



**SPECTROMETRIC OIL ANALYSIS PROGRAM
ENHANCEMENTS FOR THE ARGENTINE AIR FORCE**

THESIS
MARCH 2017

Roberto Hernán Bertram, Lieutenant Colonel, Argentine Air Force

AFIT-ENS-MS-17-M-115

**DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY**

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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**SPECTROMETRIC OIL ANALYSIS PROGRAM
ENHANCEMENTS FOR THE ARGENTINE AIR FORCE**

THESIS

Presented to the Faculty

Department of Operational Sciences

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the
Degree of Master of Science in Logistics and Supply Chain Management

Roberto Hernán Bertram

Lieutenant Colonel, Argentine Air Force

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Abstract

The Argentine Air Force continues to make a great effort to keep up to date and improve their logistics processes related to materials management. It is a permanent intention to reduce not only risks in the operation of various aerial systems, but also the direct and indirect costs associated with maintenance, in order to achieve maximum utilization of scarce resources.

This thesis is sponsored by the Direction General of Material with the aim of reinforcing the importance of predictive maintenance, motivated by the daily urgencies of shortages of materials, and lack of awareness of data recorded to achieve and predict events and unfavorable conditions for the organization. With information provided by the engine user of PTA6-25, the School Technical Group of Maintenance, and the Materials Testing Laboratory, an analysis of oil sample results and testing procedures was performed to predict and/or improve the predictive maintenance system used in the Air Force.

*To my God, my north;
to my wife, my balance;
to my daughters, my energy;
to the personnel of AFIT, faculty and staff, and trainees' colleagues, my support;
to my parents, my guides from heaven;
to the Argentine Air Force, my opportunity;
and to all those who helped me without expecting
anything to exchange in this impossible challenge reached.*

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Lt. Col. Roberto Hernán Bertram

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List of Acronyms

Ag	Silver
Al	Aluminum
ASTM	American Society for Testing and Materials
Avg	Average
B	Boron
Cr	Chromium
Cu	Copper
Cum	Cumulative
DGM	General Direction of Material
DIyP	Department of Engineering and Publications
DMM	Direction of Maintenance of Material
EAM	Military Aviation School
FAA	Argentine Air Force
Fe	Iron
GTE	School Technical Group of Maintenance
Hrs	Hours
IRAM	Argentinian Institute of Certification and Standardization
IQ	Investigative Question
LEM	Materials Testing Laboratory
Mg	Magnesium
NAVAIR	Naval Air Systems Command
Ni	Nickel
Poly.	Polynomial
PPM	Parts Per Million
RQ	Research Question

R Square	Coefficient of Determination
R.O.C	Rate of Contamination
RMSE	Root Mean Square Error
S/N	Serial Number
SAE	Society of Automotive Engineers
SDGM	Sub direction General of Material
Si	Silicon
Sn	Tin
Ti	Titanium
Zn	Zinc

SPECTROMETRIC OIL ANALYSIS PROGRAM

ENHANCEMENTS FOR THE ARGENTINE AIR FORCE

I. Introduction

Description

The General Direction of Material (DGM) is responsible for the logistical material support of the Argentine Air Force (FAA). The FAA understands logistics as:

...the set of activities required to create, provide and maintain the forces. Its goal is to provide resources with adequate fitness in quality and quantity, as well as, on time and in the right place. The particularity of the use of aerospace power, such as, scarce resources and technological constraints, requires that at all times the DGM needs to be aware of the true magnitude of existing and required resources for the institution, to be an "active force" and fulfill its mission. Therefore, any logistical plan must respond to or support the corresponding operational plan that gives origin, and it must cover the logistical forecast resource requirements, at both the strategic and tactical level. The logistical problem solution is through a process called the Logistic Cycle, comprising a set of steps in a logical sequence, necessary to create and sustain the Air Force, through the processing of logistics resources (RAC 1, 2010, p. 24).

The DGM is responsible for providing suitable resources for fulfilling the obligations arising from the mission.

The Materials Testing Laboratory is the organization in charge of conducting laboratory tests of samples taken at the site of aircraft operations. It is a subordinate unit within the DGM – Sub direction General of Material - Direction of Maintenance of Material - Department of Engineering and Publications. On the other hand, the part that fulfills the mission is the unit that operates the aircraft, Military Aviation School and

within this, the School Technical Group of Maintenance (GTE). The GTE is the division that conducts aircraft maintenance, which extracts and forwards the samples, and has the obligation imposed by the DGM to comply with spectrometric oil analysis procedures.

The laboratory oil analysis processes meet the requirements of the American Society for Testing and Materials (ASTM) standards and Naval Air Systems Command (NAVAIR) Joint Oil Analysis Program Manual (NAVAIR 17-15-50.3 / TM 38-301-3 / T.O. 33-1-37-3 / CGTO 33-1-37-3, 2013). Volume I of this NAVAIR manual details the purpose and applicability of the Spectrometric Oil Analysis Program (SOAP) provides theory and benefits, and explains the procedure for conducting sampling. ASTM D 5185-02, "Standard Test Method for Determination of Additive Elements, wear metals, and contaminants in used lubricating oils and determination of selected elements in basic oils by inductively coupled plasma atomic emission spectrometry" (ASTM D 5185-02, 2002) is another reference used by the laboratory.

The end user removes the sample and sends it to the laboratory for testing. Once the sample is received at the laboratory, spectrometric and physical-chemical analyses are performed. For qualitative and quantitative spectrometric analysis of metals in fluids, Optima 2100 ICP equipment DV (Optical Emission Spectrometer) brand "Perkin Elmer" is used. The level of intervention of the laboratory is to inform and distribute the results for decision making by end users. The reference parameters for the PT6A-25 are extracted from the NAVAIR 17-15-50.3/TM 38-301-3/TO 33-1-37-3/CGTO 33-1-37-3/change 0/30 August 2013, WP 015 00, pages 1 and 2.

The laboratory conducts the physical-chemical oil analysis in accordance with the normative details below:

- ASTM D445: Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids.
- ASTM D92: Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester.
- ASTM D974: Standard Test Method for Acid and Base Number by Color-Indicator Titration.
- IRAM 6558: Determination of acid or base number. Color indicator titration method.
- ASTM-D1500 AND D-155: Method of Test for Color of Lubricating Oil and Petrolatum by Means of ASTM Union Colorimeter
- ASTM D130: Standard Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test
- ASTM D4052 and D-287: Standard Test Method for Density, Relative Density, and API Gravity of Liquids by Digital Density Meter

The Laboratory sends report results to the responsible office for the material in use to determine the next steps.

The reason why the GTE conducts spectrometric analysis of oil is the Technical Report C.T. FA42B2-1-2 23ABR86 of the Argentine Air Force, which establishes the general procedures to comply. After about 125 hours of flight, the samples are taken and are sent to the Laboratory for examination. The result is analyzed by the engine inspector and he/she makes the decision of what needs to be done.

This thesis is sponsored by the DGM to gain additional information about the spectrometric program, generate options for improvements, and mitigate risks.

Problem Statement

Aircraft maintenance management represents a complicated activity for a manager. This activity has a broad spectrum of sub tasks that need to be measured, evaluated, saved, and distributed for making different process improvements. The costs of the aeronautical activity provide a constant pressure for shorter periods for grounded aircrafts, and also for reducing disruptions. To address these difficult activities, a correct and clear record of tasks and programs needs to be achieved to produce a vision of the status of different components, to control the time required, to manage delays and to reduce risks and thus to complete the mission efficiently.

For this reason, the FAA implemented the Spectrometric Oil Analysis procedure as an obligation for all organizations that use aircraft engines. This predictive method, however, seems underappreciated in the sense that the FAA may not be getting the full possible value. This would be unfortunate, given that this method is used worldwide for aviation since its inception in the 1960s and is also used in automotive, mining and other industries today.

That this tool is not fully exploited, possibly due to ignorance or not to desiring to measure the costs of their incorrect application or by the daily urgency of routine problems, fosters an unnecessary increase in risk to what is arguably already an inherently risk-activity. The purpose of this research is to determine the usefulness of this powerful predictive maintenance program in the conditions of implementation to date, and propose improvements that are beneficial to the FAA.

Research Objectives

The objectives of this research are to enhance the general procedure of Spectrometric Oil Analysis utilized by the FAA, based specifically in the Engine PT6 A-25, and using the maximum wear values established for the NAVAIR Manual and FAA Technical Report's process description. This research also benchmarks the FAA processes to the procedures used by other companies.

The goal is to optimize the process, to upgrade, and to extract the most benefit from this powerful method of wear analysis that leverages the engine lubrication system to assess the condition of the engine and its components. Research options include extracting as much information as possible from the sample data to determine the relationships, and using process benchmarking to identify changes in procedures and technical reports and the corrective actions, predictions, and result visualizations necessary for helping decision makers.

Research Questions

In order to achieve the research objective, the following research questions were addressed:

Question 1: Are the data extracted enough to fulfill the requirement of predicting the next result for the sample of oil, avoiding unnecessary risk management and operational risk?

