Enhancing Propulsion System Condition Monitoring for the RNZAF

Adrian Weller
Defence Technology Agency, New Zealand Defence Force
HMNZ Naval Base Devonport, Auckland, New Zealand.

Abstract

The Defence Technology Agency (DTA) of the New Zealand Defence Force has undertaken a programme of work to develop/improve condition monitoring techniques employed for Royal New Zealand Air Force (RNZAF) propulsion systems. This paper presents on the enhancement of wear debris assessment techniques. On DTA's recommendation the RNZAF recently procured a semi-automated filter debris analysis (FDA) machine, which extracts, quantifies and provides elemental composition of the extracted filter debris. This paper provides an overview of the task to implement this technology into a cohesive condition monitoring programme for the RNZAF. Considerations and lessons learned are discussed and several case studies of component failures are presented that highlight the capability of the FDA machine to accurately detect incipient oil-wetted component defects.

Key Words: filter debris analysis, condition monitoring oil-wetted components.

Introduction

DTA and the RNZAF recently reviewed the current RNZAF capability to determine the health of propulsion system oil-wetted components. While it was determined that the extant techniques were generally satisfactory to assure airworthiness there was a significant capability gap in the ability to accurately diagnose incipient defects with sufficient lead time to prevent unscheduled removals/operational disruption and avoidable secondary component damage.

The RNZAF currently rely on inspection of magnetic chip detectors (MCD's) as the primary wear debris analysis (WDA) technique. MCD inspection intervals and procedures are as specified by the original equipment manufacturer (OEM) maintenance manuals and quantitative trending of MCD debris is not carried out. Debris which fails inspection criteria is sent to DTA for further analysis on an ad hoc basis.

DTA's experience in the analysis of suspect MCD debris has been, in the majority of cases, the component of interest was subsequently rejected and found at overhaul to contain significant damage, i.e. the failure mode was already advanced. The RNZAF through vigilance of MCD inspections, conservative component removals and arguably some good fortune, have avoided any catastrophic failures that could have caused potential loss of an aircraft. However there have been numerous occasions of unscheduled removals that have significantly impacted operations.

In the past, the RNZAF and DTA have applied spectrometric oil analysis programmes (SOAP) to RNZAF aircraft. However, SOAP has not been used for over a decade due to the almost exclusive use of fine filtration filters on the RNZAF fleet. Fine filtration effectively

removes most of the fine debris that forms the health data used in SOAP. Furthermore, in the past, even without fine filtration, the benefits of SOAP were not found to outweigh the effort expended.

Assessment of debris captured in oil filters has also been used on an ad hoc basis by in the past. Although it is recognised that filters do contain valuable diagnostic health data use of filter debris analysis has been very limited due to:

- Lack of robust processes to extract/analyse debris, and hence limited ability to diagnose defects.
- Lack of analysis capability at the operational level to assess filter debris.
- The labour intensive nature of analysing filter debris, particularly in the laboratory, making routine analysis not economically feasible.

Despite the RNZAF's avoidance of catastrophic mechanical component failure there have been isolated examples of failures that did represent an unacceptable level of airworthiness risk. The most significant recent case (2007) was an RNZAF Iroquois T53 N2 gearbox in which a planetary gear failed [1]. MCD indications had occurred several times prior but only very small quantities of debris were found, which extant inspection criteria did not immediately reject the component. 3 minutes into a 20 minute hover check a final MCD cockpit indication occurred at which time the aircraft was immediately landed and secured. Subsequent removal and inspection of the N2 gearbox found that two teeth had been fractured off one of the planetary gears, see Figure 1. Catastrophic failure of the gearbox was imminent and would have resulted in a significant in-flight event had the aircraft not been carrying out a maintenance hover check. Wear found on the failed gear indicated an unusual mesh condition which had caused scuffing and spalling on the affected gear. This suggests wear debris was shed as a consequence of this unusual wear mode prior to the failure. In this case filters had not been subject to laboratory analysis.

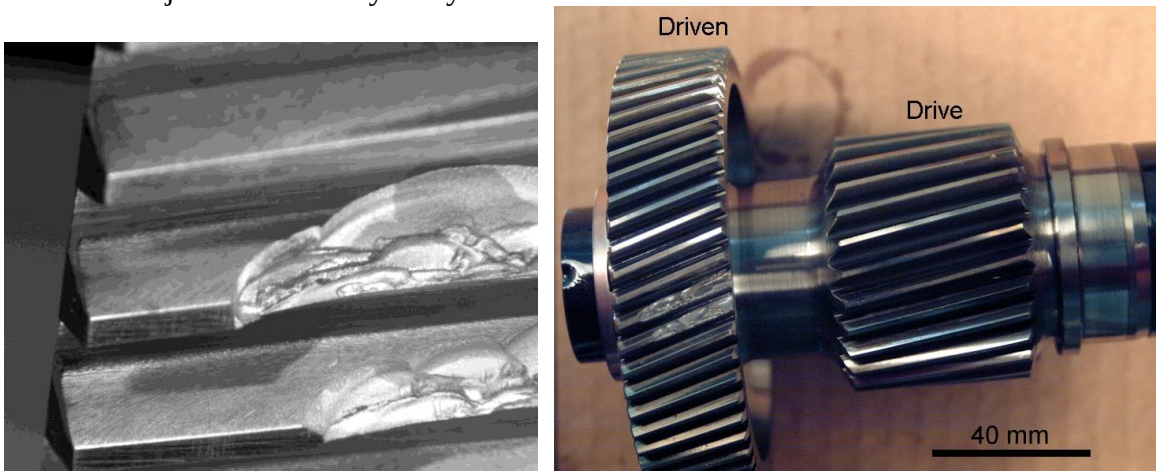


Figure 1: Failed T53 Planetary Gear from RNZAF Iroquois.

