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RESEARCH

Wear Metal Concentrations Used for Enhancing Spectrometric Oil Analysis Method Credibility and Statistical Feedback - A Step Towards Big Data Analysis

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A B S T R A C T

The well-established oil condition monitoring tool of spectrometric oil analysis is used to expand previous published experimental analysis with a view to enhancing multiple wear metal elements study in numerous different applications. This study includes gas turbine engines, piston engines, turboprop and turboshaft engines and helicopter gearbox assemblies. The database used in the original study was enhanced with numerous applications that were used to establish the credibility of spectrometric oil analysis as an important diagnostic tool.

The importance of the method lies in its ability to locate unusual concentrations of a metal element that is translated as an indication of abnormal wear of the equipment under scrutiny. The operator benefits from major failures avoidance and taking correct decisions regarding equipment maintenance and servicing or repairing, can also profit from economic factors rationality during equipment operation. Lubricant quality, identification or imminent failures, prolonged life cycle and acquisition of statistical data are conditions that emanate from the correct interpretation of the results that in turn, can avoid human lives and equipment losses due to major incidents.

1. INTRODUCTION

Oil samples taken from reciprocating engine sumps or gearboxes, hydraulic systems or closed gas turbine circuits can be estimated through the experimental results of spectrometric oil analysis and following the results of the lubricant condition further actions to be taken if necessary.

According to past established listings, a joint effort was supported to create big databases with results taken from the field of major operators and subsequently, lots of statistical data could be extracted [1]. Vast databases were one of the goals of the established oil analysis program, as the major benefits are targeting major failure prevention, economic benefits, avoidance of expensive and identification of inadequate maintenance or inappropriate equipment failure and major component failure prevention [2].

The aim of the spectrometric oil analysis program is to trace changes in the composition of the lubricant used as well as other fluids, to locate and control unusual wear and to forecast imminent component or equipment failure. The operator benefits from increased effectiveness through the right maintenance procedures and with the lowest required level of maintenance which will be, still, in accordance with the certified procedures [2]. Additionally, new standards of analytical techniques are established along with the calibration required for instrumentation and equipment, innovative equipment analysis reports are produced and finally the most cost effective means of monitoring the degradation of the lubricant used in the internal combustion engines, gearboxes and hydraulic systems are identified [1].

In previous work [2,3], the automated decision taking procedure was described through the comparison of real time measurements to existing tables containing wear metal evaluation criteria. These tables contain ranges and trends for the elements given by the manufacturers and are considered, according to their estimations, the most important as they are contained in many special alloys and provide respectively traces of wear with the presence of specific wear metals [3]. It is important to be guided through a user-friendly interface towards the decision taking procedure and at the same time to enhance the statistical data for feedback purposes.

In this work, data derived from spectrometric oil analysis are presented and accompanied with comments regarding the ability to set goals such as fault detection and healthy parts monitoring and in the case of aircraft equipment on-air failure avoidance that includes cost of aircraft and/or engines together with the possible case of loss of life, which is priceless.

2. BENEFITS OF SPECTROMETRIC OIL ANALYSIS

Throughout the useful life of lubricant, it is important to determine its quality. Spectrometric oil analysis and physical property testing can be used as guidelines to assist in identifying mechanical failures and in determining lubricant quality [2]. The diagnostic tools of oil analysis oversee potential wear or failure of the equipment used. At the same time premature lubricant failure may be detected prior to a major equipment failure or an expensive repair. It also identifies inadequate or inappropriate maintenance procedures or faulty parts and assemblies [1]. The benefits also expand to cost reduction due to repairs, as mentioned, prolonged equipment life cycle and increased efficiency [2].

Data from spectrometric and physical property testing guide towards identifying incipient mechanical failures or in determining the quality and useful life of the lubricant. Potential equipment wear or failure and premature lubricant failure may be detected prior to a major equipment failure or an expensive repair procedure. As a result, oil analysis can be used also to identify inadequate or improper maintenance procedures and unsatisfactory equipment components [1].

Lubricant sampling is a source of errors and handling can be reduced with a subsequent diminution on the contaminations risks and analyte losses. Procedures should be also environmentally friendly following the green analytical chemistry guidelines [4].