Question 2: Do the data extracted meet the quality to fulfill the requirement for predicting the next result for the oil sample?

Question 3: Is it possible to change or optimize the system of spectrometric

analysis of oil applied in the FAA?

Question 4: Does the technical report require some type of upgrade?

Investigative Questions

The investigative interrogations are used to respond to the primary research questions:

1. In what mode is the Technical Report of spectrometric analysis applied in the weapon systems today?
2. Has the process been updated with development over the years?
3. How does the engine user process the information once the laboratory results are received?
4. Has the user developed an alarm system in case of unfavorable results?
5. Does the user have a written procedure of spectrometric oil analysis in this type of engine?
6. Is the communication between the testing laboratory and the user of the results proactive?
7. Are qualitative data recorded in addition to the quantitative data in the oil analysis program?

Theoretical Lens

The data obtained is quantitative data, extracted in periods of about 125 hours of flying time in a particular engine type, with a consistent procedure used for the samples. The process of spectrometric measurement is through a machine without significant variation as it is calibrated daily.

The data obtained were analyzed to provide a wear trend for each engine by each material. The engines were then compared through correlations. After that, the study result was compared with the criteria established for the NAVAIR Manual for every

engine with the same part number and the FAA Technical Report C.T. FA42B2-1-2 (Technical Report C.T. FA42B2-1-2 - 23ABR86, 1986). At the same time, benchmarking was applied with different firms and general information about methods and procedures used in oil analysis. Finally, a prediction was made for each material in each engine for the next result.

A research limitation is that the oil samples were obtained during normal aircraft maintenance by multiple people in operational conditions, and not in a laboratory where collection parameters can be precisely controlled. As a consequence, the collection procedure's precision is unknown.

The Argentine Air Force Materials Testing Laboratory produced the data and is responsible for this type of test. The unit that operates this type of engine is the School of Military Aviation, and this engine is mounted in the aircraft "EMB312" used for the second stage of the FAA military pilot training.

Finally, the constrained data is offered for NAVAIR Manual Volume III (NAVAIR 17-15-50.3 / TM 38-301-3 / T.O. 33-1-37-3 / CGTO 33-1-37-3, 2013), which gives the values to define whether the engine has normal wear for continuing its operation or to define some type of maintenance operation that is required.

Methodology

The methodology for enhancing the FAA predicted spectrometric oil analysis program follows these steps, first, the data were received from both organizations (the laboratory tests and the end user). The data sets were compared and inconsistencies between them were corrected. Second, the procedures applied by each organization were

obtained. Third, benchmarking was applied with different firms, companies and the literature to compare methods and procedures used. Fourth, data analysis, correlation between variables, trend graphs, calculations required by technical report of the FAA, development of an alert system, loading of limiting values in accordance with the NAVAIR table (NAVAIR 17-15-50.3 / TM 38-301-3 / T.O. 33-1-37-3 / CGTO 33-1-37-3, 2013), prediction of results, and extraction of conclusions were completed, and finally, recommendations and obligations were generated from the study.

Assumptions and Limitations

The data included in the oil tests in this study are 100% of the tests available in the FAA, having substantiated the records between the user unit and the testing laboratory, for this identified weapons system and this particular engine.

The data prior to 2003 were not retained, apparently from using an erroneous concept of mandatory archive times, which in no case exceeded ten years of classification.

The FAA implemented the Military Airworthiness System in 2007 to preserve and render available all maintenance-related data. Maintenance personnel are required to use the system. Accuracy of complete information can now be more reliable thanks to the conservation of all the necessary records that guarantee the traceability of all the components that have been installed on an aircraft.

This system guarantees the preservation of all data, test results, and issues arising in the aircraft, and thus enriches the records for improving future studies linked or not to this study.

The first step, after determining the necessity to conduct oil analysis, is to establish the time between samples. In this case, the assumption is that the time was defined for facilitating maintenance work in accordance with minor inspections of the engine. Regarding this time, it is very important for the development of oil spectrometric analysis under reliable results to meet the times; unfortunately, mission requirements can sometimes increase the sample intervals.

The trainer aircraft engine was selected because it is operated by only one organization, which helps control for processes that may vary between organizations. Although the process of extracting data also has an important human factor which still induces variability in the general process as well.

A research limitation is that the particular engine states and sample collection processes that produced the extracted data cannot be exactly replicated. Any change in the extraction method could affect future results.

Implications

This research will help to support the use of spectrometric analysis as a predictive system in engine maintenance, and promote enhance uses of this nondestructive testing system.

For achieving this objective, it is necessary to apply more precision to the entire sampling process: reducing variability, applying more controlled times between samples, using stricter control of refilling of oil, refilling for leaking or consumption, and making other changes, taking note of events that occurred during engine use, such as over-temperature, engine over-speed, or by having exceeded the permissible gravity forces.

Any known event that can act in a detrimental manner to the performance of an engine should be recorded. Identifying the technician that took the sample is also important. Finally, making an in-depth analysis of the test results is critical. To be useful, the entire collection, analysis, and corrective action process should be considered.

Contributions

This research will help to reduce risk management in aircraft maintenance, reduce the possibility of catastrophic damage to materials and personnel, increase component life, save money, and improve planning for maintenance and operational activities.

When an event risk exists and the evaluation of its potential impact is high, then it is important to develop a plan to mitigate the risk (Chase et al., 2014, p. 40). As a consequence, every measure destined to mitigate risk is significant for an organization with scarce resources. Engine designs also benefit.

A robust spectrometric program can help to understand if a repair was made with correct technique, accompanied with the appropriate material, with the correct process of cleaning or preservation. It also can illustrate whether the engine exhibits normal performance and wear, and identify contaminated oil.

Chapter Summary

Due to the risk and expense of aviation activity, any reasonable attempt to reduce risk, should be considered that might prevent permanent economic and human consequences.

This predictive method is undervalued in the FAA to such an extent that sometimes the established protocols for correct use are not respected...possibly due to

ignorance, or by the daily urgency of routine competing problems. Not fully exploiting this tool may be causing unnecessary risks.

The success of this research will provide a change for maintenance management and predictive maintenance with future possibility to spread to other engines or processes in the FAA, and the upgrading of the technical report that governs this procedure.

II. Literature Review

Chapter Overview

The literature is based in four distinct aspects. These are: manufacturer reports, maintenance manuals, service bulletins, and service letters; general information on aircraft maintenance, such as aircraft power plant maintenance and type of maintenance on machines; literature referring to the procedure of spectrometric analysis of oil, such as technical reports and procedures of the Argentine Air Force and companies that offer the service of analysis; and finally, different research and articles related to oil analysis.

The mission and functions of the DGM and within the LEM, its tasks and functions, as well as the GTE, that performs maintenance of the engine studied, are presented to understand the concept of maintenance and divisions of the FAA. Additionally, we show how other organizations conduct spectrometric oil analysis programs. The literature review reports different aspects of oil analysis which should take advantage and thus enhance their usefulness with this tool of prediction. And finally, a comparison of this tool of analysis as the Air Force uses it with other organizations and literature references is presented.

Direction General of Material

The mission of the DGM is “To drive the logistics system for sustaining the material within its area of competence and infrastructure, establishing policies and objectives related to the logistical functions of maintenance, supply and transportation in order to contribute to the mission of the superior organization” (MAPO 9, 2016, p. 1).

The more relevant functions are:

- 1) To understand the execution of major maintenance activity, and possibly, the minor maintenance activity assigned to it as well.
- 2) To understand the execution of the activities of the logistics function of supply with the exception of acquisition within the procurement stage.
- 3) To understand the generation of the Logistic Capacities of Material and Infrastructure.
- 4) To understand the administration, training, improvement and training of personnel related to the Logistic System of Material and Infrastructure Maintenance.
- 5) To understand the formulation of the doctrine of procedures in the Organic, Logistic-Material and Infrastructure areas.
- 6) To understand in the approval of the technical-administrative documentation elaborated by its dependent organizations.
- 7) To understand the approval of the procedures corresponding to the logistics of the material and infrastructure maintenance” (MAPO 9, 2016, p. 1).