The recent (2009) fatal crash in the North Sea of Eurocopter AS322L2 Supa Puma G-REDL [2] particularly highlights the criticality of helicopter main gearboxes. This crash has caused significant concern as the aircraft was fitted with a HUMS and was subject to an approved wear debris inspection regime. One of the key findings of the accident investigation was that a chip on the MCD of the main gearbox was found 35 hours prior, but was not immediately diagnosed as critical, allowing the aircraft to return to service for a further 25 hours, after

which, the accident occurred. That initial chip was subsequently analysed and found to be consistent with gear material used to make the planetary gears, and had morphology indicative of a surface spallation. The investigation report states that at the time of the initial chip the gearbox oil was drained and filtered and the filters were examined with no other contamination found [2]. No detail as to the filter inspection method was provided, however it is DTA's experience on numerous occasions that filters subject to a visual inspection and deemed to be free of debris have been subsequently found to contain critical debris once subject to laboratory extraction. It is outside the scope of this paper to further discuss the Supa Puma crash, however the point made is that there still appears to be a gap in the ability to accurately diagnose oil-wetted component faults with accuracy and confidence using MCDs as the primary indicator. Discussion of vibration signatures assessed by the HUMS and the methodology of MCD indications being fed to the HUMS/cockpit indication is recognised but not discussed in this paper.

Development of Condition Monitoring Programmes in the RNZAF Context

The RNZAF operates a small but diverse fleet of aircraft that includes a significant proportion of rotary wing types (current and pending). One of the main difficulties in operating very small fleets is that unscheduled maintenance events have a large impact on the ability to deliver capability, i.e. there is rarely a replacement aircraft available to complete a mission should one become unserviceable. Therefore the early detection of a defective component is highly desirable in the RNZAF context.

In light of the RNZAF fleet, lessons learned from both past RNZAF/DTA wear debris analysis programmes, and those conducted by other militaries and industry, a set of requirements were formed from which the RNZAF wear debris analysis enhancement programme was to be developed. These requirements were that the programme must:

- Be applicable to legacy fleets without any aircraft modifications.
- Minimise required expertise and manpower.
- Provide a means of data management.
- Provide means of robustly quantifying debris.
- Provide assessment of elemental composition.
- Provide assessment of debris morphology.
- If possible be a mature technology suitable for a military environment.

DTA reviewed current of the shelf technologies available that would best meet the above requirements. After much review the FilterCHECK FC400 XRF semi-automated filter debris assessment machine manufactured by GasTOPS Inc was selected and recommended to the RNZAF for procurement. This was subsequently approved and procured in mid 2009. The FilterCHECK (FC) was envisioned to form the foundation of an enhanced wear debris analysis programme for the RNZAF. Two of the key reasons for selection of the FC were that it was developed specifically for the purpose of filter debris analysis in a military type operational environment and that it has a proven track record in delivering diagnostic/prognostic health data that has prevented component failures with significant failure warning lead time. Reference [3] provides a sound overview of the FC development and application with key users the USN and the CF. Procurement of a mature product allowed realisation of benefits from enhanced wear debris assessment to the RNZAF in the shortest

time frame, compared to in-house development of a similar capability. However, had a suitable product not been available at viable cost DTA would have embarked on development of such a system.

Overview of the FilterCHECK FC400 System

The core elements of the FilterCHECK FC400 system (Figure 2) are discussed in the following sections:

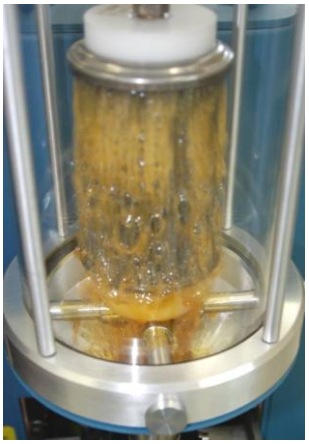
Automated Filter Debris Extraction

Filter debris extraction is carried out in a wash chamber by back washing filter elements with a continuous flow of wash fluid. Pulses of compressed air are also combined intermittently with the wash fluid to assist particle release. Figure 2 shows a filter wash in action. Once optimised, the wash process parameters, such as compressed air pressure, wash time and so on, are set for a given filter type to be processed. This ensures that the debris extraction method is consistent. This is a key requirement to allow robust quantification and trending of filter debris.

The wash chamber system has two pre-programmed wash functions; a sample wash and a full wash. The sample wash extracts a representative sample of debris for the XRF analysis over 60 seconds into the XRF filter patch (described below). The full wash then continues to wash debris from the filter for a full 10 minutes. In the standard configuration the debris extracted during the full wash cycle is counted only but not retained for analysis. The wash fluid itself is recycled through the wash chamber after being cleaned through a 3 micron rated filter.



(a) Overall Machine



(b) Wash Chamber



(c) MetalSCAN sensor

Figure 2: Elements of the FilterCHECK

Debris released from the filter, suspended in the wash fluid, is passed through the MetalSCAN sensor located at the exit of the wash chamber. The MetalSCAN sensor is an inductive coil system proprietary to GasTOPS Inc. An in-depth discussion of the MetalSCAN sensor coil system is not provided in this paper other than to say it uses changes due to the inductive effect of passing ferromagnetic (Fe) and non-ferromagnetic (NFe) debris through the system of coils. Particle size is inferred by the output signal amplitude and material type

(Fe or NFe) inferred by the signal characteristic. The signal output from each particle sensed is then classified as either Fe or NFe and then into small, medium and large size bins, as in Table 1. An inferred total Fe mass is also calculated. It is understood that the respective size and mass inference is calculated based on the response from spherical particles of a particular alloy. As debris varies in alloy type and shape these inferred sizes and mass may not exactly reflect the actual debris, but are nonetheless sufficiently accurate for a consistent debris quantification method.

Table 1: Standard Size Bins used by MetalSCAN Sensor

	Inferred size (microns)	
Size Bin	Ferrous	Non-Ferrous
Small	115-199	400-549
Medium	200-499	550-849
Large	500+	850+

Filter Patch Maker

A drawer with a funnel and Millipore type filter patch holder assembly is integrated into the FC, see Figure 3. When extended this drawer sits under the outflow of wash fluid exiting the wash chamber/Metalscan sensor. Debris is filtered through and captured onto a 47mm diameter filter patch. A Millipore nylon net patch of 20 microns mesh size is the standard type of patch used. When retracted, the sample drawer slides into the integral XRF system described below. This patch making system is designed to only capture a representative sub-sample of the total filter debris. The reason for only capturing a representative sample is to prevent excessively thick layers of debris that would effectively saturate the XRF detector if all debris was captured on one sample patch. The filter patch of debris made for XRF analysis is hereon referred to as the 'XRF patch'.