There are also cases referring to fuel wear metal evaluation, where the determination of trace metals is mandatory in the quality control of petroleum-derived liquid fuels once the presence of wear metals lead to several distinct problems, such as oxidation. It is well known that metallic species can act as catalysts in the oxidation of certain heteroatomic molecules containing oxygen, sulfur or nitrogen and/or other hydrocarbons (alkenes, indenes and cyclic alkanes) that are present in liquid fuels [5].

The effectiveness of the method depends on the speed of the entire diagnostic process: from sample taking to the diagnostic report, should take as little time as possible. In case of samples that are sent to an external laboratory and days or weeks pass before the results are received back, this can turn into a decisive factor that reduces the effectiveness of the maintenance program, as equipment might have already failed before the reports come back [6].

2.1 Wear metals

The friction mechanism in between the metallic – collaborating surfaces is responsible for the generation of wear metals. So, the ancient practise of using lubricants to avoid friction and any subsequent unwanted results related to the operating condition of the metallic parts did pay dividends. With metallic contact, a significant energy dissipative process is plastic deformation [3]. The subsequent generation of wear debris can involve fracture at different scales, tribochemical reactions and dispersal of debris [3]. Wear metals are also generated from corrosive action within the lubrication system. Taking into account the above mentioned friction mechanism, wear metals, power losses, debris and tribochemical reaction mechanisms, the importance of lubricant additives that enhance lubricity and the ability of the lubricant to sustain the operating envelope of the equipment used is promoted [2].

Lubricant condition monitoring can extract useful information and spectrometric analysis can also indicate the rate of wear and its source. Wear metals that originate from metal surfaces have the same chemical composition. Eventually, wear metal traces found in the spectrometric lubricant analysis emerge as indication of the mechanical status of the originating surface. Energy is absorbed by the metals in the sample and they emit light with wavelengths which are characteristic for each element in the sample. The intensity of the light is proportional to the concentration of the metal in the sample. This oil analysis program is used in equipment where breakdowns are catastrophic or expensive. There is extensive use in the military, mainly US Air Force, Navy, and the Army and moreover it is used by many civil aviation companies, large fleet truck operators and is also used for checking certain contractor equipment. Furthermore, a special application is its usage for checking locomotives [7].

High energy environment for exciting metal atoms is created from a heat source, that causes vaporisation of the metal elements and at the same time their excitement. For a normally operating piece of equipment, wear metals are produced at a constant rate. In some cases, the rate may be negligible, but this rate is similar for all normally operating equipment of the same model. The wear metal concentration will also increase at a constant rate for a normal operating, completely enclosed system with no oil consumption. Any condition which alters the normal relationship or increases the normal friction between moving parts will generally accelerate the rate of wear and increase the quantity of wear metal particles produced [1].

Statistical data regarding the operation of specific equipment can be used for establishing the normal level and production rate of wear metals, over a specific operating period. When these rates and abnormal levels of ppm (parts per million) in the lubricant sample are established in the respective tables, the composition of the abnormal level of wear metals produced will provide evidence of the worn parts [1, 2]. A useful characteristic of this method is that it can provide general information about the origin of metal concentration or very specific information, i.e. abnormal trace of Sn is translated to worn journal bearing/casings [2]. When abnormal rate of wear metals is traced by the laboratory analysis actions should be taken for tracing the part responsible for producing wear metals and further repairs should take place to avoid total assembly damage of failure [1].

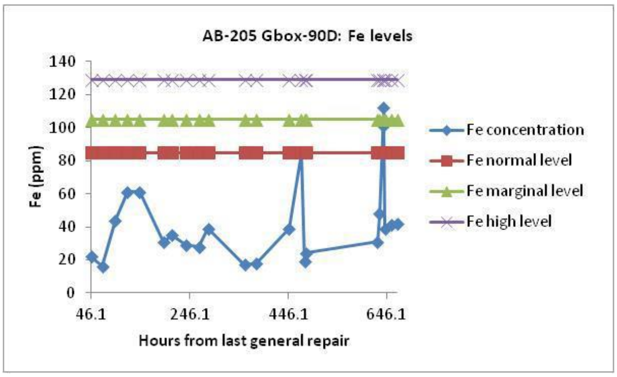
2.2 Measurements – Spectrometric analysis results

An atomic emission spectrometer was used, SPECTRO SCIENTIFIC SPECTROIL – W Military Oil Analysis Spectrometer, which is standard equipment in the Hellenic Air force Oil Analysis Laboratory and as part of the benefits of spectrometric analysis, a representative portion of the results already presented in [2] are also presented in this section to depict the ability of this method to prevent catastrophic failures. All the graphs show in X-axis the hours from last general repair and for every graph a wear metal is presented along with the normal, marginal and high levels that are taken from the Wear Metal Evaluation Criteria Table, a table established for each component according to the materials used, its operation and critical concentration levels of specific metals [1]. The calibration of the measuring equipment is achieved through base oil standards that contain specific amounts of wear metal traces and at the same time the lubricant maintains controlled viscosity and flash point.

