where they did not meet minimum tolerances. FDA is indeed finding abnormal bearing wear in other areas.

At a meeting in October 2003 hosted by the J52 engineers, the JOAP-TSC FDA technology was determined to be 95% effective in finding 4½ bearing failures. JOAP-TSC recently revisited the issue of the effectiveness of the FDA technology and found that the JOAP-TSC FDA technology is 98% effective in finding 4 ½ bearing failures. Currently, the JOAP-TSC FDA technology has been credited with finding 54, 4 ½ bearing failures prior to progressing to a catastrophic conclusion. [7]

In a recently published article, a reliability centered maintenance analysis (RCM) of FDA concluded that "FDA can be a powerful tool in identifying degraded bearings so they can be removed from service prior to failure. It meets all of the criteria established by the SAE standard for a condition-monitoring task. The analysis was an integral part of a formal RCM analysis process and provided the engineering support for identifying the potential and functional failure conditions RCM analysis requires. A separate analysis was performed to determine the appropriate inspection interval."[8]

OTHER FDA DISCOVERIES

The metallurgy of the J52 engine lends itself to providing some interesting element combinations. For example, when aluminum (Al), copper (Cu) and/or iron (Fe), exceed their respective normal ranges, it indicates that the oil pump was being damaged. Fe and Cu can indicate the oil pump and/or the number 1 bearing assembly. The number 1 bearing is not made of M-50, but 52100 steel, Fe and Cr are the principle components. A high silicon (Si) EDXRF signal can indicate the presence of glass blasting media. The presence or absence of glass blasting media is confirmed by microscopic analysis of the debris. Glass blasting media is composed of glass beads that are spherical in shape and are 30 microns and larger in diameter. Glass blasting media can contaminate the engine system. Magnesium (Mg) originates from the alloy that composes the gearbox housing. Fe exceeding its normal range can indicate gearbox and/or #1 bearing assembly.

CONCLUSIONS

The JOAP-TSC FDA technique was a huge success in its capability of identifying a catastrophic wear mode in the J52P408 4 ½ bearing assembly. <u>A success rate of 95% was attributed to the JOAP-TSC FDA technique by the U.S. Navy J52 engineering community.</u>

The PRAM beta prototypes have performed remarkably well considering some of the environments they have been thrust into. The U.S. Navy has purchased 20 production models, FilterCHECK 300's, that are stationed at land bases and on ships performing FDA on J52 engines on a daily basis. Since its' introduction and integration into the J52 maintenance program, the   JOAP-TSC FDA procedure has discovered 54 engines with 4 ½ bearing assemblies that have failed.   All aircraft with afflicted engines had their engines replaced without any further problems. Early detection of 4 ½ bearing assembly failure avoided the catastrophic conclusion of losing the crew and aircraft. **The JOAP-TSC FDA technology has been credited with keeping this invaluable aircraft operational and functional during the Afghanistan and Iraq conflicts.**

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