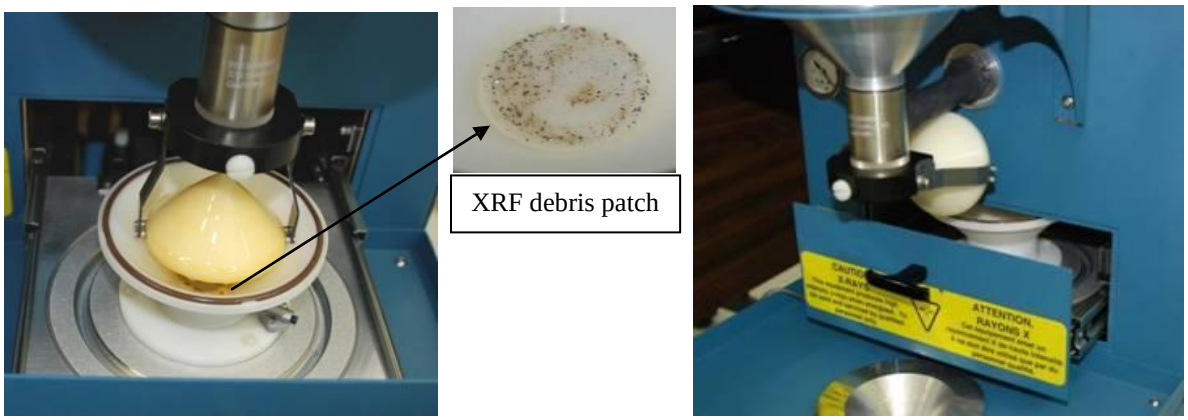


Figure 3: FC XRF Sample Patch Maker and Insertion into Integral XRF Unit

XRF System

The XRF chamber is located inside the body of the FC. When the sample drawer is retracted and the XRF system activated, the patch maker platen is lifted up into the cylindrical XRF chamber where it forms a seal and a soft vacuum is applied to the chamber. Once the vacuum and other shielding interlocks are satisfied the XRF system can be energised. This applies a

wide beam incident x-ray to the debris patch. As such the characteristic x-rays received by the detector provide an aggregate spectrum of the elements present in the debris patch.

Software

The FC400 system requires a laptop to run the FC XRF system software and to extract both the XRF and MetalSCAN data for analysis. Sample result management is done with GasTOPS Lube Analyst (LA) software, see Figure 4. The LA software allows for sample results to be traceable to their parent components (engines, gearboxes etc) and can be arranged in a Fleet > Aircraft tail > Component configuration. LA also allows for limits and recommendations to be set up as appropriate for specific components. Overall LA is similar to many other sample management software packages used in industry.

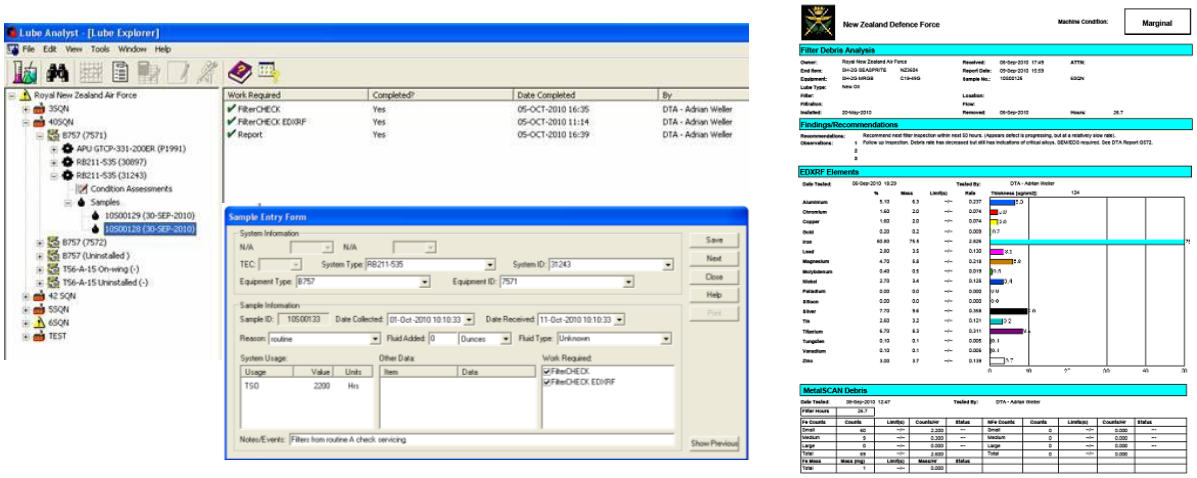


Figure 4: GasTOPS Lube Analyst Software

FilterCHECK FC400 Operation

In standard configuration the operation of the FC400 is as follows:

1. Sample filter installed in wash chamber.
2. XRF sample drawer extended – Sample wash carried out and XRF debris patch made.
3. XRF drawer retracted – XRF system energised – XRF spectrum acquisition (6 mins).
4. Full wash carried out (10 mins) – debris extracted but not captured.
5. Once both XRF and Full wash cycles have completed sample chamber is rinsed down and the final MetalSCAN counts are uploaded along with the XRF spectrum.
6. Lube Analyst software then used to compile/analyse results against the parent component.
7. LA software used to compile a summary report once comments are entered.

Total process time, filter to filter, approx 30 mins.

Total Debris Capture System

Upon initial review of the FC system operation DTA had one key concern; that not all debris was captured. Only the debris removed during the XRF sample patch is retained for further analysis. Review of MetalSCAN counts during initial testing indicated that the sample wash removed between 30-60% of the total debris. It was also observed that filters that were

heavily contaminated with finer debris, including carbonaceous fines from oil coking, tended to release only finer debris in the initial sample wash.

To address the above issue DTA devised a system to capture the debris removed during the full wash cycle. This was based on an adapted Millipore funnel system and uses a 60 micron 47mm nylon net filter patch to capture debris, see Figure 5. The 60 micron patch was selected as it was the smallest mesh opening that still allowed the required fluid flow rate to match the output of the full wash cycle. An overflow tube was also incorporated for cases of extreme debris contamination where total patch blockage occurred. The overall question with this total capture system was whether the benefit of capturing this debris outweighed the additional effort?

