The Automated Spectrometric Oil Analysis Decision Taking Procedure as a Tool to Prevent Aircraft Engine Failures

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ABSTRACT

The purpose of spectrometric oil analysis is:

- To diagnose imminent wear inside engine assemblies so that possible failures can be avoided,*
- To forecast and evaluate acquired data statistics regarding the operation of engine assemblies under known climate and operational conditions.*

Apart from the above mentioned double aim of the lubricant analysis laboratory, its importance is established from the extent of these measurements from the Air Force, where they were initially implemented, to the Navy and the Army and customers with large fleets.

The present work presents spectrometric oil analysis as a diagnostic maintenance tool, it refers to the evaluation methodology and criteria of spectrometric oil analysis that come from aeronautical equipment (as it applies to the Hellenic Air Force), it describes the operation of a database used for the derivation of automated decision taking codes according to specific criteria described in US NAVAIR technical manual and highlights the importance of this procedure to preventing failure in reciprocating piston and turbine aircraft engines. Selected data from the spectrometer are also presented to point out the importance of the methodology in failure prevention as it applies in reciprocating internal combustion engines, a helicopter gearbox and a turboprop engine.

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1. INTRODUCTION

The establishment and maintenance of a standard program that combines three separate oil analysis service programs, on behalf of the Air Force, Army and Navy has led to a consolidated effort named as Joint Oil Analysis Program (JOAP) [1]. The basis of this effort is located in creating listings of wear metals for

the equipment used by the operators and decision making guidance for laboratory use, so that the oil samples taken from reciprocating engine sumps or gearboxes, hydraulic systems or closed gas turbine circuits can be estimated through the experimental results and further actions to be taken if necessary. The JOAP goals are summarized in improving the operational readiness of the Air Force, Army and Navy

units, the economy of the equipment used and in parallel obtain and keep large amounts of data, that can be further post-processed for every equipment or assembly that participates in the program. This is achieved by correct diagnosis of oil condition and potential equipment failures and analytical data processing of the acquired data for the specific equipment regarding each phase of its operational life. Eventually new standards of analytical techniques are established and calibration standards as well as instrumentation and equipment, innovative equipment analysis reports and finally locating the most cost effective means of monitoring the degradation of the lubricant used in the internal combustion engines, gearboxes and hydraulic systems [1].

2. SPECTROMETRIC OIL ANALYSIS THEORY AND ADVANTAGES

The use of the spectrometer is clearly a diagnostic tool. It is used to determine the type and amount of wear metals in the lubricant samples [1]. Its importance lies in its ability to locate unusual concentrations of a metal element that is translated as an indication of abnormal wear of the equipment analysed [1]. Eventually major failures are avoided and decisions are taken in the correct timing for servicing or repairing the equipment. Although being itself an expensive method, the benefits from enhancing safety and promoting equipment readiness is vast [1].

2.1 Lubricant Physical Property Testing

This test has a complementary role to spectrometric oil analysis and its contribution in determining lubricant degradation or contamination which occurs from combustion blow-by, oxidation from overheating, moisture from coolant leaks, additive depletion etc, is considered very important, as the user gets a complete picture of the condition of the tested lubricant [1].

2.2 Benefits of Oil Analysis

Throughout the useful life of lubricant, it is important to determine its quality. Data acquisition from spectrometric and physical

property testing can be used as guidelines to assist in identifying mechanical failures and in determining lubricant quality [1]. The diagnostic tools of oil analysis oversee potential wear or failure of the equipment used and 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.

2.3 Wear Metals

In all equipment, in between the metallic surfaces, the mechanism of friction is responsible for the generation of wear metals. The use of lubricants is an ancient method to avoid friction and imminent unwanted results related to the operating condition of the metallic parts. With metallic contact, a significant energy dissipative process is plastic deformation [2]. The subsequent generation of wear debris can involve fracture at different scales, tribochemical reactions and dispersal of debris [2]. Wear metals are also generated from corrosive action within the lubrication system.

It is, therefore, without question that lubricant condition monitoring can extract useful information about the lubricant condition and spectrometric analysis can also indicate the rate of wear and its source. In detail, metal particles or wear metals that originate from metal surfaces, have the same chemical composition. 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 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]. This information might be very specific, i.e. abnormal trace of Sn is translated to worn journal bearing/casings or only general information might be extracted, i.e. abnormal Fe concentration which is translated into several parts being worn. In that case alerts might rise for several parts but the knowledge of the person performing the analysis is a major contributing factor as well [1].

The results represent the concentration of all dissolved metals and particles [3]. For a normally operated part, wear metals are being produced at a constant rate, which differs depending on the examined assembly. Sizes of the metal particles that are measured by the spectrometric analysis are up to 5 microns in size. Failure of tribomechanical systems can appear due to changes in lubricant characteristics. The key to maintain the condition and to achieve certain techno-economic effects is the monitoring of lubricants. [4].

In most cases the changes of the elements to functionality and the entire system is expressed through changes in lubricant characteristics. The status of the lubrication system under examination is assessed through changes of the lubricant physical and chemical characteristics. These changes directly depend on condition of all elements of the tribomechanical system and the appropriate method to identify possible damage or failure is detection through laboratory analysis of metal particles, physical and chemical processes and contaminants [4].

