Effective Condition Monitoring of Aero-Engine Systems Using Automated SEM/EDX and New Diagnostic Routines

Application Appraisal:

RAF Tornado Aircraft RB199 Engine Condition Monitoring Project

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Abstract: The Royal Air Force Tornado RB199 Engine Support Authority has implemented an innovative, efficient and cost effective wear debris monitoring (WDM) programme through the successful application and adaptation of a commercial-off-the-shelf Scanning Electron Microscope/Energy Dispersive X-Ray (SEM/EDX) system. Combat aircraft engines, such as the RB199, require conditional health monitoring of oil wetted components, specifically tribo-components, for their protection against critical failure. Such monitoring maximises component life, resulting in reduced logistic and mobility footprints, while enhancing operational availability and capability. The hostile operating environments of high performance turbine engine technology (HPTET) demand hardware robustness and/or a strategic investment in an enhanced tribology capability within the maintenance arena. For post design in-service engines the latter option using state of the art technology offers by far the more affordable option, with excellent potential, at lower initial investment, for the future higher performance combat aircraft engines. The transition of electron probe microanalysis to the field combined with accurate and precise diagnostic routines based upon reliability centred maintenance and hazard risk analyses realised an immediate payback to the RAF. The RAF, in conjunction with Rolls Royce, has established the next generation of WDM techniques to support its long-term assets.

Key Words: Aero-engine Integrity; Early Failure Detection; Condition Monitoring; Wear Debris Monitoring; Oil Wetted Components; Proactive Maintenance; Electron Probe Microanalysis; Scanning Electron Microscope; Energy Dispersive X-ray Spectrometry; Total Quality Management; Continuous Improvement.

Introduction: The RAF has conducted wear debris monitoring (WDM) programmes on its aero-engines since the 1960s, when magnetic drain plug (MDP) technology called for the establishment of early failure detection centres (EFDC) at its operating bases (1). At the outset of its service life, the RB199 engine oil system idiosyncrasies required the combination of several analytical and monitoring techniques for protection against anticipated failure modes. Later investigations revealed shortcomings in these WDM disciplines (2). First generation condition monitoring technologies, such as magnetrometry and atomic emission spectrometric oil analysis (SOA) could not provide the required protection for the RB199 engine when analysing multi-element debris and trending conditional health.

The shortcomings of SOA, reported regularly since the University of Dayton presented an American Society of Lubrication Engineers paper in October 1985 (3), precluded its application on most RAF aero-engine oil systems. Progressive RB199 engine hardware anomalies combined with the oil system's idiosyncrasies, called for more discerning quantitative and qualitative analyses through elemental composition, with a capability of discriminating between active and benign wear. The situation called for a full characterisation of the engine oil system, its sub-systems and all oil washed components to determine the cause and effects of all generated and migratory wear debris. Several almost identical oil washed component material specifications presented a considerable analytical challenge in determining wear origins. Fortunately, advances in electron-probe microanalysis technology offered a solution through automation to realise its transition from specialist laboratory to field application.

This paper presents the successful first phase of the RAF RB199 SEM/EDX Microanalysis Project, and charts the road map for a single universal RB199 EFD discipline and support for the EJ200 engine powered European Fighter Aircraft. It provides an objective account of the SEM/EDX microanalysis system project, which lead to the system's implementation at Tornado main operating bases. The paper also addresses briefly the various shortcomings of each of the WDM techniques that deemed them unsuitable for the RB199 engine case, and also generally for combat aircraft engines.

RAF Propulsion – Early Failure Detection Policy: The RAF has a general policy, requiring the condition monitoring of all aero-engine oil wetted components. This policy is implemented through EFDCs located within propulsion shops, and during deployment; the RAF takes full advantage of technicians trained and experienced on engine type and EFD techniques. From MDP specimen analyses, EFDCs provide maintenance recommendations to the operating squadrons (4). All early failure detection (EFD) wear debris-sampling techniques, with the exception of SOA, are truly non-destructive, enabling the retention of samples for retrospective investigation. While the RAF policy has traditionally pursued a common equipment policy, this proved to be a false economy and an ineffective insurance for some engines, notably the RB199. Each RAF aero-engine Support and Engineering Authority, (analogous in the USAF to the combination of a Special Project Office (SPO) and Air Logistic Centre (ALC) engineering), is responsible for formulating and implementing its own maintenance policy.