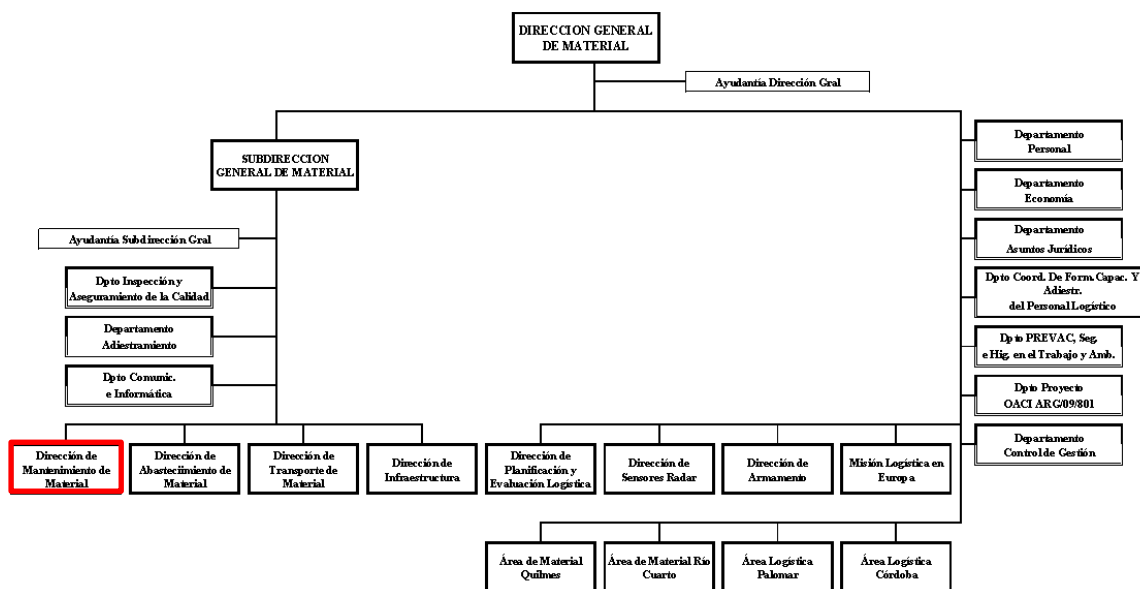


Figure 1 – Direction General of Material Chart (MAPO 9, 2016, p. 50)

Within the DGM – SDGM – DMM - DIyP is found the Division Testing Laboratory of Material.

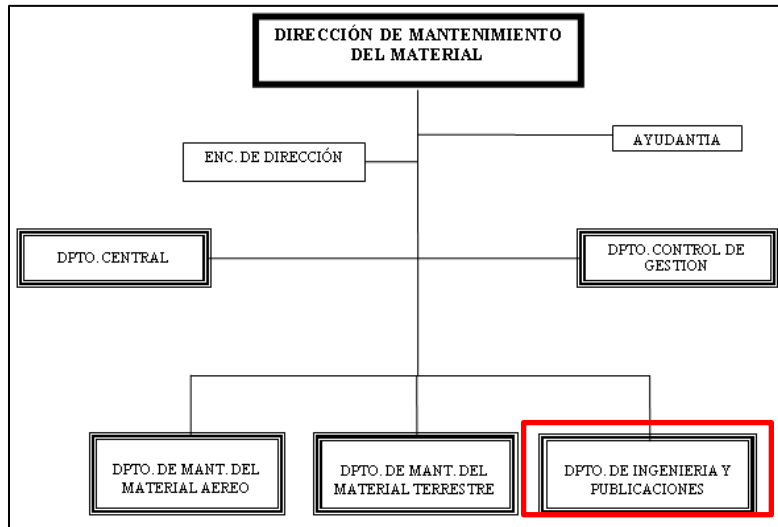


Figure 2 – Direction of Maintenance of Material Chart

(MAPO 52, 2016, p. 26)

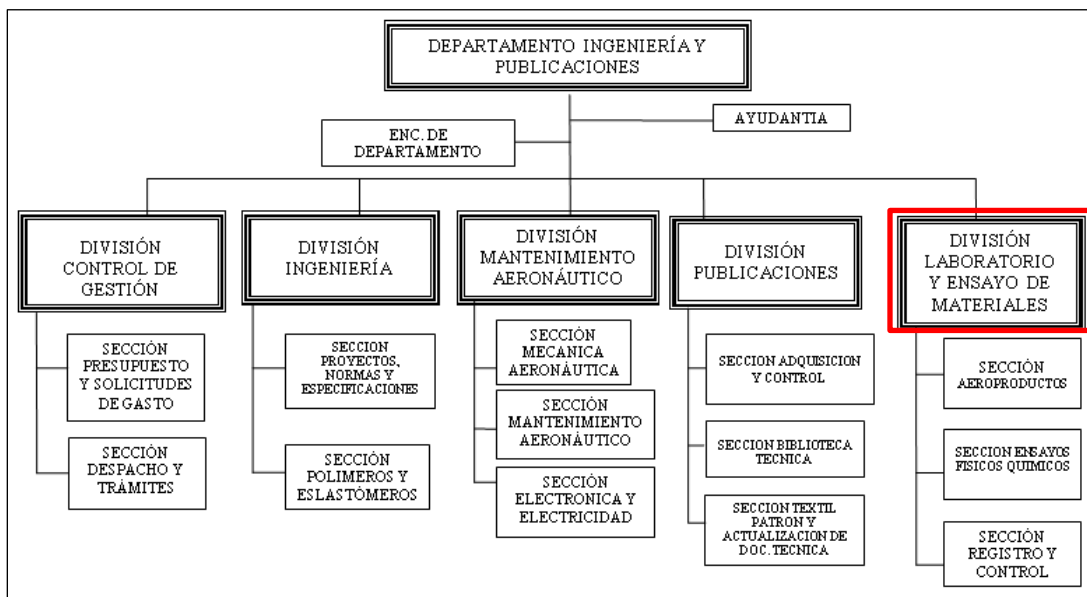


Figure 3 – Department of Engineering and Publications

(Division Testing Laboratory of Material) Chart

(MAPO 52, 2016, p. 29)

Division Testing Laboratory of Material

The task: “To develop and complete the tasks related to the accomplishment of the different analyses and tests that are carried out in the Laboratory” (MAPO 52, 2016, p. 18).

The functions:

“1) To understand the spectrometric analysis of oils, analysis of fuels, hydraulics fluids, and oxygen.

2) To understand the accomplishment of destructive, non-destructive tests and chemical analyses.

3) To understand the maintenance of the equipment under its charge and its infrastructure.

4) To understand the proposals on the appropriate equipment for the development of the tasks.

5) To understand the registration of the documentation received and the results of the different tests carried out in order to ensure the traceability of the same” (MAPO 52, 2016, p. 18).

School Technical Group of Maintenance

The user of the service provided by the laboratory is the Technical Group of Maintenance (GTE), which is within the Military Aviation School.

The task of the GTE is:

“To provide technical-logistical support to the aerial equipment and other equipment ordered and to train technical staff in their areas of proficiency” (MAPO 52, 2016, p. 18).

Its relevant functions are:

"1) To provide to the Aerial School Group the flight material in the amount, configuration and version that it requires according to the needs arising from compliance with the ordered air activity program.

2) To enlist, maintain and repair the aerial material of endowment in accordance with the responsibilities assigned by the Upper Logistic Organization.

3) To study and to keep updated the procedures and work systems that allow the optimal fulfillment of the mission ordered to the EAM, within an adequate economy of the means made available to them.

4) To permanently control the remaining potential of the available hours of endowment aircraft in order to respect the planning of the major cycle inspection work elaborated by the Upper Logistic Organization.

5) To complete the necessary records to update the technical information systems corresponding to flight folder and maintenance, history books and control of configuration and modification of aircraft and equipment" (MAPO 44, 2016, p. 69).

Other Companies

"Benchmarking is a process in which one company studies the processes of another company to identify the best practices" (Chase et al., 2014, p. 20). This was the method used for knowledge as other companies sell oil analysis services, recommending the steps that users need to follow to realize high levels of reliability in the process. It also highlights the importance of communication between the laboratory and the user and the selection of limitations in the concentration of wear materials and trends.

The example below shows the details of some services offered:

1) Oil Analyzers Inc.

The Fluid Analysis Program (<http://www.oaitesting.com/>) offers:

“About Fluid Analysis: Fluid analysis is a preventive maintenance tool that provides diagnostic testing designed to evaluate lubricant condition, component wear and contamination in mobile and industrial applications. Routine fluid analysis can detect lubricant or equipment issues before major problems develop.

The Oil Analyzers Fluid Analysis Program protects valuable equipment by providing solutions for lubrication concerns through accurate and easy-to-understand fluid analysis, timely reporting and an unparalleled commitment to personal, friendly customer service. Oil Analyzers work with fully equipped laboratories staffed by highly trained analysts and offers a complete line of oil analysis services to help you get the most from your lubricants and extend the life of your equipment” (Oil Analyzers Inc, 2016).

On the web, this company has a bibliography about oil analysis and advice about sampling, the time between samples, user forms, and the information that labs need. Besides the support, they also offer different products for sale, kits for sampling and sending samples to the laboratory, and a web-enabled way to discuss test results.

2) Spectro Scientific Inc.

They offer labs and minilabs for making different types of oil analysis (<http://www.spectrosci.com/fluid-type/oil-analysis-spectro-scientific/product/spectroil-mf-w/>) and present a booklet, “Oil Analysis

Handbook for Predictive Equipment Maintenance” (Zhao, 2014) with advice, a list of common wear materials, and the interpretation of data. In addition, they tender training and consumables on their commercial page.

3) Intertek.