Figure 1 shows a theoretical plot of wear metal concentrations in ppm against operating hours. It is important to notice that for an enclosed lubricating circuit with no oil consumption the wear metal concentration will also increase at a constant rate.

So, if abnormal friction and wear within a metallic assembly occurs, it is inevitable to see an increasing quantity of the wear metals. In Figure 1, abnormal wear (curve – C) shows a sharp increase in wear metal concentration, as opposed to curve – B that shows a slight increase of wear metal concentration for the enclosed lubrication system that is under investigation. Note that this is a theoretical curve, where no oil is added or consumed during operation. The break-in period (curve – A) shows a sharp wear metal increase but in that case it is expected because new parts or early overhauled parts produce large proportions of wear metals during initial operating period of the new components. When abnormal rate of wear metals is detected actions should be taken for tracing the part responsible for producing the wear metals and further repairs should take place to avoid total assembly damage or failure [1].

Fig. 1. Wear metal concentration vs operating hours [1].

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 particles produced. An abnormal condition of this type will sharply increase the concentration and rate of build-up of wear metals within the lubricating system. If the condition is not discovered and corrected, the deterioration will continue to accelerate, usually with major secondary damage to other parts of the assembly, resulting in the eventual failure of the entire assembly. It is important to note that newly overhauled assemblies may tend to produce wear metals in higher concentrations during the initial break-in period [1].

2.4 Measurement – Identification of Wear metals, Calibration and Method Limitations

The method of spectrometric oil analysis is able to measure extremely low concentrations of trace metals in the lubricant experiments, through the atomic emission rotrode and atomic absorption devices. The calibration of the measuring equipment is achieved through base oil standards that contain specific amounts of trace metals with controlled viscosity and flash point [1].

The method itself is effective in detecting those failures that proceed at a rate, slow enough for laboratory detection. The detectable failures consist of a slow, progressive wear metal build-up above an abnormal established level, or a series of rapid wear metal concentration increases, occurring below established abnormal level [1]. Typical sources of wear found in detectable failures:

- a) Jet/Turbine Engines: Worn bearings (balls, cages, races), bearing seals and retainers, bearing housings, constant speed drives, oil pump gears and gearbox castings [1].

b) Reciprocating / Internal Combustion Engines: Worn bearings, crankshafts, cylinder walls, oil pump gears, piston pin bushings, piston rings, push rods, rocker arms, valve guides and valve springs [1].

Failure or catastrophic failures cannot be detected by the mentioned techniques and the same applies to the failures with no wear metal indications, for example if the wear particles are too large (more than 10 microns in size) to be detected by the analysis method [1]. For analysis of larger particles, the ferrography method has to be used, that separates magnetic wear particles from the lubricant and microscopic examination enables to determine the wear mode and probable sources of wear in the technical system [3].

2.5 Practical Considerations

Practical factors such as sample integrity, contamination, spectrometer type, calibration standards, lubricant additives, corrosion, fuel dilution, new/rebuilt components, patterns of wear, effect of lubricant loss/addition/change, evaluation information, filter/screen checks, operating conditions and feedback have an impact on the experimental lubricant analysis carried out by the spectrometric method. In detail:

a. Sample integrity

The sample has to be representative of the current lubricant condition of the examined equipment so that erroneous results can be avoided [1]. Careful conducting during the sampling of oil ensures extraction according to the actual oil usage, which enables each sample as representative [3].

b. Contamination

Water, unusual colour and particulate matter may be indication of contamination that will eventually guide the operator to take another sample to find the correct concentration of wear metals. Silicon increase in lubricant samples is a trace of lubricant contamination from dirt and sand and is also an indication of the operating area (dry, sandy or dusty environment) [1]. As already is known, the abrasive qualities of dirt and sand accelerate wear [1].

c. Type of Spectrometer

Atomic emission spectrometers give higher trace metals concentration than the atomic absorption ones [1].

d. Calibration standards

The standards should not exceed the allowable self life and as a result, errors might occur into the analysis if the standards have degraded over the entire range of ppm [1].

e. Additives

It is common for lubricant manufacturers to use a metallic compound as a lubricant additive. These compounds contribute only a small amount to the analysis of the oil sample and it is, of course, important for the operator to recognize the source of metals. In this case, a sample of the new oil (not used in the component) can be used to determine the amount of trace metals from the additives and after establishing this concentration to proceed with the analysis of the wear metals [1]. It is worth noting that metals from the additives can be Zn, Ca, Ba, or Mg and that indicates the change of additives [3].

f. Corrosion

Water intrusion is the largest contributing factor to corrosion. Proper sealing of equipment helps in avoiding this source of contamination and the operator must be experienced to discriminate a sample with corrosion products, so that the respective correct decision is taken [1].

g. Fuel Dilution

For leaded gasoline use, the lubricant might be contaminated with lead [1].

h. New/Rebuilt Components

Figure 1 – curve A applies for new or recently serviced equipment. Wear metals are produced at an accelerated rate [1]. This break-in period, is difficult to be evaluated and ranges from 20 hours for jet engines and gearboxes to about 100-200 hours for reciprocating engines. If wear metal concentrations during this break in period is high,

an oil change is required, so that concentrations can be reduced to normal levels. [1].

i. Patterns of Wear

In Figure 2 curves A and B represent wear metal concentration for reciprocating and jet engines respectively. The curves reach a level of stability because of lubricant replenishment. The wear metal concentration level reaches a steady state point which is a function of two variables: (1) the rate of lubricant consumption and replenishment and (2) the rate of wear metal production for the specific equipment [1].