These policies are based upon recommendations from the engine responsible design authority (manufacturer) and RAF specialist engineering support services. Such agencies constituted an RB199 EFD project team, formed to review current RB199 WDM techniques, which then evaluated the SEM/EDX microanalysis system and its interfacing with an integrated engine database and routine fault analyser.

Tornado RB199 Engine Anomalies: The Tornado aircraft RB199 modular engine is a highly complex 3-spool system generating up to 16,000 lbf of wet thrust. RAF engines had developed difficulties with the in-service integrity of the No4 bearing failure of which, in the worst instance, could result in seizure of the High Pressure Turbine (HPT); the secondary damage being extensive and potentially threatening to the aircraft [5,6]. It is also anticipated that the engine will face escalating reliability problems through increasing exposure of installed long-life gearboxes [7]. Gearbox degradation through normal direct mechanical/tribological wear, or indirectly as a consequence of migrating oil transportable debris, demands closer and more discerning conditional health monitoring to avoid a major operational and logistic problem. Monitoring the engine oil wetted components is exacerbated by such migration and cross contamination of debris throughout the oil sub-systems. Current analytical techniques and monitoring disciplines supporting the RAF EFD policy have proved to be technically ineffective and operationally unresponsive, as well as financially wasteful in managing the logistics of the fleet and maintaining serviceability. The engine oil system's coarse filtration (80 μ) and high oil usage rate (1-2 lt/hr), dictated that any conditional health policy should be based upon the wear debris captured by each sub-system magnetic drain plug (MDP). Planned improvements to RB199 engine oil system purity will, in the future, enable MDP sampling to be supplemented by routine quantitative filter debris analysis (QFDA) using a new SEM/EDX analytical process.

Rolls-Royce RB199 Engine Condition Monitoring Initiative [8]: In parallel with the RAF RB199 engine problems, Rolls-Royce initiated a task to identify new monitoring technologies, capable of a single point replacement of the various in-service and developing field techniques. The main objectives were:

- High versatility (particle size range, capture device, analytical capability)
- Non-destructive specimen sampling
- Suitable and affordable for field application of all engine types
- High data confidence (>80%) - minimal subjectivity
- Simplistic operation and cost effective upkeep
- High degree of accuracy and repeatability
- Progressive and trainable diagnostics
- Compatibility with on-line monitors (data correction)
- Data fusion with off-line monitors (vibration analysis and performance analysis)

RAF RB199 Engine EFD Project Background: A TQM and risk management approach was lead by the RAF Aircraft Integrity Monitoring Equipment (AIME) engineering authority (EA) in Jan 96 to determine the most effective conditional health monitoring technique to secure the integrity of the RB199 engine. Active participation by end users at EFDCs proved invaluable in determining a rational system specification for the front line to manage the engine's continued in-service integrity.

Achieving a challenging project timescale demanded a fast track, low risk, turnkey arrangement; this precluded any potential WDM option requiring R&D. The review team sponsored by the RAF's AIME EA, included the Defence Evaluation & Research Agency (DERA) Structural Materials Centre Farnborough, Rolls-Royce Materials Laboratory and the Tornado Propulsion Flight EFDC at RAF Coningsby. Potential options were evaluated in strict compliance with Chief of Defence Procurement Instructions and RAF Project Management guidelines

Wear Debris Monitoring Technology Evaluations

(1) Rotating-Disk Emission Spectrometric Oil Analysis: The RAF investigation sponsor had co-lead the 1994/95 USAF HQACC/SA-ALC-LDN combat aircraft engine trending and diagnostic (ET&D) integrated process team (IPT), which also addressed oil analysis. These investigations had been driven by several A-10 Class A TF34 engine gearbox failures. HQACC/LG reinforced the 1994 JOAP IGT [9] long-term objectives by endorsing the IPT's recommendation to pursue technology evaluations, with a view to replacing atomic emission SOA for combat aircraft aero-engines. While SOA can perform its intended function and achieves cost avoidance for certain components such as gearboxes, the joint SA-ALC HQACC study showed a much higher cost incurred by its discipline and process anomalies.