Intertek offers oil analysis service around the world, as well as training and consumables. In its presentation, this company shows in the title, “Wear Metals Testing for Lubricants and Fluids Lubricant and Fluid Wear Metals Testing”, that “Wear metals testing in lubricants, oils and other machine fluids helps clients avoid expensive damage and downtime to high value engines, gears, generators, turbines and other important equipment.” “Early detection of wear metals in lubricants and greases improves machinery reliability, especially if done as part of a professional oil condition monitoring program. Intertek wear metals testing detects the presence of suspected metal wear contamination, down to parts per million range (ppm), and is an early warning for impending machinery damage or failure” (Intertek, 2016).

4) Mobil Corporation.

In its page on the web, they mention their oil analysis program, and the importance of the six steps for applying that program: “1) Identify mission-critical equipment, 2) Register your equipment, 3) Establish oil analysis best practice, 4) Oil Sample and Analyze, 5) Interpret, and 6) Take corrective action and document results” (Boissel, 2016).

5) Mack Trucks.

They recommend for their diesel and natural gas engines a program of oil analysis, under the name MaxiGard/2. In this program, they provide information about “Drawing an Oil Sample, Sample Frequencies, Sample Information, Engine Information, Oil Information, Coolant Information, and Operating Information” (Mack Trucks Inc, 2002, p. 12). After that the title “Interpreting Oil Analysis Results” gives recommendations about wear metals, contaminations, viscosity of the oil, dilution of oil with fuel, water in oil, coolant and soot, and possible root causes of failures. The MaxiGard/2 presents a table as a guideline, which is shown below:

TEST/PROPERTY	METHOD	MAXIMUM
Viscosity, cSt (@ 100°C) (Change from new oil)	ASTM D445 ¹	Increase: 8 cSt Decrease: 3 cSt
Soot Content, % wt. ⁶	LEM or TGA ²	5.0
Fuel Dilution, % vol. ⁶	ASTM D3524	3.0
Water, % vol.	ASTM D1744	0.2
Total Base Number (TBN)	ASTM D4739	Minimum: 2.0
Glycol (Coolant)	ASTM D2982	Any Detectable
CONTAMINANTS: ³ — Silicon, ppm by wt. — Sodium, ppm by wt. — Boron, ppm by wt. — Potassium, ppm by wt.	Atomic Emission (AE)	Above New Oil: 15 ppm 100 ppm 50 ppm 50 ppm
WEAR METALS, ppm by wt.: — Iron — Lead & Copper (both present)	AE	150 ppm 50 ppm ⁴
Wear Metal Evaluations: — Trend Analysis ⁵	AE	100% increase above trend (average)

Figure 4 - Mack Trucks, Inc. MaxiGard/2 Oil Service Guidelines

(Mack Trucks Inc, 2002, p. 21)

This introduces an interesting concept about wear evaluation where they put “100% increase above trend (average)” as a maximum value permitted.

Comparison among the Air Force and other companies

External firms need to add value to the service offered, and as a consequence, they are concerned that test results have congruence with the reality of the state of the equipment analyzed. The life of the company depends on the success of its activities.

In the case of FAA, the lab does not have the responsibility to analyze the state of the engine, only being informed of the result of the sample. Another big difference between both situations is the freedom in the market that private companies suffer, versus the captive clients in the case of the use of the laboratory of the Air Force.

In the first case, the companies need to be upgraded with the latest technology to remain in business, while in the second case, the user and the laboratory always have other priorities before upgrading to the latest technological advances. “In most government services, there is no market to capture. In place of capture of the market, a governmental agency should deliver economically the service prescribed by law or regulation” (Deming, 1991, p. 6). This then fits exactly with the real situation explained above.

While the commercial companies sell a compact complete package, the particular case of user and laboratory in the Air Force, it is possible to appreciate a fragmentation that is not positive for the development of the program of spectrometric analysis of oil.

As a consequence, “In a climate of fragmentation, people go off in different directions, unaware of what other people are doing. They have no chance to work to the best advantage of the company nor with themselves, and little chance to develop” (Deming, 1991, p. 466).

Applying the Mobil recommendation, to the Air Force, the weak links of the six-step chain are step 3) sampling and analyzing, step 5) interpretation of result, and step 6) documentation of results.

MaxiGard/2 by Mack gives a high level of importance to the interpretation of the data through trend analysis, more than maximum values, and the manual is explicit in a paragraph that states “A single oil analysis report is not an absolute indicator of engine condition” (Mack Trucks Inc, 2002, p. 11), and in the Air Force, this would seem the only relevance of the program.

General Information

This part makes reference to different books, reports and manuals that are useful for developing tools to help reduce risk in maintenance.

A book that gives a lot of information about the analysis of oil is “Machinery Oil Analysis” by Larry A. Toms and Allison M. Toms (Toms et al., 2008). It highlights the importance of correct operational and maintenance policies in organizations. As well, it describes ways to make calculation of trend of wear, useful for applying in every historical data set of samples.

Another relevant item is “Wear particle atlas” by E. Roderic Bowen, and Vernon C. Wescott, that gives advice about sampling correctly (Bowen et al., 1980).

“The Oil Analysis Handbook” by John S. Evans & Trevor M. Hunt (Evans et al., 2008) describes the typical materials found in oil, and types of parameters that need to be evaluated for verifying the correct state of oil.

“Inductively Coupled Plasma Atomic Emission Spectroscopy applied to the Analysis of Wear Metals in Lubricating Oil and Related Studies” by Julie Michelle

Freelin (Freelin, 1990) presents the procedures for taking samples, applications in different industries, and more common wear materials.

“A Model to Predict the Residual Life of Aircraft Engines Based upon Oil Analysis Data” by Wenbin Wang, Wenjuan Zhang (Wang et al., 2005), is a paper that uses the sample oil for predicting the residual life of the components.

“Application of the Weibull Proportional Hazards Model to Aircraft and Marine Engine Failure Data” by A.K.S. Jardine, P.M. Anderson, and D.S. Mann (Jardine et al., 1987) develops a Weibull distribution for failures in engines based on the antiquity of these (As primary cause) and particles in the oil of the samples (as a secondary cause).

“Procedure-Based Maintenance” by Jack R. Nicholas, Jr. and Drew D. Troyer (Nicholas et al., 2005) is a paper presented in Reliability World 2005 Conference Proceeding that gives the justification for what is necessary to move toward procedures in maintenance.

“The Lubrication Field Test and Inspection Guide” by James C. Fitch (Fitch, 2000) advises that oil analysis can build without expensive and sophisticated techniques, but for this it is necessary to take into account important details.

“Asset Basic Care from a TPM/Six Sigma Perspective” by Steve Reilly shows the keys for having success with this program, that are useful for other programs too, as spectrometric oil analysis. They are “Simplicity..., Understanding..., Reliability..., and Effectiveness...” (Reilly, 2006).

“How to Read Your Oil Analysis Report” by Cheryl Huff and Charles Boswell (Huff et al., 2005) is a paper presented in the Lubrication Excellence 2005 Conference

Proceedings. It shows the importance of interpreting the results, choosing alarms and a correct plan, and the last step, executing the plan established.

“Effective Data Collection for Thorough Failure Analysis” by L. Leugner (Leugner, 2005) presents in its summary 7 steps useful to enhance a process of failure analysis.

“How to Set Alarms for Oil and Wear Debris Analysis” By Matt Spurlock (Spurlock, 2005) is an article presented in the Lubrication Excellence 2005 Conference Proceedings and in it, the best advice is selecting more than one alarm and combining them.

References

The references for making conclusions about the results in this engine is the NAVAIR 17-15-50.3 Table shown in Figure 5:

JOAP ATOMIC EMISSION ROTRODE												
	Fe	Ag	Al	Cr	Cu	Mg	Ti	Ni	Sn	Si	B	Zn
Abnormal Trend (PPM Increase in 10 Hrs)	4	3	4	3	3	3	2	3	4	3		
Normal Range	0-11	0-6	0-11	0-4	0-6	0-6	0-1	0-4	0-19	0-27		
Marginal Range	12-14	7	12-13	5-6	7	7	2-3	5-6	20-22	28-30		
High Range	15-17	8-9	14-15	7	8-9	8-9	4-5	7-8	23-24	31-34		
Abnormal	≥18	≥10	≥16	≥8	≥10	≥10	≥6	≥9	≥25	≥35	10	10

Elevated boron (B) and/or zinc (Zn) concentrations usually indicate contamination with another oil type, primarily MIL-PRF-2104. Recommend resampling and retesting immediately. If new value exceeds 8.0 PPM, run check with D19-0 to ensure proper instrument function. When proper function is confirmed, report both results and suspected contamination with MIL-PRF-2104 to chain of command, maintenance chief, cognizant engineering authority (Army and Navy only), and other personnel as specified by local written procedures. Recommend flushing and retesting of contaminated pre-oilers, carts, or other reservoirs where contamination is found until both B and Zn concentrations fall below 8.0 PPM. Refer to JOAP Manual Volume II, WP 021 00 for more information. Recommend segregation of confirmed or suspected contaminated stocks, and submit information (batch no., lot no., MIL-PRF, nature of problem, etc.) on such stocks through the Defense supply deficiency reporting system.