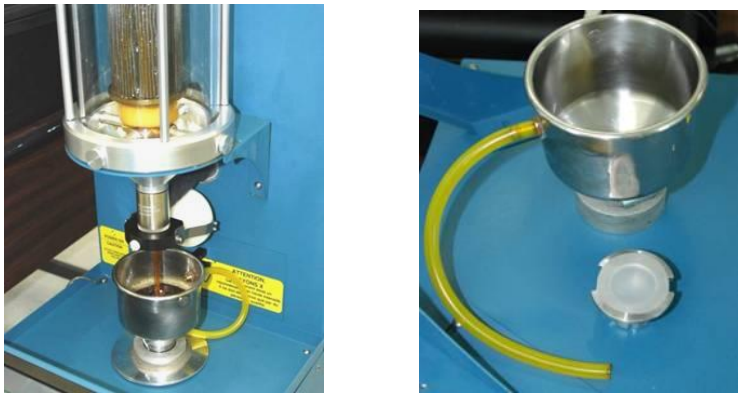


Figure 5: System devised to capture filter debris extracted during full wash cycle.

Introduction to RNZAF Service - Approach

The focus of the introduction to service was ensuring that a sound understanding of the machine's analysis capability was developed and the FC analysis of filters from aircraft was undertaken in a way that would build up fleet data while still being compatible with extant serviceability criteria.

With respect to extant OEM wear debris serviceability criteria, it is noteworthy that inspection guidance and criteria varies significantly in quality, from very well defined, to relatively ambiguous. Filter debris analysis is in most cases not well defined by OEM guidance with many not specifying the appropriate technique for debris extraction and analysis. This generally results in very 'coarse' visual inspections of filters for gross contamination only. Therefore in the majority of cases use of the FC was considered more robust than current operational level filter inspections.

An introduction to service plan was devised by the RNZAF/DTA to address the above considerations. This entailed a FC trial programme being run over a period of 12 months, during which time the following would be in place:

The FC machine was to be run under full DTA control at DTA's laboratory. This was to:

- Carry out testing on the machines fundamental analysis capability.
- Process samples in a controlled environment in lieu of approved FC procedures.

- Allow traditional laboratory analysis (optical microscope, scanning electron microscope/energy dispersive x-ray spectroscopy (SEM/EDS)) analysis to be conducted by DTA staff in parallel to the FC testing. i.e. provide a robust backup analysis to the FC result, therefore ensuring a critical defect not immediately apparent in the FC results was still detected.

The FC Trial was to be run under an RNZAF Trials Directive in order to:

- Provide engineering authority to conduct the trial.
- Direct that filters shall be sent for FC analysis whenever they are removed – both routine removals and non-routine removals for by-pass events, trouble shooting etc.
- Direct that extant filter inspection procedures still define the serviceability criteria; with FC results as advisory only (unless they provide compelling evidence of a critical defect).
- Define procedures for filter sample preparation and sample data collection.

The overall approach with the FC trial was to have any filter removed subject to FC analysis, but not to impose any additional filter inspections above what extant maintenance required. This was to impose the least maintenance effort at the early stage of the trial when benefits had not been proven.

At the conclusion of the trial, dependant on results, it was intended that a full set of approved procedures for sample processing, component specific limits etc would be developed ready for hand over to full RNZAF control. At that point only abnormal FC samples would be sent to DTA for full SEM/EDS analysis. The envisioned permanent FC programme is described in Figure 6.

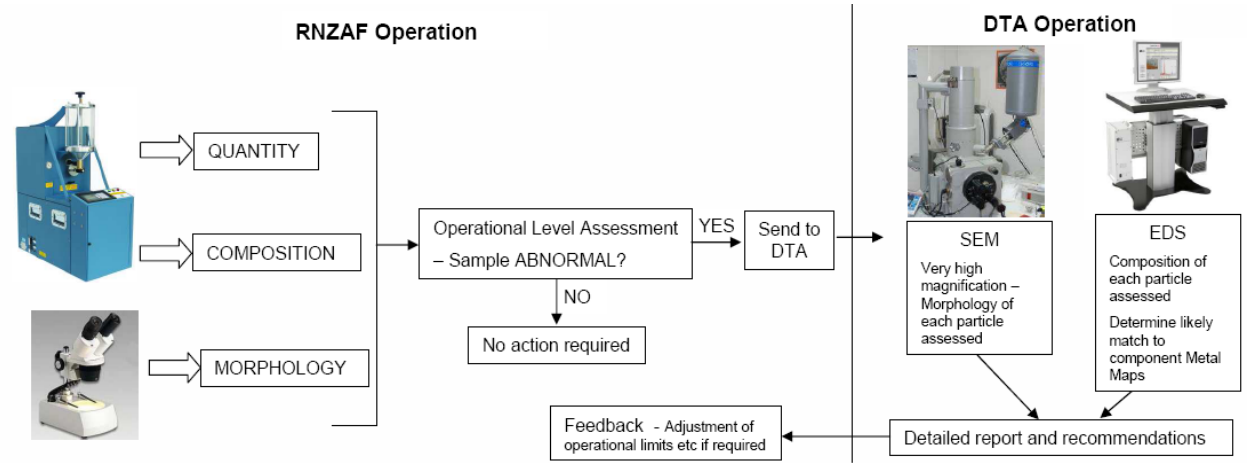


Figure 6: Proposed Permanent FC Analysis Process

Assessment of FC Analysis Capability

MetalSCAN sensor

At the time of writing a full quantitative review of the MetalSCAN (MS) sensor performance had not been undertaken. Qualitatively comparison between the size of Fe debris counted in the small, medium and large size bins was found to be consistent with size distribution as measured under optical microscope/SEM. The MS sensor appears to be relatively insensitive to NFe debris with only larger chunk like particles counted on the order of 0.5 mm diameter and larger, which is consistent with the Table 1 NFe size bins the MS is calibrated to. However it does highlight that NFe particles such as silver plating will not likely be counted, leaving the XRF system and visual inspection as the only reliable means of detection of smaller NFe debris.