It is an incorrect and non-validated assumption in atomic emission SOA that all the wear particles generated by the wear process are detectable by the spectrometer. Accurate wear rate and total wear trending and modelling is almost impossible using the concentration methodology, as there is no correlation of system oil loss with loss of oil transported wear particles. There is also little or no correlation between the "abnormal wear" step function in wear metal generation and the 10-hour trend requirement, with the one exception of the onset of abnormal wear. Reducing the detectable amount of wear metals effectively increases divergence between the total wear and measured wear trend curves. SOA is largely unreliable through the nature of the arc/spark source causing incomplete burning of particles, and poor particle transport efficiency of the rotating-disk electrode ($\leq 8\mu m$ max). Furthermore, spectrometric measurement error of >1 ppm exceeds most engine wear rate limits, thereby precluding reproducible results and a meaningful 10-hour trending programme.

The SOA process, being destructive in nature, further precluded retrospective investigation and database development. The technique is considered to be past its time for high performance aero-engine WDM.

(2) Energy Dispersive X-Ray Fluorescence (EDXRF): Almost in parallel with the USAF IPT studies, the RAF had been evaluating and implementing EDXRF analysis of wear debris for RB199 engines to provide a "further analysis" capability in the field. The RAF RB199 Review Team subsequently demonstrated the ineffectiveness of EDXRF for multi-element analysis [10].

Standardisation across six Tornado EFDCs could not be achieved, even when presented with seeded homogeneous certified reference materials [11]. EDXRF requires homogeneous surface defect-free large fragments (>150μm), whereas the critical debris size for most high performance aero-engine bearing materials is between 5-50μm. The variation in composition of routine wear debris sampling is so wide, that regression based calibrations, upon which XRF depends, did not work; trending was impracticable.

It is currently impossible to de-convolute accurately XRF spectra acquired from of a complex, non-homogenous mix of debris particles into component alloys, as a consequence of overlapping particles, inter-element X-ray absorption, fluorescent effects and specimen topography affected the geometry of the X-ray. Also unacceptable nickel masking effects could not be eliminated through improved tuning by tungsten filters. The time taken to acquire meaningful spectra is one hundred times that taken by a SEM/EDX system, and even through optimisation it cannot reliably detect other wear materials. The technique's anomalies demanded an expensive correlation programme, similar to SOAP, to establish if fleet standardisation was possible. Ineffective operator training and poor OEM support also accelerated the breakdown in confidence in the technique. Consequently, following two validated and avoidable catastrophic failures, the RAF decommissioned its six ED-XRF units from Tornado RB199 EFDCs after only 12 months use.

(3) Fourier Transform- Infrared (FT-IR): The 1994/95 ET&D IPT pursued the JOAP TIG recommendation for technology evaluation, bringing together the TSC, HQACC, SA-ALC/LDN and OC-ALC/LPA as a TQM activity. The prime focus of attention was given to Fourier Infrared (FT-IR) Spectroscopy and Ferrographic Wear Particle Analysis by FT-IR Microscopy. The RAF discounted FT-IR Spectrometry, as unsuitable for the analysis of wear debris metallic particles, although recognising its more meaningful application in physical property testing (PPT) of oils. It was also considered to be operationally unresponsive and manpower intensive. The RAF had no requirement for the PPT of aero-engine oils or time change policies, as a consequence of high rates of oil usage. FT-IR Ferrographic Microscopy was similarly considered to be inefficient and unresponsive for self-sufficient front line application.

(4) Magnetrometry - (Debris Testing): Debris tester measurement error and poor repeatability are a consequence of the limitations of sensor head design. Investigations at RB199 engine EFDCs demonstrated the instrument's insensitivity and erratic nature for both absolute wear and wear production rate limits. In addition, the sensor cannot account for differing magnetic susceptibility; it provides only "ballpark" concentration readouts, where benign wear particles mask those of critical active wear. Little noticeable improvement was gained through supplementing it by costly "further analysis" at external scientific establishments. Indeed, the reliance upon external scientific support proved, through inappropriate timescales, to be operationally unacceptable and difficult to prioritise maintenance activities. Notwithstanding the debris tester's limited independent value as an engine health indicator, sensor head modifications enhanced sensitivity and improved repeatability, but still only offered a minimum capability in the form of an interim wear-rate "trigger".