The serial numbers appearing in Table 1, belong to reciprocating radial and boxer engines and a 90^{o} helicopter gearbox [2]. In Figure 1 the wear metal concentrations for Fe and Cu are presented [2] with Fe climbing over the marginal level and Cu over the normal level.

Table 1. Equipment, type and serial numbers inserted in the database [3].

Engine/ Gearbox S/N	Engine/Gearbox Type	Aircraft S/N
36176	R-2800	40
L2789	IGSO-540	128
A13-1062	GBOX 90-D AB 205	391



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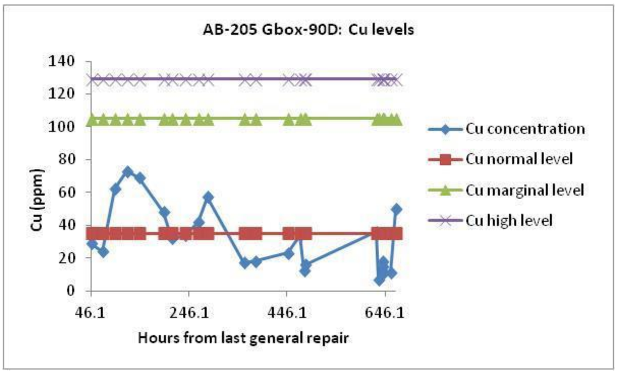

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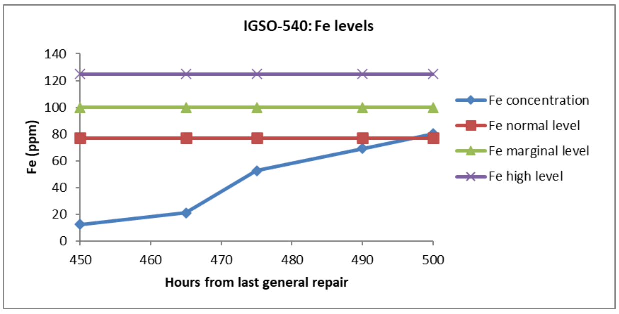
Figure 1. The wear metal concentrations for Augusta Bell 205 helicopter 90 degrees gearbox, (a) Fe levels and (b) Cu levels [2].

More testing data are available for the case of piston engines, such as the Lycoming IGSO-540 opposed (boxer) supercharged engine and the Pratt and Whitney radial R-2800. In Figure 2 results for a specific serial number IGSO-540 engine are presented.



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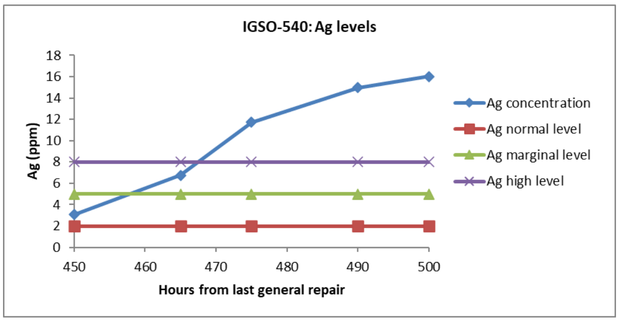

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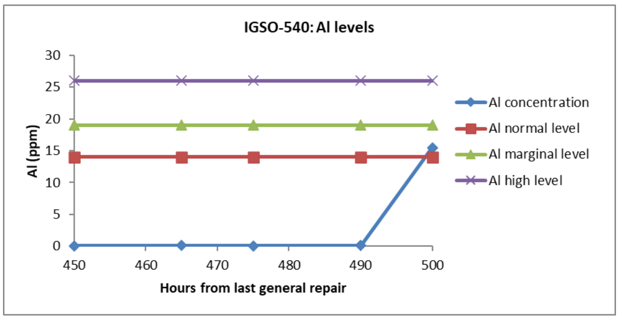