XRF System

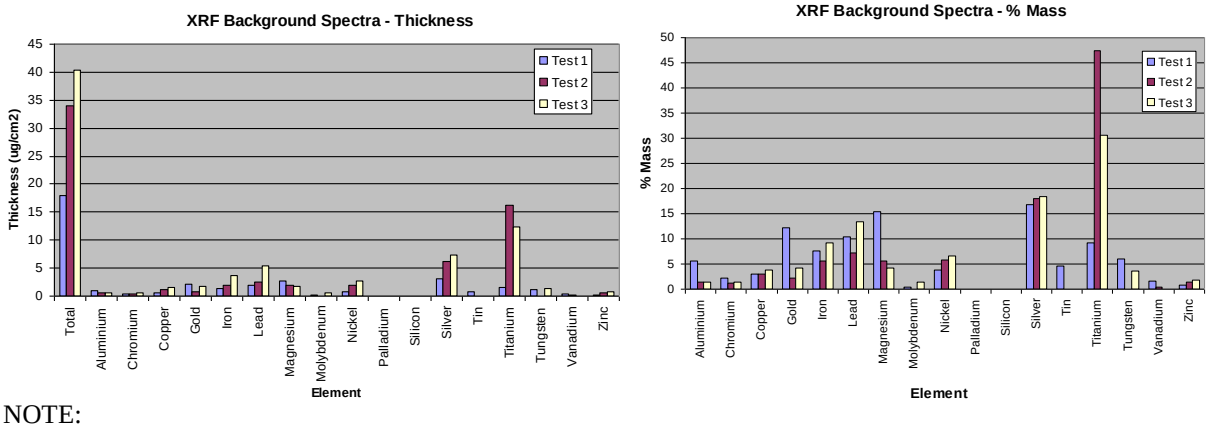
Testing was carried out on the XRF system to determine what, if any, background noise was present in the spectra acquired, and the ideal 'thickness' of debris on the XRF patch for robust analysis. Background noise is defined in this context as the baseline XRF spectrum obtained due to the XRF filter patch itself and that of the residual wash fluid, without any filter debris being present. To determine background noise the XRF system was energised and XRF spectra acquired in the configurations defined in Table 2, with results in Figure 7.

Table 2: Background XRF Spectra Test Configurations

	Test Configuration		
Test	Sample patch holder/funnel [a]	20 micron 47 mm Nylon net Millipore patch	Wash Fluid Rinse – 'Dirty' recirculated Fluid [b]
1	x		
2	x	X	
3	x	X	x

[a] Cleaned with light solvent and dried – no residual wash fluid.

[b] Rinsed down with recirculated wash fluid that had been operating in the FC and had processed approx 50 actual filter samples.



NOTE:

- Thickness is the measure of mass calculated by the GasTOPS XRF spectrum analysis program based on thin film analysis techniques.
- % Mass is the proportion of the inferred thickness of each element.

Figure 7: Background XRF Spectra Obtained

Background spectra test results indicated that there was some background XRF emission from the filter patch support screen assembly itself, the largest single peak being that of silver. Addition of the 47mm 20 micron nylon net Millipore patch showed a large increase in the quantity of titanium detected, indicating the presence of titanium in the Millipore patch itself. Review of the Millipore nylon net material suggests this is due to the addition of titanium dioxide typically added to nylon material for a 'white' colour appearance. A discernable increase in silver was also noted although no explanation was apparent.

Addition of the recirculated wash fluid again showed an increase in the total mass detected indicating the wash fluid does contain matter that influences the XRF spectrum. Discernable increases in mass of both iron and lead were apparent indicating that these particles may be present in the recirculating fluid and may become deposited on the XRF debris patch even though the 20 micron patch mesh size is clearly larger than the 3 micron rating for the wash fluid filter.

The above test results were not meant to be an exhaustive analysis of the background XRF noise, rather they were used to set sensible guidelines for interpretation of XRF spectra from actual filter samples. To obtain robust XRF spectra of actual filter debris there must be sufficient mass of debris present on the sample patch. Given that the total mass of the bare filter patch with residual wash fluid is approximately 40 $\mu g/cm^2$, a guideline was set for at least 3 times this mass to be present for an XRF spectrum of a filter sample to be considered valid.

XRF Detection of Critical Alloys

One of the key requirements of the FC was to be capable of detecting critical alloys in filter debris, particularly gear and bearing materials. Samples of common critical bearing and gear alloys were obtained from material removed by diamond file from actual bearing and gear components of known alloys. The exact composition of each debris sample was validated using SEM/EDS. The alloys tested are in Table 3, where the as manufactured composition is also given for reference.

Table 3: Actual Alloy Compositions of Several Common Critical Oil-wetted Components [4]

								Other elements not in XRF	
Alloy	**Alloy Spec**	**Cr**	**Fe**	**Mo**	**Ni**	**Si**	**V**	**C**	**Mn**
M50	AMS 6491	4.1	89.3	4.3		0.2	1.0	0.9	0.3
M50 NiL	AMS 6278	4.2	86.4	4.3	3.4	0.2	1.2	0.1	0.3
SAE52100	MIL-S-7420, AMS 6444	1.5	96.8					1.0	
AISI 4340	AMS 6415	0.8	96.0	0.3	1.8			0.4	0.7
AISI 9310	AMS 6265	1.20		0.12	3.30	0.25			0.55

Each of these samples was deposited on a clean XRF patch in the FC machine and subject to XRF analysis. The most extensive analysis was conducted on M50 NiL bearing steel (AMS 6278) with varying quantities of debris on the XRF patch. Results are presented in Figure 8.

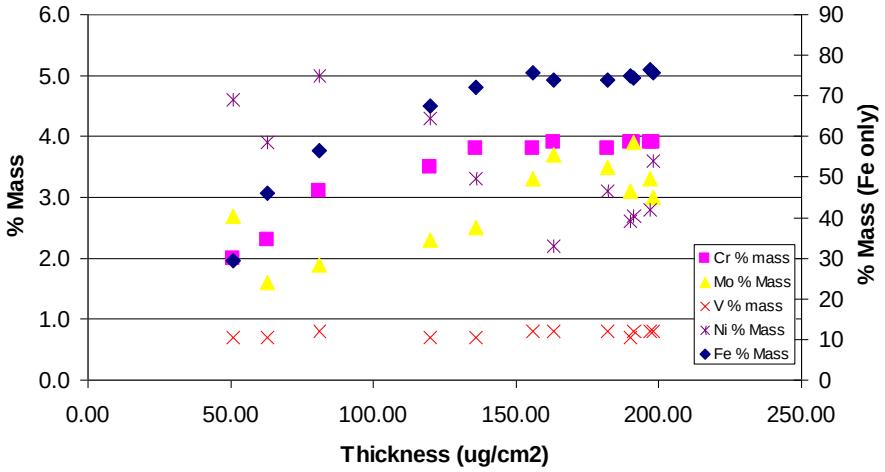


Figure 8: XRF Spectra M50NiL Sample vs. Sample Thickness

Figure 8 shows the calculated % mass of the principal alloying elements of M50 NiL steel vs. thickness of debris. Compared to the actual composition of M50 NiL the FC XRF spectra show good agreement with sample thickness above 120 μg/cm^2. Tests for samples of other alloys were also conducted which gave similar results, with the XRF spectra showing proportions of key elements approaching the actual proportion with increasing sample thickness. A sample thickness of 200-400 μg/cm^2 appeared to give the most accurate spectra as the ratio of signal from the debris to background noise increases. Overall the XRF spectra of the respective alloy samples showed good agreement with SEM/EDS spectra comparison of composition.