(5) Optical Microscopy: The RAF stands out from almost all other air forces with its more objective optical analysis of MDP debris. However, it is recognised that during visual inspection, the reliability of the human brain/eye combination is relatively low, due to tiredness, limited expertise, and pressure of work or distraction. It has become an established practice throughout industry to eliminate human intervention as much as possible, relying instead on fully automated "no eyes" non-destructive inspection systems. Optical systems, either in use or under development for RB199 EFDCs, have run counter to this practice. The RAF's development of an enhanced optical microscope procedure, using a manual optical split-image and wear-debris atlas with CCTV, based ostensibly upon morphology, proved ineffective. Used in conjunction with debris testing at RB199 EFDCs, optical microscopy is slow, manpower intensive and, being dependant upon image resolution is largely subjective. The RB199 wear particle atlas (WPA) [(12)] project was unsuccessful as a result of not standardising the library images with in-service EFDC equipment. Improved magnification (600x) microscopes only exacerbated manual operator difficulties by constantly having to change between depths of field to accommodate the different lenses when separating out particles. A comparison between optical and scanning electron microscopy (SEM) demonstrated a daily analytical throughput of a thousand times in favour of the SEM, which also provides excellent back-scattered imaging, though this information ranks only secondary to compositional analysis in order to identify wear material type and origin. Opinion that optical microscopy provides quick and reliable analysis when faced with the aforementioned operational pressures is questionable.

(6) In summary: SOA, magnetrometry and EDXRF techniques often lead to randomly occurring cumulative errors with poor analytical reproducibility, all having demonstrated shortcomings and inconsistency in detecting incipient failure. They also require expensive correlation programmes to maintain analytical standardisation. Stand-alone or a combination of existing WDM disciplines, allowed RB199 No 4 bearing failures to continue largely undetected, while a large number of engine modules continued to be prematurely rejected through false calls. Utilisation had become reliant upon costly and imprecise logistical support, which could no longer be tolerated. Automated SEM/EDX microanalysis was the only suitable stand alone condition monitoring technique, evaluated from current and developing technologies, with a potential to achieve the maintenance management, logistic and operational targets.

RB199 Engine EFD Review Team Recommendation: Notwithstanding the high initial investment cost, acquisition of an automated SEM/EDX microanalysis was strongly recommended. A commercial-off- the-shelf universal system was justified on the grounds of expediency, in managing RB199 engine No4 bearing characteristics. Through an immediate return on investment, the planned 6-month field evaluation was compressed, enabling early minor development to interface a combined database/fault analyser with the SEM/EDX for universal operation. This early SEM/EDX success and experience also highlighted the feasibility to develop a far less expensive system. To achieve universal engine support by a single "bulls-eye" WDM discipline, development of a mobile application specific system was enabled through sustained engineering support arrangements with both Rolls-Royce and LEO Electron Microscopy Ltd, the SEM/EDX system integrator [(13)].

RB199 WDM Project Definition – SEM/EDX Selection Criteria

(1) General RB199 WDM Specification: The overall RB199 engine WDM specification embraced the aforementioned Rolls-Royce Engine Condition Monitoring (ECM) Initiative objectives. A self sufficient WDM system for Tornado RB199 EFDCs, capable of "hitting" incipient failure first time, every time, needed to provide:

a. Rapid and automated analysis of 100% of RB199 engine MDP samples, (16 EFH interval and reduced interval sampling). Full analysis (morphological and chemical) of 1500 individual particles, with diagnostic recommendations, such as presented on average by one engine set (5 MDPs) to be achieved within 15 minutes.

b. A fully qualitative and quantitative analysis of multi-element materials for a particle size range of 5 μm and upwards, capable of discriminating between active and benign wear generated particles. Full characterisation of individual particles, with a software capability for automatically de-linking overlapping particles.

c. A root-source wear diagnostic capability, using both absolute and trending limits by compositional analysis backed up by automated morphological analysis of constituent materials and particle details.

d. A consistent statement on the condition of the engine oil wetted components, being able to first detect and then discriminate between a range of damage and failure mode symptoms with 90% confidence.

e. A system specific compatible suite, to minimise variations in human/machine interface, with automated control to enable simultaneous analysis.

f. User friendly novice operation, with clear unambiguous procedures

g. Simple and environmentally acceptable means of sample preparation, without the need for polishing and coating, yet compatible with debris testing, optical microscopy and electron probe microanalysis.