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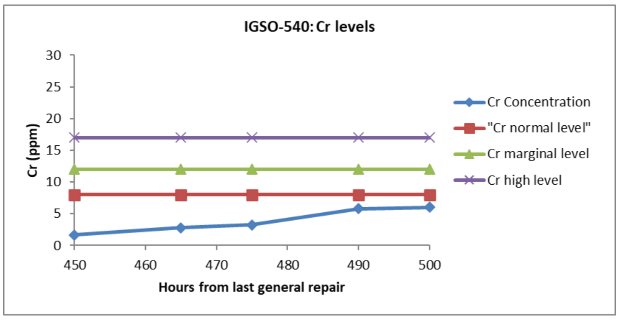

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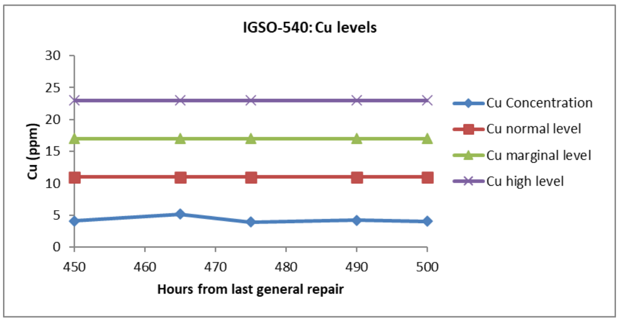

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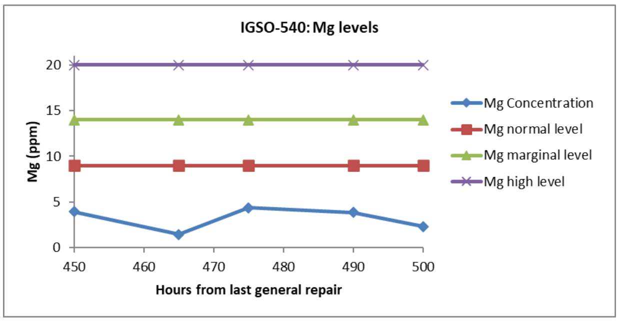


(f)

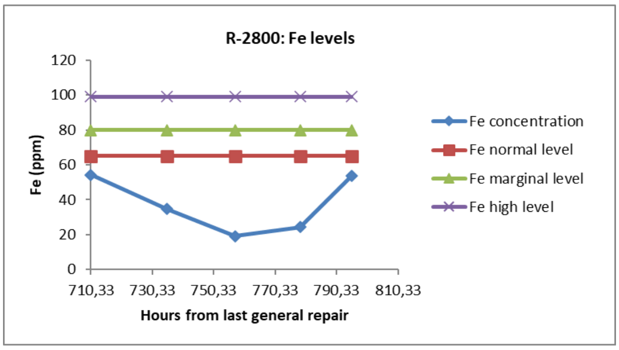
Figure 2. The wear metal concentrations for Lycoming IGSO-540 piston engine, (a) Fe, (b) Ag, (c) Al, (d) Cr, (e) Cu and (f) Mg levels.

From Figures 2 (a) – (f), data showed an abnormal increase for Fe and Al concentration after 490 hours of operation after last general repair, while Ag concentration is past the high level dictated by the manufacturer from 470 hours. Other metals, Mg, Cr, Cu show normal concentration and trends. It is with the responsibility of the laboratory to check: (a) trend of the samples, that is the wear metal concentration divided by hours of operation and (b) check whether this trend is within certain limits already imposed by the manufacturer. At this time, recommendation for an extra oil/filter change can be applied or a decision to ground the aircraft for the necessary inspections.

Depending on the component used for spectrometric analysis, the number of elements that are being monitored can be greatly increased. It is important according to the component manufacturer to monitor as many elements as possible to get a clear picture of what the lubricant condition is. It can be the case, that piston engine sumps are monitored with many elements analysed and the same applies for turboprop engines and gearbox assemblies. But one has the picture of the many components lubricated in the piston engine and the reduced number of components in a turbojet of turboshaft engine. The different materials used, though, can produce many sources of contamination, such as special bearings, different roller bearings, gears with varying materials than other gears and washers/bolts dipped in the oil sumps.

More testing regarding the Pratt and Whitney R-2800 radial piston engine is presented in Figures 3 (a) – (f) to enhance the spectrometric analysis credibility and useful data acquisition for statistical feedback.