Fe			Accessory gears, main bearings, races and splines
Fe	Cu	Ag	Main bearings and bearing cages
Fe	Cu	Al	Accessory bushing bearing turning in magnesium housing

Fe	Cu	Mg	Accessory bushing bearing turning in magnesium housing
Ag			Plating on bearing cages
Si			Oil contamination
Sn			Plating on planet gear bearing carriers

Figure 5 – Reference JOAP ATOMIC EMISION PT6A-25

(NAVAIR 17-15-50.3 / TM 38-301-3 / T.O. 33-1-37-3 / CGTO 33-1-37-3, 2013, WP 015 00, p. 1-2)

The trend formula revealed in Figure 6 is used for defining if the engine has a normal or strange behavior and whether it is in condition for continue operation or if it needs some maintenance or inspection. The value calculated is compared with the reference value in the first row of data (“Abnormal Trend”) in Figure 4.

Trend values for 10 hours are calculated as follows:

$$\frac{A - B}{C - D} \times 10 = \text{trend value for 10 hours}$$

C - D

A = ppm this sample

B = ppm last sample

C = operating hours this sample

D = operating hours last sample

Figure 6 – Trend Formula Evaluating

(NAVAIR 17-15-50.3 / TM 38-301-3 / T.O. 33-1-37-3 / CGTO 33-1-37-3, 2013, WP 001 00, p. 4)

Another control for evaluating results and making decisions is the table presented in Appendix A – Decision Making, where it recommends a step-by-step what to follow in every case, in function of the result in accordance with the second, third, fourth, or fifth row (Figure 5), and between the previous and the current sample.

Maintenance Manual of the Engine

The maintenance manual does not require spectrometric oil analysis. This is a condition from the FAA. The manual includes information about materials that the user can find in the oil (Appendix B). This information is provided for use in the oil filter analysis program, but it may well be used for the spectrometric analysis of oil. The table is useful for identifying the material found (“Specification”, and “Material”) related to the part (“Nomenclature”) and its location in the engine (“Engine Location”) (Pratt & Whitney Canada, 2012, p. 223-227).

In the same manual, common contaminant materials (Appendix C) are listed to aid in the determination of what types of material could be found in the results of the tests, and where they could be coming from. This information is important for linking contaminants and materials to qualitative information, such as indications of malfunctions, operation in corrosive environments or issue developments in the engine.

Chapter Summary

The chapter began with the mission/tasks and functions of the air force in order to show where responsibilities exist, and that policies reflect the good, but also the bad results.

This chapter also reflects the existence of a varied supply of laboratory services for oil testing and different procedures and methods that they recommend for obtaining productive results for users.

Regarding manufacturer's documentation, although the engine does not have an oil spectrometry program, the manual contains useful information to deepen the analysis required by the Air Force through its technical circular.

As far as the reference documentation, NAVAIR provided information that is very useful for its use in maintenance but it is not used 100% by the Air Force, and as a consequence, it takes unwanted risks which wastes both knowledge and resources.

There is also an innumerable number of articles in the literature related to the documentation of processes, what types of analyses are possible to perform, and the importance in the recording of the activities, all of which are necessary in order to improve current programs.

III. Methodology

Chapter Overview

The data were received by the user unit and compared with the laboratory data. More information was not possible to obtain as the information is not integrated in one program.

The available data were processed in accordance with different method, and the analysis was divided into two parts: macro and micro analysis.

The first part is based on information related to programs of oil analysis and maintenance, recommendations of different literature about oil analysis programs and companies that offers services of oil analysis, and the Joint Oil Program of the US Armed Forces, all oriented to procedures, practices, sampling, and improvement of process, without using software tools.

The second part is based on the use of descriptive statistics for sampling, for knowing about the variability of the process of extraction; for comparison of the cumulative rate of concentration of different materials for observing abnormalities among engines; for correlations associated with graphs for interpreting the behavior of the engines for each material; for automation of the NAVAIR table for knowing the state-run range of concentration and trend of wear material and contamination with respect to the references; and finally, for regression of the cumulative concentration of materials tested for obtaining a prediction of the next result in each substance.

Data

The data received from the FAA corresponds to the Embraer "Tucano" EMB312 weapon system, incorporated in the institution in the year 1987.

The number of engines amounts to 19 Pratt & Whitney (PT6A-25) with a total of 270 oil spectrometry tests. All data are quantitative, counted in parts per million for concentration of wear indicators, from test results. The date of extraction of the sample, hours of operation since the last test, quantity of oil added between samples, hours of operation, time since last repair of the engine, and time since a new engine was installed are all recorded.

All these data belong to a single operating unit, and the accumulation of data was completed with the information received from the laboratory of tests, from the oldest data of January 2003 to the most recent of October 2016.

The data is shown in Appendix D - Engine Data Sheets, for every engine available.

Macro Analysis

Macro analysis is based on observing differences between the procedures established by the Air Force and the real application, on how the program must be applied, and on how it is implemented.

Aspects examined are the importance that the program has for the user unit, checking variability in sampling when the program started in the unit, and so on. The quality of the communication among the laboratory and the user is considered for seeing differences in the practice.

Finalizing this part, the written procedures are checked, and the process for updating the program needs to assure for continued improvement.

Micro Analysis

Micro analysis began by first receiving the data, which is checked for normality and the tools used were Excel for descriptive statistics and graphing the frequency of the test. After that, JMP is applied for testing normality of the sampling process, for analysis of data between hours since the last test of the engine, and finally for analysis of means for variances in sampling. This part is under the title “Sampling Procedure”, and the intention is that with this visual information to inform the user for correction of bad procedures to improve extractions in the future.

The second part under the title “Evaluation for comparison of wear material”, the formula of Rate of Contamination (Figure 7) is used in a cumulative way (Cum. R.O.C), adding result test by test, and JMP is used to see different behavior among engines for each material. The idea is to highlight if one material in one engine or more engines have an abnormal increase, and this information will use for taking different measures.

After that “Correlations”, in this title, the data are used for observing the relations among variables, first, the totality of engines (19) and tests (270), second, each engine individually, and then adding graphs of concentrations of material by engine, giving useful visual help interpret these correlations.

Fourth, “Automation of NAVAIR Table”, in this step, Excel is applied to visualize in an automatic way how the results are compared with the reference. Besides, it is a way to keep the register of the tests for future analysis and reports.

The last procedure employed is the data through regressions. A goal of regression is to obtain a prediction of the next result of the test. Knowing that the user unit operates with Excel, it is selected to make a prediction of the next result, being hours since the last test of the independent variable and the cumulative concentration of material is in parts-per-million. It is a way to see whether the next value is within the reference given by the NAVAIR table or not, and the manager can make decisions about the operation and maintenance of the engine.

Chapter Summary

Since almost every firm explains that the reduced variability of sampling is really important for a good result in the program of oil analysis, and as consequence, the intention is to evaluate with descriptive statistics, frequency of tests, and normality is fundamental for knowing if the program is managed in a correct way or needs some form of correction.

The other steps undertaken made a visual and numerical analysis of behavior for seeing in different ways the evolution of wear material, and consequently, for knowing the state of the engine. Finally, regression is used for predicting the next result (future result), and thus give to the manager one more option for making decisions with the intention of reducing risks.

IV. Analysis of Data and Results

Chapter Overview

This chapter is based on the method described in the previous chapter. For macro analysis, the information extracted by different companies is used with theoretical knowledge and experience for seeing abnormalities in procedures, practices, and technical reports.

Micro analysis involves descriptive statistical analysis of variance among serial numbers of engines, correlations among variables, automation of the NAVAIR table for viewing the alarms, and regressions used to make predictions for the next result.

Macro Analysis Development

In a macro analysis, the first thing that the table shows in Figure 5, is twelve elements that need to be checked, including Fe – Iron, Ag – Silver, Al – Aluminum, Cr – Chromium, Cu – Copper, Mg – Magnesium, Ti – Titanium, Ni – Nickel, Sn – Tin, Si – Silicon, B – Boron, and Zn – Zinc.

Titanium, tin, zinc and boron values do not appear in any of the tables of the 19 engines. This happens because the laboratory does not perform the analysis because the user never requests that these elements be analyzed in each test.

This situation leads to the appearance of a deficiency that must be removed, since titanium, as with iron, is so important in demonstrating if the engine is showing a problem of wear, for example.

The second observation is that the weapon system (Tucano) entered the FAA in 1987, and the requirement for making oil analysis started in 1986 with the oldest data

from 2003. This could happen for two reasons with the same degree of danger for maintenance. First, they did not apply the technical report from 1987 until 2003, or second, they did not maintain the register of different tests. Both are problems that the FAA needs to avoid for reducing risks, gaining reliability, and improving processes.