(2) WDM Diagnostic Software: The SEM/EDX WDM diagnostic software was required to provide:

a. Historical data used to create engine specific wear data, with the ability to trend non-critical components (normal/abnormal thresholds).

b. Normal operation and different failure modes used to establish limits of wear generation for certain materials (alert/rejection criteria).

c. A capability of alerting module and component specific problems automatically based upon trend rules (fault signatures).

d. A seamless interface control between SEM/EDX analysis and engine specific fault analyser and database.

SEM/EDX Microanalysis Selection Strategy: It was readily recognised that protecting RB199 engine integrity, could only be obtained through a higher, yet "value for money", insurance premium, any risk being mitigated by using off-the-shelf proven technology. A medium financial risk was recognised in the pursuance of achieving a stand alone integrated discipline. The further analysis of MDP debris at research and scientific centres in support of the RAF and German Air Force Tornado aircraft had demonstrated undisputedly the effectiveness of SEM/EDX systems [(14)], albeit they were manual systems covering only just over one per cent of all MDP sampling. The feasibility study focussed on technology transition from scientific centres employing specialist operators, to a field automated system to be operated by propulsion technicians with no equipment experience. In addition to an analytical capability, the principal selection criterion was cost effectivity. The feasibility study covered a comprehensive field trial, addressing universal support from MOB through to deployed operational squadrons [(15)].

Automated SEM/EDX Microanalysis Project

Investment Appraisal: A comprehensive and objective cost benefit analysis was facilitated by the RAF's policy of retaining historically engine wear debris at its EFDCs. The appraisal adopted two methods. Firstly, an initial desktop investment appraisal was largely based upon SEM/EDX experience at Rolls-Royce Materials Laboratory Bristol, DERA Structural Materials Centre Farnborough and Naval Aircraft Materials Laboratory Portsmouth. From the analyses of retained RB199 wear debris, it was acknowledged that at least three recent catastrophic engine failures would have been averted, by detecting incipient or impending failure (wear) progression, representing a £750K hardware saving. Secondly, the appraisal undertook a series of analyses by a recently SEM/EDX-trained RAF propulsion technician of ten engines' wear debris to determine their conditional health, compared with existing WDM techniques. The independently validated results, showed three engines with abnormal wear (failed several hours after in-service sampling), three engines trending towards the advanced stages of wear and four "normal" engines, i.e. progressing through normal wear rate conditions. The appraisal of three independent WDM programmes also showed that cost management of each; in terms of costs per sample, favoured the stand-alone SEM/EDX microanalysis system. It also recognised a potential for reduced sampling.

SEM/EDX System Overview: The system uses sophisticated analytical routines to identify, characterise, analyse and interpret engine wear MDP and/or filter captured debris deposits. While maintaining laboratory standard and continuity, the system demonstrates enhanced usability, making it a fully practicable solution for front line (intermediate level) and overhaul and repair (R&O (depot level)) establishments. Tailoring of the standard hardware, firmware and software resulted in a system specific compatible suite based upon a SEM, that can be used to semi-automatically analyse engine wear debris and provide reliably routine diagnosis (Figure 1).

The overall control programme is initialised via a simple sequence of "windows" operations, the data generated is applied to a new diagnostic methodology and recommendations are provided based on the known rules of the subject engine system. The diagnostics are based on a versatile algorithm which processes the compositional and morphological data gathered from each individually scanned particle, and applies it to engine specific criteria. Known engine failure characteristics established from the Failure Mode Effects Criticality Analysis (FMECA) case studies and the thresholds of general engine behaviour are used to train the software to identify normal, marginal, and abnormal wear trend and absolute conditions. The system is capable, to a high degree of confidence, in detecting wear sources and the incipient failure of oil-wetted components at an early and manageable stage [16], offering a realistic proactive maintenance policy (Figure 2).

Sample Preparation: Following their removal from installed engines, magnetic plugs are submitted in sets to the EFDC. Solvent cleaning of the plugs is first carried out to remove all organic residues. The complete contents of the plugs are then transferred directly onto an adhesive, electrically conductive medium suitable for SEM use. The debris is manually manipulated into the desired field of view (6mm x 5mm) within the central region of the tab. Particles are 'spread' using a non-metallic implement and a low powered optical microscope, to achieve a "rough particle" standard of preparation.