It was observed that Vanadium was always robustly indicated, that is in alloys that do contain Vanadium (M50, M50 NiL) it was indicated in relatively accurate proportion, and in alloys that do not contain Vanadium (9310, 4340, 52100) it was not indicated at all. Molybdenum was also similarly robustly indicated. As such, the presence of both Mo and V, along with Cr are concluded to be key indicators of M50 and M50 NiL bearing steels.

As 9310, 52100 and 4340 steels contain lower proportions of alloying elements it was more difficult to obtain robust accurate spectra, i.e. the signal to noise ratio was lower. For example, while 9310 and 4340 both indicated the presence of Cr and Ni they were not robustly distinguishable from each other.

The above testing of known alloys prepared from actual components with minimal contamination from other alloys and debris represents the most ideal conditions for obtaining accurate XRF spectra using the FC. As the XRF system only provides an aggregate of the debris composition it will become increasingly difficult to identify critical alloys when they are mixed with other ‘normal’ benign metallic debris. This is an important point as the goal of the FC is to provide long lead times in detection of defects, which may mean only small quantities of critical debris are present, i.e. the initiation of a bearing fatigue spall. Alloys such alloys such as 52100 with low levels of alloying elements are essentially indistinguishable by XRF spectrum alone when mixed with metallic debris from various components that use high chromium steel. Therefore it is considered necessary to conduct an examination of the debris morphology under optical microscope as part of the FC process to close this potential gap for these critical particles going undetected from the Fe debris rate quantity and XRF spectra alone.

Component Condition Indicators

From the review of FC capability the FC only provides robust quantification of ferrous debris, although this is satisfactory as the majority of critical oil-wetted components are ferromagnetic. Quantification is given as the total counts in each MS size bin and the total inferred mass. Each quantity can then be converted into the average debris rate over the period the filter was installed, by dividing by the period the filter was installed, referred to as the time on filter (TOF). As the TOF can vary greatly the calculation of debris rate from the debris quantity is critical for robust assessment of component health.

Debris rate = Qty / TOF (e.g. Total Fe counts/hour and Total ferrous mass/hour)

The total Fe debris count rate and total Fe debris mass rate were selected as the primary quantity condition indicators. The total Fe count and mass alone were selected as secondary metrics from which the total sum of debris over several samples could be assessed to diagnose the extent of a particular defect if required, i.e. equate to the area of a spall. Limits for wear rate and quantity were to be derived from fleet data for each component type monitored with baselines developed from serviceable components.

For elemental composition the condition indicator was to be the presence of key alloying elements found in critical alloys, such as those tested in Table 3. The exact elements targeted were to be selected based on component material maps (metal maps) of bearings and gears for each specific component monitored. In addition any other known failure modes were reviewed to target any other indicating elements.

One limit imposed to all samples based on evaluation of the XRF system was the minimum debris thickness of 120 $\mu g/cm^2$. XRF samples with insufficient debris to meet the minimum thickness were to be repeated with additional sample debris, or regarded as inconclusive if no further debris was extracted.

Overall the approach to developing limits was to build up data of the wear rates and XRF spectra ‘fingerprints’ that define a complete wear debris ‘profile’ of each component monitored over its time in service from overhaul to overhaul, i.e. wear in – normal running – wear out. Feedback from any component overhauls/repairs was also sought to validate FC profiles and failure signatures.

Sample Filter type

Each component to be monitored will have a different lubrication system design, but will usually include one or more filters that are designed to filter all fluid scavenged from the system before it is returned to the main reservoir; usually termed the scavenge filter. As the scavenge filter collects debris from almost all the oil wetted system, including the ‘working’ components, it is generally the primary filter selected for FC monitoring. A review of the lubricating system design should be carried out to ensure that the appropriate filter(s) are selected for each component monitored.

Review of RNZAF Fleet Data

At the time of writing this paper a limited number of filter samples had been processed from components in service. However several case studies are presented below which highlight the capability of the FC to detect defects.

RB211-535 HPT Bearing Failure

The RNZAF have 2 Boeing 757-200s with Rolls Royce RB211-535E4B engines. A significant bearing defect was detected in one RB211 engine by the FC in the very first set of RB211 filter samples processed. Filter and MCD samples were sent for urgent analysis as part of preparations for a critical mission of the RNZAF 757. In lieu of any other fleet FC data for this engine type the respective sample results could only be compared to each other and assessed in conjunction with DTA FC experience with other components. Results for the respective engine serial numbers (ESN) 30897 and 31243 are summarised below in Table 4.

Table 4: RB211-535 FC Results - Comparison of 'Defective' and 'Normal' Engine

ESN 30897

Time on Filter (hrs)	300

Size Bin	Counts	Counts/Hour
Small	347	1.16
Medium	29	0.10
Large	0	0.00
Total	376	1.25
Fe Mass	**Mass (mg)**	**Mass (mg)/Hour**
Total	6	0.02

Element	% Mass	THICKNESS (µg/cm2)
ALUMINIUM	13.4	37.8
CHROMIUM	2.8	7.9
COPPER	0.4	1.1
GOLD	0.6	1.7
IRON	67.7	191.2
LEAD	-	-
MAGNESIUM	0.6	1.7
MOLYBDENUM	0.1	0.3
NICKEL	2.0	5.6
PALLADIUM	0.0	0
SILICON	0.7	2
SILVER	2.1	5.9
TIN	0.0	0
TITANIUM	3.0	8.5
TUNGSTEN	5.7	16.1
VANADIUM	0.3	0.8
ZINC	0.5	1.4
		TOTAL (µg/cm2)
		282

ESN 31243

Time on Filter (hrs)	300

Size Bin	Counts	Counts/Hour
Small	26	0.09
Medium	3	0.01
Large	0	0.00
Total	29	0.10
Fe Mass	**Mass (mg)**	**Mass (mg)/Hour**
Total	0	0.00

Element	% Mass	THICKNESS (µg/cm2)
ALUMINIUM	10.1	5
CHROMIUM	4.3	2.1
COPPER	4.0	2
GOLD	5.2	2.6
IRON	24.7	12.3
LEAD	-	-
MAGNESIUM	1.3	0.6
MOLYBDENUM	0.8	0.4
NICKEL	9.7	4.8
PALLADIUM	0.0	0
SILICON	2.5	1.2
SILVER	11.7	5.8
TIN	0.0	0
TITANIUM	20.6	10.2
TUNGSTEN	1.8	0.9
VANADIUM	0.6	0.3
ZINC	2.7	1.3
		TOTAL (µg/cm2)
		49.5

Table 4 shows ESN 30897 had an order of magnitude greater debris count rate, suggesting it was abnormal compared with ESN 31243. The XRF spectrum for 30897 showed debris was primarily Fe but also had key elements of chromium, nickel and vanadium present. It also showed a high tungsten peak. These key elements were considered to be robustly indicated with a sample thickness of 282 µg/cm^2. In comparison the XRF spectrum for 31243 was

essentially too devoid of debris for a reliable spectrum to be obtained, i.e. there was little debris at all in the filter.