Fig. 2. Wear metal concentration vs operating hours [1].

j. Effect of fluid loss/addition/change

In Figure 3 the actual effect of periodic lubricant addition can be seen. For the use of reciprocating engines, oil depletion is rapid and replenishment is frequent, concentrations of wear metal will change erratically [1]. Records of last oil change and oil addition should be kept so that information won't be misleading.

Fig. 3. Effect of periodic fluid addition and fluid change [1].

k. Evaluation information

Correct evaluation of oil samples is critical to ensure that the problematic parts are changed in time rather than an oil change or reducing the sampling interval. It is also important to keep information on component maintenance [1].

l. Filter/Screen Checks

If large particles are found on filter screens, there is a great possibility that they are accompanied by high concentrations of wear metals. Visible particles on filter screens and high wear metal content may be detected independently [1].

m. Operating conditions

At maximum load, equipment tend to produce high concentrations of wear metals and normal levels are monitored under normal load and less demanding conditions [1].

n. Feedback

Another important factor for the evaluator is to keep records of maintenance and operating information. A maintenance recommendation is a result of gathered information from records that indicate overboosts, overspeeds, ovetemps, replacement of piston-rings, ovetorque, 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]. Inadequate reporting has an adverse effect on the evaluator decisions, i.e. the addition of lubricant between sampling may result in abnormally low wear metal results if the sample is taken just after an oil addition [1].

2.6 Atomic Emission Spectrometric Oil Analysis – Other Testing Methods

Atoms, molecules, ions and different kinds of chemical compounds can be excited with absorption of different kind of energy such as thermal, chemical and electric. The emission spectrum of each element that exists in a high energy environment comprises of a characteristic wavelength set used for recognition of the element (light emission during their relaxation process). The greater the concentration of that specific element in the oil sample, the stronger the light intensity of the main wavelength. Measuring the intensity of the main wavelength the concentration of the element is determined. The function that describes the relationship between the intensity of emitted light of an element and the

concentration of the element in the sample is the following:

$$\Phi_{\varepsilon} = A_{ji} \times h\nu_{ji} \times n_j \times V \quad (1)$$

where:

Φ_{ε} : radiation emission power from energy state j to energy state i ;

A_{ji} : the possibility according which an excited atom will supersede this situation;

$h\nu_{ji}$: energy from emitted photon;

n_j : number of excited atoms of an element to total atom number (population density);

V : volume of monitored element.

From function (1) it is derived that the intensity of emitted radiation is proportional to the population density of excited atoms and to an extent of the element concentration in the sample.

High energy environment for exciting metal atoms is created from heat emission from a source, whether it is a flame or electric arc or any other source that causes vaporization of the metal elements and at the same time their excitement.

This radiation energy is scattered through a prism and due to diffraction it "hits" as a light spectrum, the shape of which is determined from the excited atoms structure. Every element has its own characteristic spectrum with spectrum lines that correspond to different wavelengths. Atomic emission spectrometry allows for analysis of all excited atoms, many ions and a small number of chemical compounds (small molecules or free radicals) such as C_2N_2 , NH and OH [1].

In previous work, metals like Fe and Cu were selected for identification with atomic absorption tracing method. These elements are typical and contained in the examined Mercedes-Benz OM 447 HLA engines [4]. On the basis of changes in their concentration in the oil charge, their origin can be determined and also the degree of wear. Results showed that even with growing trends for Fe and Cu concentrations in the last sampling, the wear of the lubricating systems of all tested engines are within the manufacturers' allowable limits. The researchers also pointed out that during the first 10000 km of testing, fall of oil viscosity was evident (at 30000 km oil is changed) [4].

Another method for monitoring the oil condition described in [5] is fluorescence emission ratio of the lubricant, that gives information that characterize and evaluate oil quality. This method can be used for monitoring oil quality in hydraulic systems of compressors and turbines and is reliable in operation. The basic characteristic of this method is the estimation of parameters that affect the physical and chemical properties of the lubricant under examination. The researchers also pointed out that numerous methods are available for diagnosing the physical-chemical properties changes of lubricants but the primary and significant action is to obtain a representative sample [6].

In [6] the researchers pointed out that if there is wear of the contact surfaces, there are wear particles present. Experimental results showed a change in the viscosity index of lubricants. The same group of researchers pointed out that the origin of metal particles maybe from additives, wear of components, fuel, air and liquid for cooling that might penetrate the lubricating system [7]. The mechanism of change in the system elements is identified by testing of physical – chemical and tribological properties. The conditions in which the engine elements are found are complex and are determined to a large extent by oil properties [7].