Notwithstanding, the manual procedure's effectiveness when considering the broad spectrum of samples presented, continuous improvement investigations into electro-magnetic preparation are already underway.

Analytical Routine: The analytical routine developed at Rolls-Royce Materials Laboratories provides a seamless process from identification through analysis and diagnostic interpretation. The process developed can be summarised as follows;

- The identification of particles via the IA thresholding of a 50x Backscattered Electron SEM image (Carbon grey level = 0, particles 70-250)
- IA processing of the field features giving individual morphological measurements such as size, shape, compactness and aspect ratio to aid in fault type identification.
- Primary and Secondary quantitative X-ray analysis to filter benign materials and classify critical alloy types (150 ms/1000 ms acquisition times)
- The sequential processing of up to 20 full chip detector or filter samples
- The import of debris derived system data into the Rolls-Royce fault diagnostic package for trending and indication of appropriate maintenance recommendation

The complete process is automatic, taking on average one hour to process four full engine samples (20 debris deposits). The EFDC operative is freed to concentrate on other duties such as sample preparation or plug cleaning.

Back-to-back benchmarking of the automated process and expert intensive manual SEM approach revealed excellent data correlation's and highlighted the huge time saving (minutes Vs hours) associated with the technique. It was concluded that the 'quality' and accuracy of the system has not in any way been jeopardised [17].

Phase I Main Operating Base (MOB) - System Performance: Six RAF Tornado MOBs are now equipped with SEM/EDX systems. The fleet leader has been in service for over one year and has processed and diagnosed over 8500 MCD samples.

Thus far, with the 100% utilisation of the system and an inspection periodicity of 16 EFHs, the RAF has not experienced a single catastrophic bearing failure on the RB199 engine. In the 12 months preceding the implementation of SEM/EDX seven catastrophic failures occurred. All modules implicated by SEM/EDX diagnosis that have been returned to third line maintenance facilities have displayed incipient bearing damage. Furthermore, regular "false pulls" of gearboxes, as a consequence of debris migration from other components, has almost been eradicated.

The operational effectiveness to-date from '**N**' arisings is summarised as follows:

Hits	100%
Misses	0 (several gearbox arisings remain unconfirmed)
Escapes	0
(Confidence	95%)

The short and longer term cost benefits of the system have been proven by:

- The elimination of nugatory engine rejections (~50% to <5% forecasted)
- The reliable detection of bearing/transmission damage (~60 hour lead-time)
- The responsive nature of the system (full diagnosis <1 hr from receipt)
- The reduction in secondary component damage (pin-point fault identification and timely rejection)
- The projected extension of time between overhaul (oil-system cleanliness)

Further maintenance cost savings are also being investigated, including the relaxation of the current MCD inspection frequencies.

RB199 Engine Wear Debris Modus Operandi

(1) Phase II – Tornado RB199 Support Bases: The much lower throughput of some five bases, but providing sufficient operational and maintenance support, warrants the scaling of a less expensive reduced functionality SEM/EDX system. These bases are important elements in the universal support of the engine. Several of these bases are semi-permanent detachments, supporting moderate to high mission tasks.

(2) Phase III – Tornado Deployment & Mobility: The ad-hoc detachment of Tornado operational squadrons, will be afforded the same standardised WDM procedure for the safe protection of RB199 engines during mobility. In pursuance of this mobility requirement, the SEM/EDX project has recognised the need for significant development and has progressed through its feasibility study to project definition, where the specification is being finalised.

Conclusion: With the use of appropriate Diagnostic routines, the application of modern electron microscopy and integrated X-ray microanalysis for routine condition monitoring has proved operationally and cost effective. System capabilities significantly outweigh current wear debris analysis technology and the transfer of laboratory based equipment into front-line maintenance establishments has been proven without consequence. The front line has recognised SEM/EDX as an essential engine condition monitoring tool, protecting RB199 engine integrity and enhancing Tornado aircraft availability, at reduced costs.

System versatility facilitates an equally effective solution to all off-line monitoring requirements, with the application of a generic system to multiple engine types the next logical step. Compatibility with future on-line technologies and fusion with other engine health parameters has already been considered, the SEM/EDX system providing an excellent means of on-line monitor calibration and fault confirmation.

The next generation of dedicated ECM tool is efficient, cost effective, compact, usable and reliable; Rolls Royce, in unison with its current and prospective customers will be pursuing its application to all other engine projects during over the coming years.