The XRF spectrum of 30897 was reviewed against the metal map for the RB211-535. This indicated only one plausible alloy, 18-4-1 steel (18% W, 4% Cr, 1%V), used in several main engine bearings as an inner race material. Due to this finding and the high debris rate compared with the opposite engine, the overall assessment of the FC result was 'Abnormal' with the diagnosis of a potential main bearing defect made.

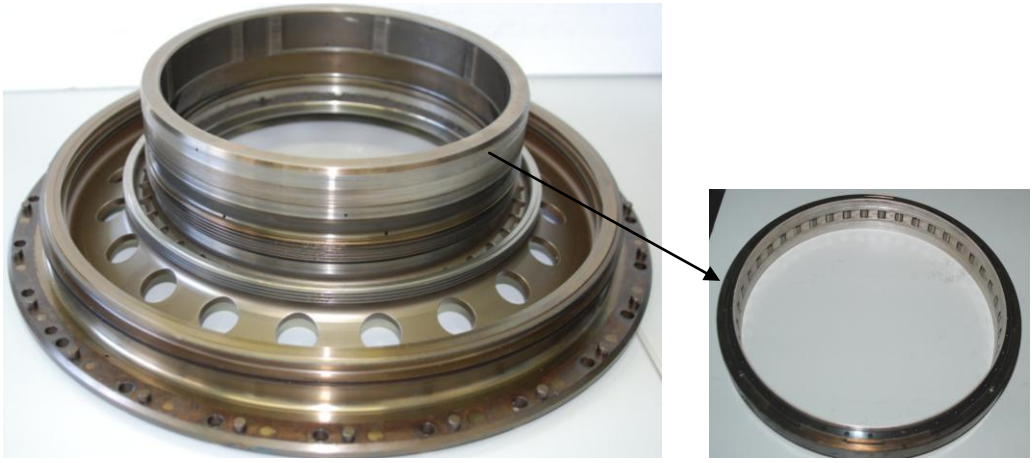
Review of the extracted filter debris under optical microscope and SEM/EDS found it to consist primarily of fine curls of cutting debris exhibiting some heat tinting. This type of debris morphology was not a typical bearing fatigue spallation and as such was considered an unusual wear mode.

Associated with the 30897 filter debris was debris on the master MCD of 30897. The MCD debris consisted of a wipe of fines and several small particles. SEM/EDS analysis was conducted on the small discrete particles present; the fines were unable to be extracted from the Sellotape adhesive. EDS spectra showed particles of silver plating and steel consistent with 4340 steel. Several particles were also found to consist of approximately 6-9% W, 3% Cr and 0.5% V, indicative of 18-4-1 steel, which were similar in morphology to those found in the scavenge filter sample. Overall the size and quantity of the respective particles did not fall within maintenance manual criteria for immediate engine rejection and without further data would be diagnosed as potential minor distress to a bearing, but would not have invoked the highest level of alert.

However with the FC data and the MCD indication together a robust conclusion was able to be made that the defect was serious and warranted the engine being placed on highest alert. This decision resulted in a decision to change the aircraft scheduled for the mission. Subsequent inspections found debris to be generated by the engine after only several hours further operation and was therefore removed for investigation.

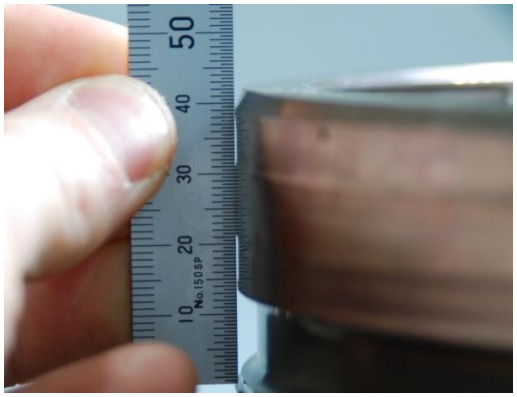
Teardown inspection of engine 30897 revealed the HPT aft shaft bearing cage (made from silver plated 4340 steel) was rubbing heavily with the inner race of the HPT aft shaft (made from 18-4-1 steel), as shown in Figure 9. This wear mode was entirely consistent with the debris extracted from the scavenge filter and validates the diagnosis that was able to be made using the FC results. Validation of this failure mode now enables robust limits to be put in place for the FC to ensure decisive diagnosis if such a FC result is obtained again. This will entail setting a limit for W in the XRF spectrum and setting limits for wear debris rate.

It should be noted that FC analysis of the filters from both the engines submitted was conducted under extreme time constraints. The FC enabled initial results to be obtained within 1.5 hours of receiving the samples. Manual filter debris extraction and analysis would have been unable to deliver a result in the required timeframe and with equivalent diagnostic information.



(a) HPT Aft Shaft with Inner Bearing Race

(b) HPT Aft Bearing



(c) HPT Aft Shaft Inner bearing race showing extent of material 'ground' away – see gap under steel rule.



(d) HPT bearing showing heavy rub to bearing cage.

Figure 9: Damaged RB211-535 HPT Aft Shaft Bearing

In this case the FC provided valuable diagnostic data to enable the correct maintenance action to be taken avoiding a bearing failure, but did not significantly lengthen the lead time given until the engine was required to be removed. However had this engine been subject to routine FC analysis it is considered likely that initiation of this defect would have been detected far earlier based on the quantity of material removed from the bearing inner race.