In a trial to identify the occurrence of wear in the automatic transmission mechanism, the researchers concluded that normal wear particles were produced [8]. Even if Fe had the highest concentration compared to Al and Cu, it was still within the acceptable level and it was suspected that mechanical wear was unlikely to occur but another wear mechanism involving oxidation and corrosion is more likely to arise and is highly associated to the traced elements concentrations. This mechanism was suggested due to inconsequential depletion of anti-wear additives. Eventually, it was concluded that additive concentration is important to be analyzed in order to understand the severity level and mode of wear relationship to the transmission component [8].

It is also experimentally shown that viscosity, viscosity index and high temperature high shear (HTHS) viscosity affect friction results [9] and also the oil film thickness measured from a capacitance sensor [10] and Laser Induced

Fluorescence (LIF) sensor in a single ring simulating test rig, which in turn, has an effect in cavitation appearance and initiation and also friction measurements [10], [11]. Degradation of viscosity index improves result in reduction of molecular weight that leads to viscosity loss and oil film thickness decrease, that in turn cause undesirable phenomena of friction and wear [6].

Another group of researchers demonstrated that monitoring the condition of oil can increase the availability of equipment and improve fault prevention by allowing early intervention in degradation. They monitored the evolution of lubricant degradation for a fleet of diesel engine buses in three well defined phases: (a) by periodic sampling of lubricants by experts (b) results analysis and forecasts based on algorithms and (c) by developing a forecasting method based on time and statistical analysis. [12]. To forecast the evolution of oil degradation they used several approaches: viscosity, total acid number (TAN), total base number (TBN), water content, specific gravity, particle count (visual analysis), spectrometric and ferrographic analysis. The degradation of the lubricant was evaluated with several measured properties and physical-chemical analysis. These include: anti-freeze, appearance, fuel and water content, soot, nitration, oxidation, sulfation, viscosity, viscosity index, total base number, wear metals (Al, Cr, Fe, Mo, Na, Ni, Pb, Si, Sn, V) and particles. An increase in the wear metal concentration suggests an increasing in the abnormal operating conditions that require fast maintenance attention [12].

In another research, LIF method was used to visualize degraded oil samples that were used to investigate the influence of lubricant quality on ring-pack lubricant film thickness measurements [13]. The results showed significant differences in the lubricant film thickness profiles for the ring-pack when the lubricant degrades, which, in turn, will affect friction and fuel economy. As the lubricant degrades, a change in the chemistry (additive depletion, oxidation and nitration) and viscosity can alter the lubricant film thickness experienced by the piston-ring and thereby the piston-ring friction. The evolving viscosity of the lubricant is equally as important as the changes in lubricant chemistry through degradation.

Since engines operate at high temperatures and speeds modern lubricants are specified in terms of high temperature and HTHS viscosity. All the samples in the measurements undergo a decrease in viscosity as the lubricant degrades through service. Changes in load had less of an effect than the change in viscosity [13].

2.7 Analytical Methodology of Aircraft Equipment Wear Metals

Evaluation of Sample Results:

The automated laboratory recommendation is part of a database in MS Access environment. This database is based upon limits that are set within the program. Even if these limits are statistically correct, this type of recommendation is being regarded as a proposal. The following procedure is used from the analyst to evaluate the sampling results [14]:

- a) To evaluate the wear metal concentration limits in every sampling result through a Criteria Evaluation Table for every engine/component. Wear metals that are within a critical concentration, that require monitoring of lubricant analysis for that particular equipment, have arithmetic criteria that are derived from the Criteria Evaluation Table, as the ones applicable for that particular component. If unusual concentrations are traced, they can also be used for maintenance recommendations or resampling.
- b) To compare wear metal concentrations of the present sample with the levels of the previous one so that changes showing developing or imminent equipment wear/problems can be determined.
- c) To determine wear metal trend between the last sample and the present with the trend decision that can be found for every element that concerns the operator in the Criteria Evaluation Table. Excessive increase will be manifest. Trend limits are based on wear metal concentration increase for equipment operation in a period of 10 hours. For example: 2 ppm increase is about 10 ppm in 10 hours and 15 ppm in 25 hours is about 6 ppm increase in 10 hours. Trend values are calculated with the following formula [14]:

$$\frac{A-B}{C-D} \times 10 = \text{trend for 10 hours of operation} \quad (2)$$

A: ppm present sample

B: ppm previous sample

C: operating hours present sample

D: operating hours previous sample.

In general, trends are included within one of the following categories:

- 1) Trend level considered normal (small or no change) [1].
- 2) Marginally to medium increasing or decreasing: Usually is considered normal due to spectrometer measurement (statistical) tolerances, difference between the sampling procedure and factors concerning use or lubricant addition [1].
- 3) Trend level sudden increase or decrease, within its limits: Usually is interpreted as a sign of problems. A sudden increase can indicate the beginning of problem in the equipment, whereas a sudden decrease may indicate faulty sampling procedures, lubricant addition or change without a recording or problems identifying the sample origins. In that case an investigation has to take place to clarify the causes of this phenomenon [1].
- 4) Abnormal trend increase or decrease: Usually it is a sign of sampling procedure problem (lubricant addition, sampling identification, etc) and investigation is required [1].
- 5) Trend increase above limits: in general they are related to equipment problems. Resampling is required and maintenance actions recommendation [1].