Acknowledgements:

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Figure 1

SEM/EDX - Automated Wear Debris Process Logic

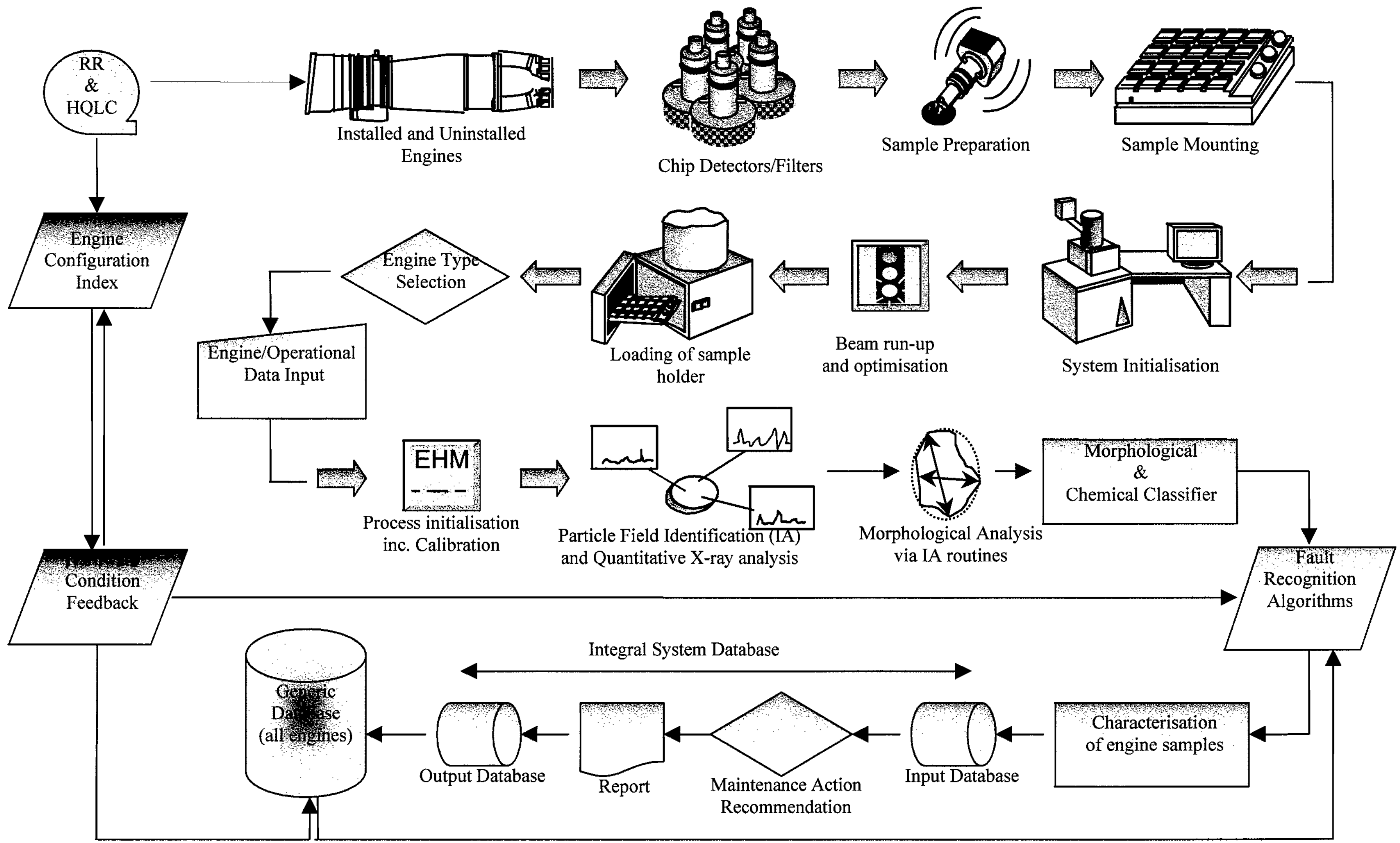

Figure 2 Rolling contact fatigue failure of the No4 Thrust bearing believed to release little or no debris prior to failure. SEM/EDX analysis using version 1 diagnostics still giving 30 hours lead-time and a clear call to reject.