Another signal is that the forms used for the laboratory have the date, in English format (month/day/year), while the forms used for group of maintenance are different (day/month/year). This caused some errors on the forms and can introduce mistakes in the analysis of the data. This is the consequence, but the root cause is the lack of communication between the organizations for a program that's existed for almost thirty years.

Continuing without using a laboratory machine, the Technical Report C.T. FA42B2-1-2 23ABR86 that is the law for this type of program, is the general framework, and paragraph 19 tells "In all cases the samples must be extracted within 30 minutes after stopping the mechanism, after it reaches the normal operating regime...". In paragraph 20, "The samples must always be extracted from the same place which was determined by the manufacturer's manual or in case of not being stipulated, the Units, Technical Organs and the LEM will evaluate the place of extraction ...".

As this technical report is a common regulation for every aeronautical engine in the Air Force, the GTE was consulted about the written procedure for the PT6A-25 and the response was that they do not have the written procedure. This is another signal that the variation between samples could be high. "As modern condition-based maintenance tools and analysis methods come into use, most of which are non-intrusive, the requirement for procedure based maintenance becomes even more important.

Analysis of data from modern tools such as vibration monitoring, lubricant and wear particle technique...and almost all other technologies depend for accuracy upon knowledge of the operating state of the equipment. Operating conditions and surrounding environmental parameters must be carefully established and recorded in order that thorough analysis can be performed. This can only be established by adherence to carefully written, detailed procedures and checklists” (Nicholas et al., 2005, p. 257).

Taking into account this last paragraph, it is possible to extract the importance of procedures and records of qualitative data. Those are vital for making correlations between variables and the determination of the wear state in which each engine is found.

“The more detailed the procedures and the more insistence on compliance with procedures an organization has, the more precise and less error prone its maintenance will become. The result will be an increase in reliability closer to the limit that design and other factors will permit” (Nicholas et al., 2005, p. 260).

“The reasons for developing detailed procedures were compelling. Military personnel rotate frequently from station to station. Their duties change as they are promoted ...”

“Word of mouth and on-the-job training and intuition were simply too unreliable to assure safety and consistency in maintenance practices” (Nicholas et al., 2005, p. 259).

Data about novelties in the engines during operation, over temperature, oscillations in speed, abnormalities in torque, change of oil, exchange of ancillaries, particles found in magnetic plug, other type of test results, as vibration analysis, filter debris analysis, change of filter, compressor washing, and so on, are absent in reports. In

addition, “The outside appearance of machinery can help us come to certain conclusions about the oil and abnormal conditions inside” (Fitch, 2000, p. 7). It can also help to make correlations, but it is not present in the reports.

Another requirement of the Technical Report C.T. FA42B2-1-2 is that the user needs to apply two formulas for measuring rate of contamination and trends. Neither the formula for rate of contamination nor the formula for the trend is supplied for the user. “No matter how mathematically valid trend calculation is, the equipment maintainer expects the trend data to clearly and consistently indicate machinery condition, i.e., the rate-of-change of component damage and the risk of failure. Unrealistic or unreliable trend data generates a lack of confidence in condition monitoring” (Toms et al., 2008, p. 311). If “Unrealistic or unreliable trend...” produce a loss of trust, there is more reason to lose trust if there is the absence of data analysis after obtaining the results.

One of the recommendations for calculating the rate of contamination of an engine is given by D. Lotan in an article of the Society of Automotive Engineers (SAE) as follows (Figure 7):

$$m = \frac{q \left[C_B \left(1 + \frac{qT}{2V_o} \times \frac{n-1}{n} \right) - C_A \left(1 - \frac{qT}{2V_o} \times \frac{n+1}{n} \right) \right]}{n \log [1/(1 - qT/nV_o)]}$$

where:

- m = rate of contamination (representative of the rate of wear)
- q = leakage (oil consumption per hour)
- V_o = capacity of the oil circuit where oil circulates (tank + piping + volume of oil contained in accessories - oil volume in operational condition)
- C_B = particle concentration as detected by analysis B (after n filling ups)
- C_A = particle concentration as detected by preceding analysis A
- n = number of fillings between analyses A and B
- T = engine running time between analyses A and B
- V_A = total oil volume added between analyses A and B

Figure 7 - Rate of Contamination (Lotan, 197, p. 12)

The formula used in the Air Force is a derivation of this SAE paper with some differences (Figure 8).

$$\text{Vel. Cont.} = \frac{Q \cdot [C2 \cdot (1 + Q \cdot T \cdot (N-1)) / 2 \cdot V \cdot N - C1(1 - Q \cdot T \cdot (N+1)) / 2 \cdot V \cdot N]}{N \cdot \ln[1 / (1 - Q \cdot T / N \cdot V)]}$$

Donde C1 = concentración SOAP anterior (PPM)
 C2 = concentración SOAP actual (PPM)
 V = volumen del tanque (Lts)
 Q = consumo horario (l/h)
 T = tiempo entre muestreos (Hs.)
 N = numero de veces que se recargo aceite.
 (en muchos casos N=T)

Figure 8 – Rate of Contamination FAA

(Technical Report C.T. FA42B2-1-2 - 23ABR86, 1986, Paragraph 9.6)

Vel. Cont. = speed of contamination (Rate of contamination).

Where:

C1 = concentration of the previous test (PPM – Part Per Million).
 C2 = current concentration (PPM).
 V = capacity of the tank (liters).
 Q = Time consumption (liters / Hrs).
 T = time between samples (hours of operation).
 N = number of refills.

The first two differences are the parenthesis $(1 + Q \cdot T \cdot (N-1))$ and $(1 - Q \cdot T \cdot (N+1))$ where both terms are divided by $2 \cdot V \cdot N$, while SAE proposes $(1 + (Q \cdot T / 2 \cdot V) \cdot ((N-1) / N))$ and $(1 - (Q \cdot T / 2 \cdot V) \cdot ((N+1) / N))$. The third difference is in the logarithms of Napier (Ln) in the Air Force and logarithms of tenth base (Log) in SAE in the denominator. While these differences are not very important, the meaning is that after the technical report was approved, someone corrected the mistake by hand writing both parenthesis, in an incorrect way, and the technical report was never updated after 1986. This program was never brought up-to-date. This is an illustration that continuous improvement is not applied in spectrometric analysis programs.

The second formula included in the technical report of the program (Figure 9) is about trend. It shows an increase of contamination between samples.

$$\text{Incremento} = [(C1 - C2) \times 10] / T$$

Donde: C1 = concentración anterior (PPM)
C2 = concentración actual (PPM)
T = tiempo entre muestreos (Hs.)

Figure 9 – Increase in contamination FAA

(Technical Report C.T. FA42B2-1-2 - 23ABR86, 1986, Paragraph 9.5)

Incremento = increase of contamination between samples.

Where:

C1 = concentration of the previous test (PPM – Part Per Million).

C2 = current concentration (PPM).

T = time between samples (hours of operation).

This formula is useful for engines or equipment that are tested every 10 hours, plus or minus a small difference. As a consequence, 10 – T needs to tend to zero for optimizing the result, for reducing variability.

The NAVAIR table (Figure 5 – Reference JOAP ATOMIC EMISION PT6A-25) shows in the row “Abnormal Trend (PPM Increase in 10 hrs)” the maximum values permitted for every type of materials that need to be analyzed and compared, but every 10 hours. The same formula is included in Figure 6 – Trend Formula Evaluating.

The FAA does testing every 125 hours, as a consequence, it wastes a fundamental reference to determine the evolution of wear. The question could be “Why waste knowledge?” (Deming, 1991, p. 466). As one of the premises of management says, if “You Can't Manage What You Don't Measure” (Reh, 2016), or if it is measured with a bad technique, it may be managed in a bad way too.

If the procedure requires that samples, measurements and comparisons need to be performed every 10 hours for taking advantage of the experience of the Navy of the United States, and those are performed in a period 12 times higher than desired, the program will never show the actual state of increase. So, the Air Force is losing money, time, and knowledge, and is assuming a risk that cannot be allowed, since it is presumed that it is doing well and is actually being misinterpreted.

The user needs to know that "..., the data trending procedure must automatically adapt to equipment usage and sampling circumstances and then provide numbers that reflect equipment condition changes in an incremental fashion" (Toms et al., 2008, p. 311). One possibility could be to take samples every 10 hours. The other adapts the formula to 125 hours between samples, changing the value 10 in the formula (Figure 6 – Trend Formula Evaluating) by 125. The second option is easier to carry out in the program, but it is less sensitive to change than the first option.

Micro Analysis Development

In a micro analysis, the data was processed with tools, such as Microsoft Excel and JMP Software. Then the results were used for making conclusions.

Sampling Procedure

In Figure 10, the procedure presents the variation among samples in each serial number engine. The vertical axis shows hours of operation since the last test of the engine (Hrs Since Last Test), and the horizontal axis presents the engine serial number (S/N). Each dot in the graph represents a test made and the red line shows the mean value of hours between samples.