SH-2G(NZ) Seasprite Main Rotor Gearbox

The RNZAF operate 5 Kaman SH-2G(NZ) Seasprite helicopters which are frequently deployed on ship. The main rotor gearbox (MRGB) is a single point of failure in the propulsion system and therefore requires robust condition monitoring. The only extant wear debris monitoring is via the use of indicating MCDs. Chip indications prompt visual inspections of the MCDs.

The RNZAF have suffered one bearing failure of a MRGB in the SH-2G(NZ) fleet history in 2008. This gave several chip indications that gave adequate warning to prompt investigation, however these only provided approximately 10 hours of operation before a final MCD

indication was analysed and corroborated with filter debris as an M50 bearing failure. The MRGB has since been added to the FC programme where scavenge filters are analysed every phase service (200 hours).

Early detection of SH-2G Bearing MRGB Defect

Detection of an abnormal MRGB wear mode in a MRGB was recently made by the FC. The MRGB was subject to a FC analysis of the scavenge filter on its first phase service since overhaul (TSO: 140.9 hrs). This first FC analysis gave the highest Fe debris count ever recorded by the FC, as in Table 5. Compared to the only other serviceable MRGB FC sample at that time this result was approximately 10 times greater indicating that it was likely a abnormal condition. The XRF spectrum was not overly conclusive other than debris was ferrous based and had some indications of Cr, Mo and V, compared with the only other MRGB sample. Table 5 summarises the initial results.

Table 5: SH-2G MRGB Abnormal FC Results

'Abnormal' MRGB

Time on Filter (hrs)	140.9

Size Bin	Counts	Counts/Hour
Small	1726	12.25
Medium	1001	7.10
Large	5	0.04
Total	2732	19.39
Fe Mass	**Mass (mg)**	**Mass (mg)/Hour**
Total	127.6	0.91

'Serviceable' MRGB

Time on Filter (hrs)	215.6

Size Bin	Counts	Counts/Hour
Small	261	1.21
Medium	52	0.24
Large	0	0.00
Total	313	1.45
Fe Mass	**Mass (mg)**	**Mass (mg)/Hour**
Total	6.7	0.03

Due to the potentially abnormal result the sample was examined by optical microscope and SEM/EDS. SEM/EDS examination showed a sparse distribution of particles consistent with spallation flakes. The composition of these particles was found to be a close match to M50 bearing steel. As such the result for the filter debris was determined to be abnormal and contain indications of M50 bearing debris. At this point no MCD debris was found and the size and quantity of the M50 debris in the filter sample did not at all exceed maintenance manual inspection criteria. Despite this the RNZAF agreed to a reduced filter inspection interval and samples were collected as in Table 6.

Table 6: MRGB Filter Samples

Sample	TSO (Hours)
1	140.9
2	154.8
3	163.6
4	172.1
5	182.6
6	195.4
7	218.2
8	268.9

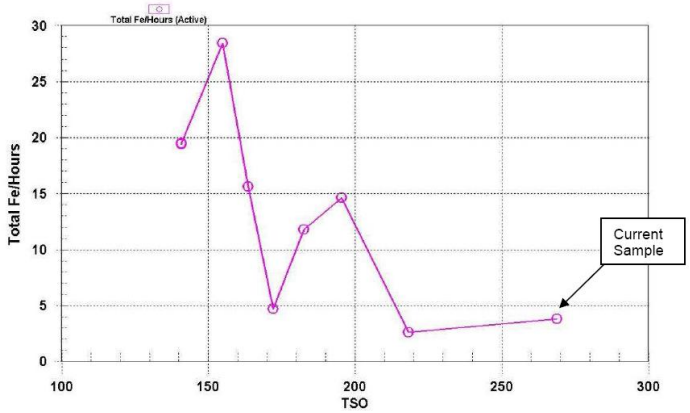


Figure 10: MRGB Debris Rate vs. TSO

FC analysis of the samples in Table 6 showed a continuation of a relatively high debris rate, although this did decrease over the initial level, as in Figure 10. XRF spectra of each sample were relatively consistent but were not conclusive. Due to the persistently high debris rate however these samples were still assessed as abnormal and subject to examination by optical microscope where further M50 bearing spallation particles were found and confirmed by SEM/EDS. The size and proportion of these M50 spallation particles to other debris tended to increase over each subsequent sample, suggesting progression of an M50 bearing spall. It was noted that much of the debris samples that were reviewed to confirm the presence of M50 particles were from debris captured by the DTA designed total capture system during the full wash cycle.

In all samples, including the most recent, it was concluded that the MRGB had an incipient M50 bearing spall, but debris did not exceed maintenance manual limits. This indicates that the detection capability of the FC far exceeds that of the extant MCD system and OEM inspection criteria, at least for this type of defect. At the time of writing the MRGB was still in service but remained on a reduced filter inspection interval. If this failure is validated it will highlight the ability to provide long lead time until failure with over 150 hours already progressed since the original FC indication.

The above example also highlights the requirement for supplementing the FC with optical microscopy to examine particle morphology to ensure defects are detected. In this case while debris rate was abnormal, the XRF spectra were inconclusive, most likely due to the high background of apparently benign ferrous debris.

Conclusions

This paper has focussed on the aspects associated with introducing the FC to RNZAF service in a manner that fully exploits its capability to detect incipient oil-wetted component defects. From this work it is concluded that determination of the machine's actual analysis capability is essential to ensure a robust processes are set up to ensure valid results are obtained.

The FC XRF system was determined to have a background noise in spectra that is due to the filter patch and residual wash fluid itself. This resulted in a guideline for minium sample thickness to assure a satisfactory 'signal to noise' ratio and establishment of the requirement for use of optical microscopy to catch particles of critical alloys with low levels of alloying elements. Experience has indicated that capture of debris during the full wash cycle is of diagnostic benefit.

To date limited RNZAF fleet data has been obtained. However the FC was shown to have detected a bearing failure in an RB211-535 engine which was validated by subsequent teardown inspection. Early detection of a bearing defect in a Seasprite Main gearbox by the FC was also indicated with over 150 hours lead time but is still to be validated.

Overall, it is concluded that the FC is an excellent example of how conventional technology can be developed to enable filter debris analysis to be a viable and effective wear debris assessment technique.

Future Work

Based on the background work in this paper and further RNZAF fleet data a full set of procedures and component limits will be developed to enable the FC to be operated at operational level maintenance to detect abnormal component conditions.

Feedback from maintenance and teardown inspections will continue to be used to validate limits developed. Application of the FC will be examined for substantiation of time between overhaul extensions on components where appropriate.

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