Determination of proper recommendation using the Decision Taking Guide in Table 1 [1]:

The majority of sampling results will be normal according to recommendation code, A. If a recommendation for maintenance action is indicated from the Decision Taking Guide (Table 1), this complementary diagnostic guide table has to be re-examined. These tables provide additional information regarding possible failures that justify taking into account the laboratory recommendation for equipment use [1].

Table 1. Decision Taking Guide [1].

RANGE THIS SAMPLE	RANGE, PREVIOUS SAMPLE	TREND	RECOMMENDATION CODE CATEGORY I
NORMAL	Normal	Normal	A
	Normal	Abnormal	B or C
	Marginal	N/A	A or B
	High	N/A	A or B
	Abnormal	N/A	A or B
MARGINAL	Normal	Normal	A or B
	Normal	Abnormal	B
	Marginal	Normal	A
	Marginal	Abnormal	B
	High	N/A	A or B
HIGH	Abnormal	N/A	A or B
	Normal	Normal	B
	Normal	Abnormal	P
	Marginal	Normal	C
	Marginal	Abnormal	P
ABNORMAL	High	Normal	C
	High	Abnormal	P
	Abnormal	N/A	C or B
	Normal	Normal	P
	Normal	Abnormal	P
	Marginal	Normal	C
	Marginal	Abnormal	P
	High	Normal	C or E
	High	Abnormal	P
	Abnormal	Normal	P or F
	Abnormal	Abnormal	T

3. DATABASE CREATION - DATA DERIVED FROM SPECTROMETRIC ANALYSIS

The Database creates, after calculations, the recommendation code including the necessary actions to be taken from Table 2.

Table 2. Standard laboratory recommendation codes – Spectrometric Analysis of Aeronautical Equipment [1].

CODE	GENERAL LABORATORY RECOMMENDATIONS
A	NORMAL sample results, continue routine sampling
X	Analysis results supplied to customer; no recommendation required
Z	Previous recommendation still applies

CODE	INSPECTION RECOMMENDATIONS
R**	Do not fly or operate; inspect filters, screens, chip detector and sumps, advise laboratory of results.
T**	Do not fly or operate, check for discrepancy and advise laboratory of results or disposition. If discrepancy found and corrected continue operation and submit resample after *** hours of operation. If discrepancy is not found it is not found recommend remove component from service and send to maintenance.

CODE	OIL CHANGE RECOMMENDATIONS
J	Contamination **** confirmed. Change oil, sample after *** minute run-up and after *** operating hours
W	Contamination ****suspected. Change oil; run for ***additional hours, take sample hourly.
CODE	LAB REQUESTED SAMPLES (Requires Resample)
B*	Resample as soon as possible; do not change oil
C*	Resample after ***hours, do not change oil
E*	Do not change oil. Restrict operators to local flights or reduced load operation, maintain close surveillance and submit check samples after each flight or *** operating hours until further notice.
F*	Do not change oil. Submit resample after ground or test run. Do not operate until after receipt of laboratory result or advise.
G*	Contamination ****suspected. Do not change oil, resample unit and submit sample from new oil servicing unit.
P*	Do not fly or operate, do not change oil; resubmit resample as soon as possible.
Q*	Normal PPM reading was obtained from test cell run after complete P.E. where oil lubricated parts were changed/removed/replaced. Monitor engine closely after installation to ensure a normal trend before release to routine sampling.
NOTES: * Resample (red cap) required ** Maintenance feedback required; advise laboratory of findings *** Laboratory will specify time limit ****Contamination is defined as water, coolant, silicon, etc and not wear metals. Use the appropriate recommendation codes for increasing trends or elevated wear metal conditions.	

3.1 General

The automated decision taking procedure in the database follows the laboratory recommendations according to Table 1 (Decision Taking Guide) and furthermore within a user - friendly environment for the user.

Table 3. Ranges and trends for turbofan engine F110-GE-100 (F-16 Aircraft), atomic emission method as provided from GENERAL ELECTRIC [1].

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti
Abnormal Trend (PPM increase in 10 hours)	3	2	2	2	4	2	2	5	2
Normal Range	0-8	0-3	0-3	0-6	0-12	0-6	0-5	0-12	0-5
Marginal Range	9-11	4-5	4-5	7-8	13-16	7-8	6-7	13-15	6-7
High Range	12-13	6	6	9	17-19	9	8	16-19	8
Abnormal	14+	7+	7+	10+	20+	10+	9+	20+	9

To materialize the automated decision procedure, all analyses taking place must be compared to the Wear Metal Criteria Tables (Table 3).

3.2 Automated Decision Process - Database

For The creation of automated decision taking, all data from spectrometric analysis have to be compared to the standards already existing in US NAVAIR Technical Manuals, i.e. the tables containing the Wear Metal Evaluation Criteria (Table 3). These Tables contain ranges and trends for the elements given by the manufacturers and are considered, of course, 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 [15].

The following Table 4 shows the used engine-gearboxes and Air Force aircraft types which they belong.

For the database, SRANGES Table was created, that contains all necessary data in order to make the comparisons, i.e. data from the Wear Metal Evaluation Criteria for each engine type or equipment. Meanwhile, more tables were created that contain data regarding serial numbers of equipment and aircrafts, so that additional data can be available, i.e. which military unit is their operator. These data are useful so that future statistics and conclusions can be derived regarding engine use in particular geographical areas of the country of known climate and land conditions.