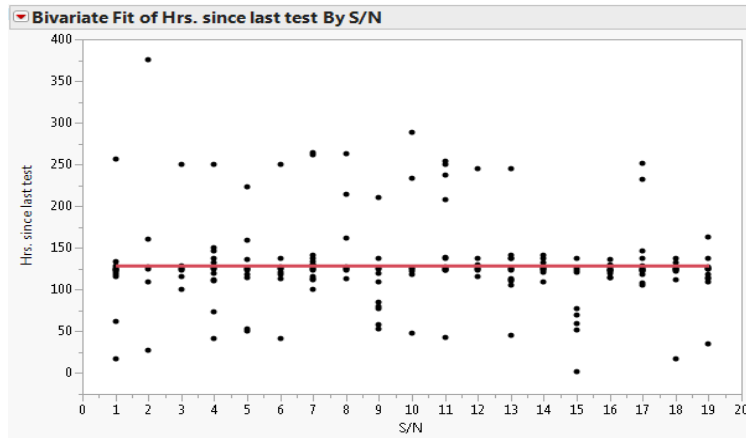


Figure 10 – Variation among samples by S/N

Based on Data Analysis (Excel) and making Descriptive Statistics of 270 samples, over 34774 hours of flight, the results are presented in Figure 11. Analyzing this figure, it is possible to conclude that the mean (128.682 hrs) is close to the ideal number of 125 hours, but the standard deviation is a big value (43.704 hrs).

<i>Hrs. Since Last Test</i>	
Mean	128.682
Standard Error	2.65974
Median	125
Mode	125
Standard Deviation	43.704
Sample Variance	1910.0378
Skewness	1.553987
Range	374.5
Minimum	1.5
Maximum	376
Sum	34744.05
Count	270

Figure 11 – Descriptive Statistics

In Figure 12, the graph displays a distribution around the bin 128.1 hours with 178 samples between 106.75 and 128.1 hours of operation for every engine. It shows 10 samples in the period between 234.85 and 256.20 hours, and it shows that one sample

was overlooked, 10 times. On the other hand, in the bins under 106.75 hours, 25 samples were made and no qualitative data was registered as to change of components, other types of tests, and so on. In addition, 64 tests were made in values over 128.1 hours of operation which proves a lack of confidence, interest or knowledge in the program of oil analysis by the user, and the laboratory too. After that, the same procedure was made with JMP, and the conclusion is that the distribution of sampling is so far a normal distribution (Figure 13). The small p-value rejects the null hypothesis that the data is from the normal distribution.

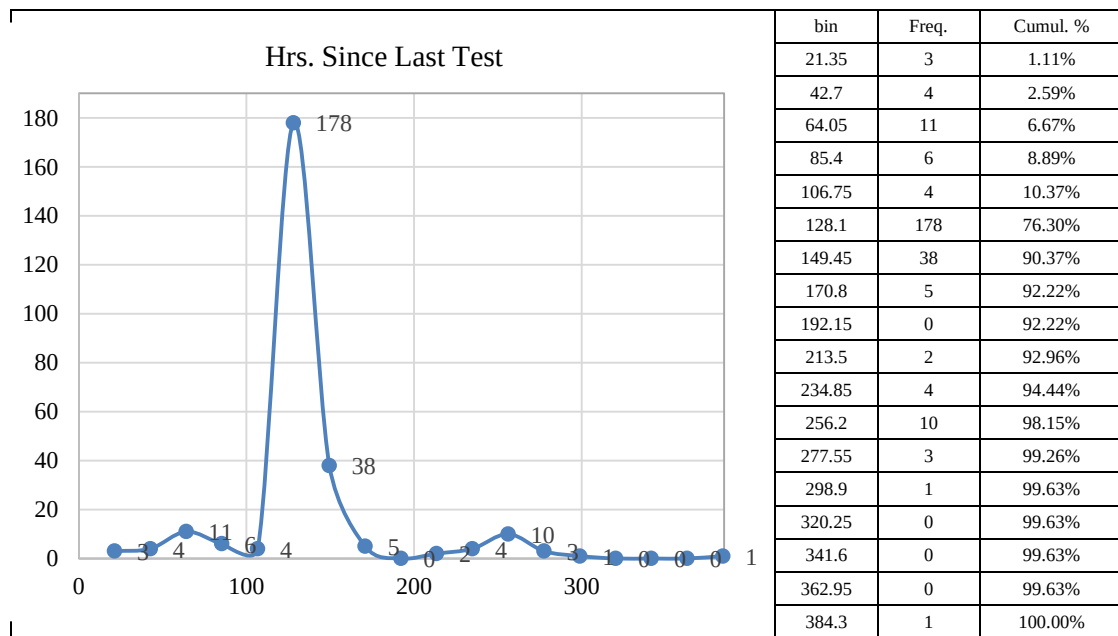


Figure 12 – Frequency of Tests

The data is checked by Student's t (Figure 14) and in the right part, it presents the connecting letter report and shows that the levels not connected by the same letters are significantly different from each other.

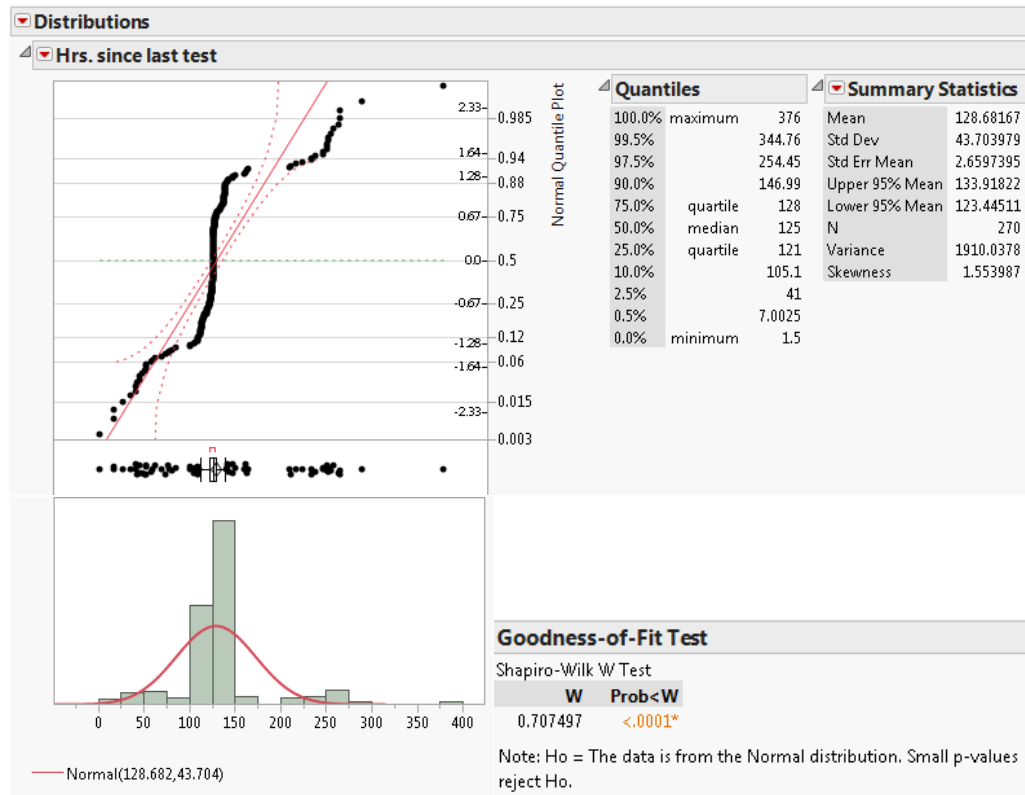


Figure 13 – Fit Model of Hours Since Last Test by Normal Distribution

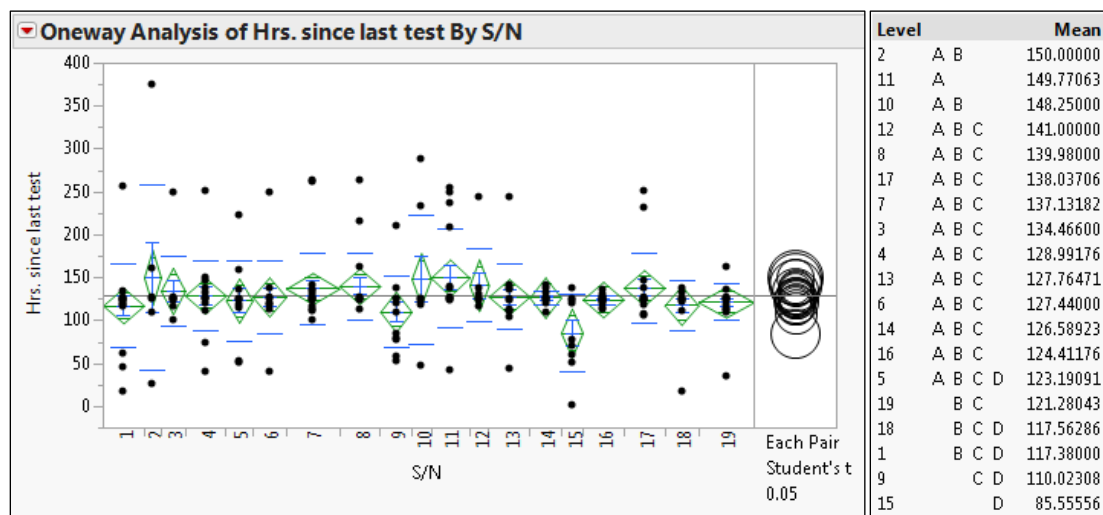


Figure 14 – Analysis of data - Hours Since Last Test by S/N

Figure 15 (Analysis of Means for Variances in Sampling) displays the RMSE (Root Mean Square Error) of the overall sample equal to 43.11. Engine S/N 2 has a value around of 107, S/N 10 close to 80, and three engines in values less than 20.