In Figure 3 (a), Fe concentration shows inconsistency that can be due to oil contamination. Concentration is still under normal level. In Figure 3 (b), Ag concentration increases to a level higher than marginal which is a cause of concern and then, all other metal concentrations, Al, Cr, Cu, Mg are still under the normal level for each one of them. The high concentration of Ag can be attributed to specific components. Ag is contained in many special alloys and provide respectively traces of wear with its presence as specific wear metal in the sample analysis.



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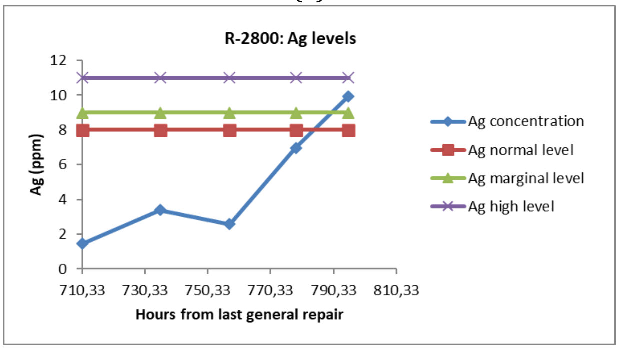

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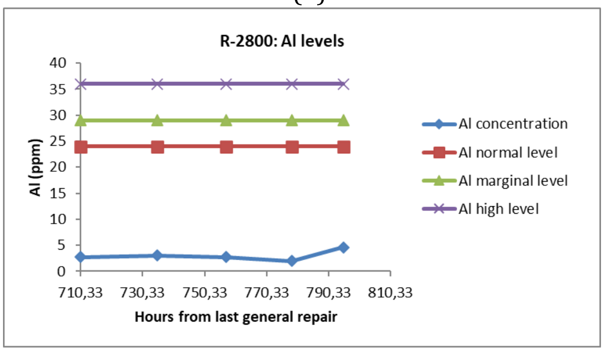

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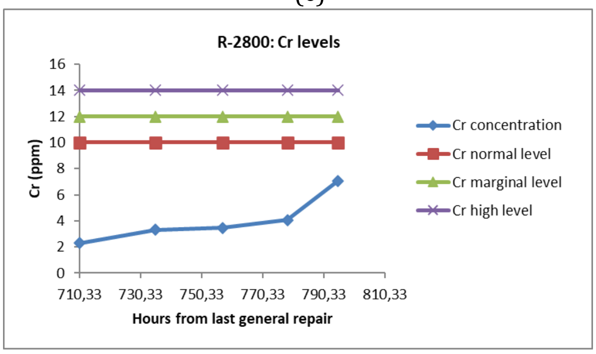

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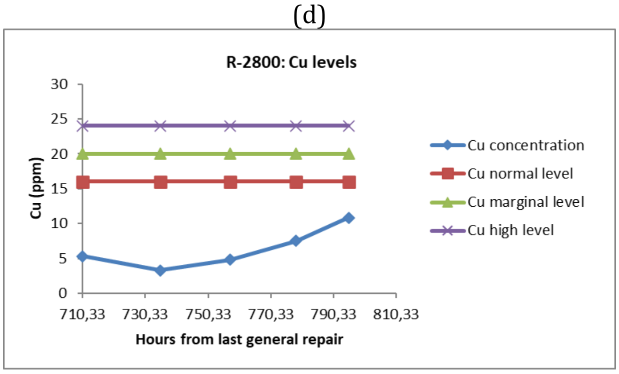

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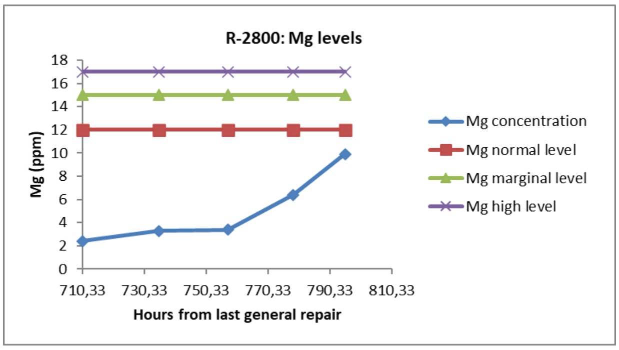

(f)

Figure 3. The wear metal concentrations for Pratt and Whitney piston engine, (a) Fe (b) Ag, (c) Al, (d) Cr, (e) Cu and (f) Mg levels.