The user begins from a basic menu with several options. In order to complete an analysis, the user presses button labeled "update" and so, the respective forms are filled with the necessary data and they are presented in table TESTS. The respective results have information about the range, trend, and final laboratory decision. These are the requested final results and laboratory recommendations that can be shown on screen when the user enters the engine/component serial number. This table is the last stage before updating Table TESTS, which, as mentioned is a spectrometric analysis storage in graphs, the wear metal concentration is presented in the last six (6) analyses from oil samples taken from that specific engine, component or gearbox.

Table 4. Used engine-gearboxes and Air Force respective aircraft types [15].

Engine Type/Equipment	Aircraft Type
F110-GE-100	F-16C
GBOX 42-D AB 205	AB 205
GBOX 90-D AB 205	AB 205
ASZ62IRM18	PZL M18
IGSO – 540 – A1E	Do 28
IO-360-D	T-41D
IO-540-C4D4D	TB 20
J33-A-35	T-33
J69-T-25	T-37
J79-GE-17A/C	F-4E RF-4E RF-4(GAF)
J85-GE-13	F-5A/B
J85-GE-15N	NF-5
J85-GE-21	F-5A/B
J85-GE-4	T-2
O-360-F1AG	RG-172
O435-23	OH-13H
R-1340-61	AG-164A
R-1820-76D	HU-16B
R-1830	C-47
R-2800	CL-215
VO-435B	47G-5
TVO-435	47G-352
TF-41	A-7H
T56-A15	C-130H
T56-A7	C-130B
GTCP85-180 (APU)	C-130H C-130B AM 32A
TF-41-402D	A-7D
T53-L-13B	AB 205
T53-13B	AB 205
XMSN AB-205	AB 205
PTGT-3 (763, 765)	AB 212
PTGT-3B (190, 196)	AB 212
XMSN AB-212	AB 212
GBOX 42-D AB 212	AB 212
GBOX 90-D AB 212	AB 212
ATAR 09 K50	F1-CG
M53-P2	Mirage 2000

Graphical representation of wear metals found in the lubricant contains graphs for each one

of the measured from the spectrometer elements, as well as ranges determined from similar tables for every engine or component as in Table 3. Eventually, the user can monitor the wear development of each metal as an existing and as a comparing value in the program and can evaluate sudden increase or decrease as a function of operating hours and in relation to existing specifications of every engine, component or gearbox. It is not necessary to make six consecutive measurements for every serial number so that graphs could be extracted from the database. The Table 5 shows the serial numbers that were inserted and their respective engine/aircraft type.

Table 5. Equipment, type and serial numbers inserted in the database [15].

Engine/ Gearbox S/N	Engine/Gearbox Type	Aircraft S/N
109433	T56-A15	746
109435	T56-A15	752
179523	R-1820-76D	070 R/H
510032	R-1820-76D	070 L/H
56845	IO-360-D	185
56854	IO-360-D	182
A13-1062	GBOX 90-D AB 205	391

The above serial numbers belong to turboprop/turboshaft engines, reciprocating radial and boxer engines and a 90° helicopter gearbox. For the engine and gearboxes full data were already available so that all the database fields could be filled-in, decisions to be made and the respective graphs to be derived for the wear metals found in the lubricant of each equipment [15].

It is important to note that the user may see the upper and lower limit of the specifications existing in Wear Metal Evaluation Criteria Tables, as long as he places the engine/gearbox of interest as an input. These criteria are included in Table RangesNew [15].

Selective queries were created in SQL and specific data can be extracted and further monitored.

Figures 4 and 5 show the respective actions flow charts followed by the Laboratory and the Database.

Fig. 4. Actions followed by the spectrometric oil analysis laboratory.

Fig. 5. Database flow chart.

3.3 Specifications of used Fuels and lubricants

Aircraft engine fuels follow one of the following classifications as presented in Table 6.

Table 6. Aircraft engine Fuels classification [15].

CLASSIFICATION	NATO CODE	DESCRIPTION
JP-4	F-40	Gasoline type
JP-5	F-44	High flash point, kerosene type
JP-5/JP-8 ST		Special test fuel, high flash point, kerosene type for engine development and specific characteristics testing

All spectrometric analyses play a very important role because they can detect imminent failures on the basis of already known standards and in parallel with testing useful information and statistics are derived. Respectively, conclusions are drawn regarding wear development via lubricant spectrometric analysis. Furthermore, significant and helpful conclusions are derived from the comparison of the lubricant condition before and after usage of a new fuel. In that case it is possible that the new fuel can differentiate the wear metal development, as they are traced. Lubricants used from the Hellenic Air Force aircraft engines and gearboxes are supplied from commercial companies. Required lubricant types are: MIL-L-7808J, MIL-L-23699D, MIL-L-2105, MIL-L-46000, MIL-L-22851D, MIL-L-6081, MIL-L-6082D.

From the above lubricant list, MIL-L-2105 is used in gearboxes and MIL-L-22851D in reciprocating engines. MIL-L-7808J is used specifically in jet engines. These three types of lubricant are mostly used. Supplying companies are: Castrol, EXXON, Mobil, Shell, Avin [15].