The oil sample might be contaminated with traces of water and particulate matter with the addition of unusual colour. This may be indication of contamination that will eventually guide towards taking a second sample as it is imperative to focus on finding the correct concentration of wear metals. As part of contaminants that the analysis might face in the different operating environments, silicon (Si) increase in lubricant samples is such a trace from dirt and sand and it is also an indication of the operating area (dry, sandy or dusty environment) [1]. In this case and as is already known, the abrasive qualities of dirt and sand accelerate wear [1,2].

It is worth pointing out that the measurements contain data that were loaded from previous, very old databases such as LLC Corporation's dbase III and IV. Gathering experimental data between general repairs is important, and so these data were also used and compared to the existing wear metal evaluation criteria and used in the graphical representation. The material of components might have been modified with new materials that have different tribological and tribochemical behaviour, such as piston engine main crankshaft bearings.

All data collected from the spectrometric oil analysis are gathered to a user-friendly Microsoft database system [2] that can automatically compare the data inserted with the existing Wear Metal Evaluation Criteria Tables taken for every equipment used from the operating manuals. Then, the automated decision is based on comparison between trend, present and previous measurements and a laboratory recommendation code is derived for further actions-if necessary, from the operator's side.

Another important factor for the evaluator is to keep records of maintenance and operation of equipment that are subject to laboratory analysis. After analysing the samples, a maintenance recommendation is a result of gathered information from records that indicate misoperation, overspeeds, overboosts, overtemps, replacement of piston-rings, overtorque, vibration, corrosion, repair or adjustments on components, colour of oil, mission profile information, compressor stall, unusual noises from the component and filter/screens and chip detector inspections [1,2]. The evaluator's decision is affected by inadequate reporting, in this case the addition of lubricant between sampling may result in abnormally low wear metals if the sample is taken just after an oil addition without keeping any records [1].

The case of oxidation in the lubricant sample is described in [8], where researchers found normal wear metals in the analysis. It was suspected, after evaluation of Fe, Al and Cu wear metals, that mechanical wear was unlikely to occur but another wear mechanism involving oxidation and corrosion was more likely to have happened and is highly associated to the traced elements concentrations.

3. CONCLUSIONS

The spectrometric oil analysis diagnostic method is an expensive tool used to determine the wear metals in the lubricant sample. It is limited by some serious disadvantages that involve the sampling method integrity and analysis, but has also strong points that are summarised as its ability to locate unusual concentrations of a metal element that indicates abnormal wear and needs immediate action regarding the equipment analysed, lubricant physical property testing and major failures avoidance. It is important to differentiate between residues and wear metals dissolved in the lubricant, i.e. broken components cannot be identified by the spectrometer. The laboratory method estimates friction; due to friction, wear happens in between the surfaces of the assemblies and the statistical operating data is evaluated by the respective manuals. Laboratory recommendations are a result of careful and in-depth analysis of equipment operating history and have to be applied [9].

- The spectrometric analysis methodology is affected by practical factors such as sample contamination, type of spectrometer, calibration standards, oil additives, corrosion, fuel dilution, new/rebuilt components, oil loss or addition or change and operating conditions. Combination of the above factors or all of them can alter the analysis results.

- The ability to evaluate the samples in a representative (of the oil condition) and correct manner is critical to ensure that extra or already programmed maintenance procedures are followed.

- The ability to detect faults and monitor healthy parts has obvious advantages due to forecast of imminent failures, additional general repairs or maintenance.

- Method is expensive but cost is not compared to human life losses, or aircraft and equipment respectively.

- The statistical information derived from every part and serial number of equipment enhance method credibility and empirical support and solidifies the databases that contain critical information about past analyses and monitor the equipment used.

- The origin of metal particles maybe from additives, wear of components, fuel, air and liquid for cooling that might penetrate the lubricating system [10].

- Results, showed in this research and past publications [2], that follow spectrometric oil analysis data together with correct interpretation help avoid major equipment failure. Close cooperation with the laboratory ensures that adequate maintenance procedures are taking place that result in reduced maintenance cost, increased operational and personnel safety.

- The data derived from the analysis are added to the existing database systems enhancing the statistical information of every equipment used. Eventually, the confident user benefits from this operation and is guided towards using big data analysis tools such as AI (artificial intelligence) to analyse, store and use this information.

Acknowledgement

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