3.5 Spectrometric Oil Analysis Results

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 for each component. In Figures 6a-6e the graphs show the wear metals concentration for Continental IO-360-D piston engine. It can be noticed that all wear metal concentrations, Fe, Cr, Cu, Ag, Al, Mg, are within the normal wear metals levels that are proposed from the Wear Metal Evaluation Criteria Table for that specific component.

(a)

(e)

Fig. 6 (a)-(e). The wear metal concentrations for Continental-Lycoming IO-360D opposed piston engine.

(b)

(c)

(d)

(a)

(b)

In Figures 7a-7f the AB 205 helicopter gearbox (90 degrees) data are presented, which show abnormal Cu and Fe concentration that needs to be further evaluated from the operator. Fe is above marginal level of the Wear Metal Evaluation Criteria Table and Cu above normal level. Ag concentration is not a cause of concern due to the amount of hours from last general repair. Ag levels are not given as well.

(c)

(a)

(d)

(b)

(e)

(c)

(f)

(d)

Fig. 7 (a)-(f). The wear metal concentrations for Augusta Bell 205 helicopter 90 degrees gearbox.

(e)

(c)

(f)

(d)

Fig. 8 (a)-(f). The wear metal concentrations for radial piston engine Wright Cyclone R-1820-72D.

Figures 8a-8f show a radial piston engine R-1820-76D oil analysis (Grumman HU-16B), with the only cause for investigation being the trend noticed for Al concentration.

(a)

(e)

Fig. 9 (a)-(e). The wear metal concentrations for turboprop Rolls-Royce Allison engine T-56-A15.

Figures 9a-9e show the Allison turboprop T56-A-15 (C-130H Hercules) oil analysis measurements with all wear metal levels (Fe, Cr, Al, Cu, Mg) showing normal levels according to the Wear Metal Evaluation Criteria Table.

3.6 Laboratory Operating Cost

The basic instrument used for the analysis is the atomic emission spectrometer. Two trained users are enough for its operation, sample preparing and sampling recording (the samples itself and the folders kept at the laboratory). For the analyses consumables are used at an extra cost. Table 7 represents the total operating cost.

(b)

Table 7. Spectrometric (atomic emission) laboratory operating cost [15].

Laboratory Operation Requirements	Cost (€)
SPECTROIL Atomic Emission Equipment	65000
Trained Users	25000/yr
Consumables	6000/yr

In total, the above mentioned cost is comparatively low if someone thinks of its valuable services offered for engine-component fault diagnostics. This is evident after describing existing examples of engines that escaped from total or part destruction during testing or operations. In such cases, avoiding such a failure is enough to justify not only the laboratory establishment but also the cost of more than one in the Air Force Units that support aviation equipment spectrometric analysis.

3.7 Examples – Maintenance Cost

The spectrometric oil analysis laboratory is estimating initial failure. When the wear metal concentration is problematic, the laboratory addresses the maintenance section and they are responsible for taking further actions. These actions include inspection of all filters, initially, main and secondary ones. This check is performed for residue identification. If they are found, a component of the engine has failed or it is broken and has to be identified.

It is important to differentiate between residues and wear metals dissolved in the lubricant. When a component is broken, spectrometric oil analysis cannot trace or even suspect that there is a possible failure of a component or equipment. This happens because the laboratory estimates friction. Due to friction, wear happens in between the surfaces of the assemblies and manuals such as US NAVAIR specifications, evaluates them [1,3].

Lubricant contamination is a result of the friction that generates wear metals. Contamination, of course, to a great extent can cause problems to other engine sections, apart from the ones initially located, due to lubricant recirculation within its closed circuit. A possible failure and the need for engine general inspection/overhaul due to lubricant contamination, is a usual phenomenon and the manufacturer knowing the extent of damage, has established particular sampling intervals or tactical inspection.

The technical/maintenance department is on its side, always in contact with the laboratory. In case they discover traces of metal in the filters, they refer to specific manufacturer manuals, replace all the problematic components of the equipment and inspect the engine thoroughly not only with visually but also with testing for possible failures [16].

Examples:

- In a J79-GE-17A turbojet engine, during a ground test in the engine test cell, an increase in iron (Fe) concentration was traced, not outside limits, not in normal level either. Trend was coming close to the abnormal measurement limits and every hour a spectrometric oil analysis was performed during testing. Finally, that small Fe concentration increase was traced – it was due to a holding ring that was free to rotate, causing itself to wear out and also its respective bolt. The mentioned worn parts are directly translated to ppm increase of wear metals in the lubricant. Testing was directly stopped and inspection was carried out where this specific problem was identified. If the above mentioned problem was not traced, it would inevitably cause the transfer gearbox bearing to fail and as a consequence complete engine failure due to shaft destruction. The extent of damage is too big if someone considers that the problem was traced in faulty bolt connection. That is a consequence of lubricant recirculation in a closed circuit that finally resulted in engine part repair.
- Reciprocating piston engine R-1820-76D was grounded when the laboratory (after the analyses) found out that: Ag was increasing by 1.2 ppm and Fe by 41 ppm. After the necessary investigation no particular damage was identified. The limits, though, were considered abnormal because it was not taken into account that the engine had only a few hours of operation after general repair. According to this example, it was not estimated in the correct manner the fact that the engine just came from general repair, where the limits of wear metals for a few hours of operation are different. That is the reason that hours from last general repair are also recorded for laboratory use.

- In another engine R-1820-76D (another serial number) an increase in Ag and Fe was initially monitored in the lubricant. The laboratory made the right decision to ground it, because this increase in wear metals was due to main crankshaft bearing failure [15].

3.8 Data Feedback

Spectrometric oil analysis laboratories keep statistics and the same applies to independent companies. They are also known as investigation organizations. Apart from bibliographical support, there is also empirical support that develops from the conditions that the Air Force units face. Moreover, other organizations-groups are the factories themselves, quality control and manufacturer's investigation departments.

Data feedback is materialized between laboratories and the respective section of the manufacturer's equipment maintenance. When failures arise, they become known and discussed in the various component improvement programs.

Greek climate conditions are thoroughly covered by US NAVAIR manual that is considered strict enough to the limits that encompass knowledge and experience from operational activities in every climate conditions.

Climate affects certain element appearance:

- Due to proximity to the sea, for example, high concentrations of Fe and Mg are traced.
- In cold days no sampling can take place because cold atmospheric air creates additional Mg even by 10ppm at the lubricant.
- During the Gulf War, increased Si concentration was monitored and it was necessary to introduce certain modifications to oil filters.
- Spray aircrafts have a water ingestion problem (intense corrosion).
- Aircrafts operating upon aircraft carriers have an intense corrosion problem due to air ionization and in general the very different operating conditions.
- Humidity, in general, causes metal oxidation and dust increases Si concentration.

- As part of a full cooperation between the people involved, all of the above are mentioned and recorded from the level of local laboratory to the manufacturer [15,16].

3.9 Operating Cost Depreciation

The above mentioned examples are characteristic of the goals set through the foundation of spectrometric oil analysis laboratories. These goals are, on one hand, friction investigation and fault detection so that all of the rest "healthy" components stay out of trouble and on another, on-air failure avoidance that includes cost of aircraft and/or engines together with the possible case of loss of life, which is priceless.

Table 8. Repair and buying cost for aircraft and helicopter engines [15].

Engine Type	Engine category	Byuing Cost (US \$)	General repair (hours)	Partial Repair (hours)
J79-GE-17	Turbojet	≈500000	3650	1090
T53-L-701A	Turboshaft	240000	N/A	N/A
T55-L-11D	Turboshaft	282000	N/A	N/A
T53-L-13A	Turboshaft	148911	N/A	N/A
T53-L-13B	Turboshaft	148911	N/A	N/A

The cost of several part-general repairs is mentioned, indicatively, as well as the cost of buying for specific engines that these data were available (Table 8). It is not necessary to calculate depreciation, due to unstable conditions, that is, according to the place of the laboratory, the specific equipment used, hours of operation or fault frequency differentiations that might exist. The J79-GE-17A example is characteristic of the spectrometric laboratory's ability and in the end, its cost effective maintenance for as long as it is in operational activity [15].

4. CONCLUSIONS

The aim of the spectrometric oil analysis program is to trace changes in the composition of the lubricant used as well as other fluids in order to locate and control unusual wear and to forecast imminent component or equipment failure. From the operator's point of view this is translated to increased effectiveness through the right maintenance procedures, at the right time and with the lowest but according to the certified practices, level of maintenance.

An effective program of lubricant maintenance for modifying from the beginning the methods used, is a very important element of the oil analysis program, because the sampling evaluation procedure is affected as well as the repair decisions. There is also a possible effect on decision change regarding security, reliability and the application of maintenance procedures. In that manner, the basis for improved help regarding fault diagnosis is provided from the laboratory that supports the operator and useful data are gathered regarding sample results for a specific component with an unnatural wear metal pattern. This procedure, solved cases in some problematic components with their replacement, without taking out the whole assembly for general repair.

The knowledge provided regarding increasing contamination variations in a specific equipment object, has also helped to an increased operational planning, for example no – flight orders until the problem of increasing relative concentration variation is fixed. In that manner, the possibility of a remote (from base) engine change is avoided. Additionally, the information knowledge creates dynamic criteria evolution used for the sample evaluation. This procedure confirms that these criteria applying to already found lubricant condition changes are precisely related to the real lubricant condition. So, the possibility of an unjustified equipment withdrawal is decreased and meanwhile, the criteria levels are ensured to be at a relatively low level for safe equipment operation.

Possibly, the most important element of the decision taking process for the operator is the laboratory's recommendation for taking maintenance actions followed by lubricant sample analysis. Laboratory's recommendations are a result of careful and in depth analysis of equipment operating history and have to be applied. In contrast, it is within the responsibilities of the operator to decide what actions are to be taken in relation to whichever laboratory recommendation [14,16]. It is necessary to cooperate closely with the laboratory to ensure that adequate maintenance procedures are taking place that result in reduced maintenance cost and increased operational and personnel safety [15,16].

Another important issue that needs to be further investigated is the lubricant's physical-chemical properties change due to operation. As other researchers pointed out, viscosity and viscosity index change were also identified that in turn, lead to minimum oil film thickness variations and eventually change cavitation patterns and initiation.

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