The best practice of sampling is in engine S/N 16, S/N 14, and S/N 19, and they could be the goal for future tests. The others are far off the ideal method of extraction.

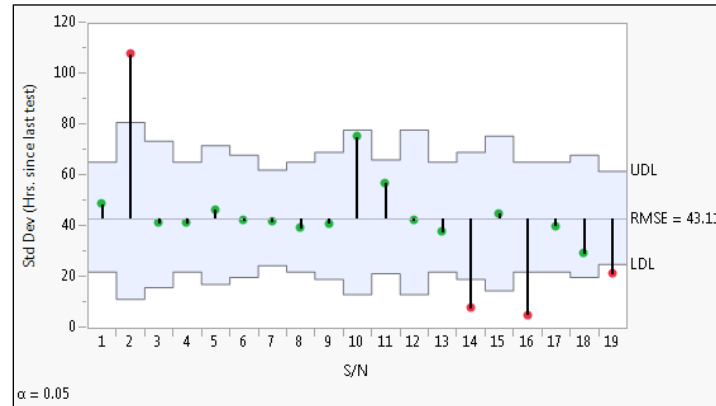


Figure 15 – Analysis of Means for Variances in Sampling

Evaluation for comparison of wear material

The formula of R.O.C. (Figure 7 – Rate of Contamination) was applied to every variable (Fe, Ag, Al, Cr, Cu, Mg, Ni, and Si), in a cumulative method. Variable by variable was made, and after that the relationships among engines were examined.

The first analysis is between Cumulative R.O.C. Fe by S/N and the result is presented in Figure 16. It helps to understand that some engines are significantly different from others (right part of the figure).

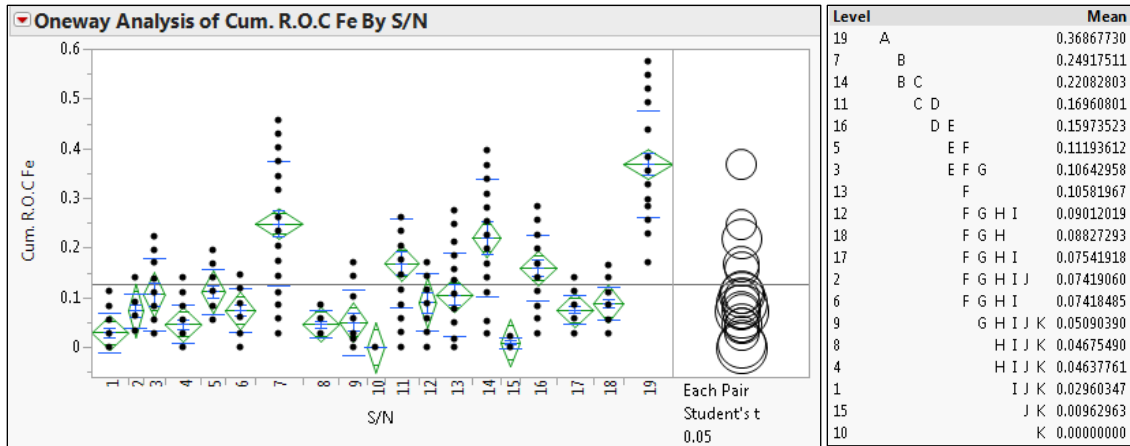


Figure 16 – Cumulative R.O.C. of Fe by S/N

In Figure 17 - Analysis of Means, three engines have mean values really different from the others, S/N 19, 14, and 7, and this sends an alarm that could be useful for the manager, for making a thorough evaluation of the engine. The average value of the overall sample is 0.1259, while for S/N 19 it is about 0.35 (almost three times more than the average). S/N 7 is about two times the average, and S/N 14 one and a half times the average.

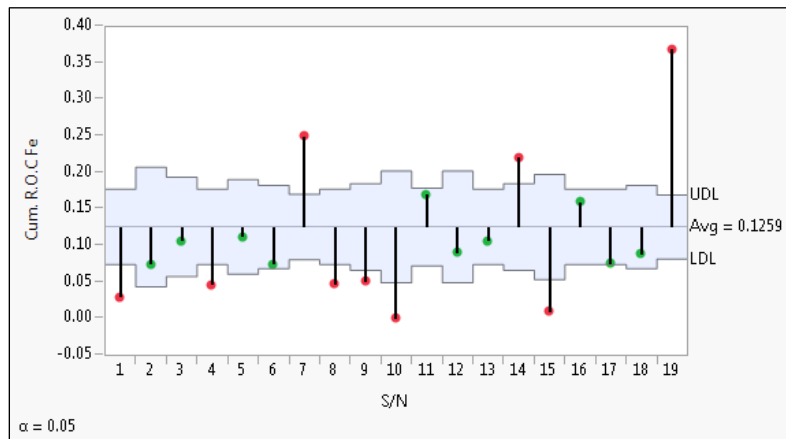


Figure 17 – Analysis of Means - Cum. R.O.C. of Fe by S/N

In the case of Ag, all values are zero in 270 samples, and as a consequence, the graph displays zero for every engine (Figure 18).

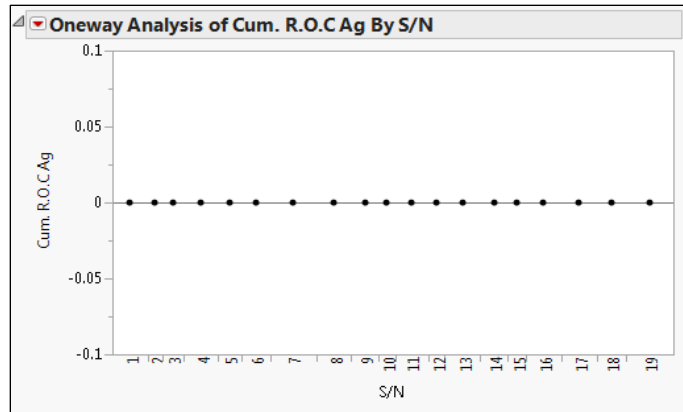


Figure 18 – Cumulative R.O.C. of Ag by S/N

Repeating the same procedure, Figure 19, presents the cumulative value of AI by S/N, and the relation between them in different letters; same letter, levels (S/N) are not significantly different; different letters, levels are significantly different one from another.

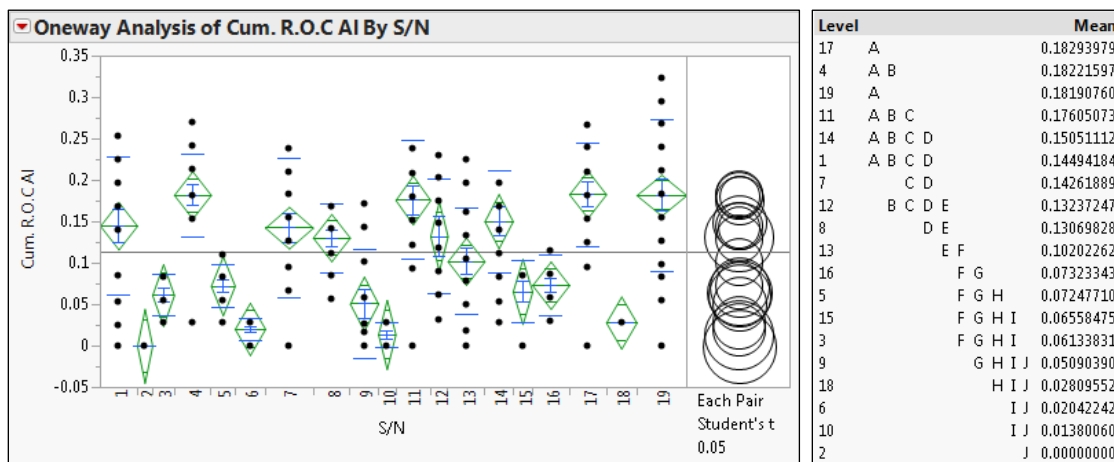


Figure 19 – Cumulative R.O.C. of AI by S/N

Figure 20 shows the analysis of means and the S/N 4, 11, 17, and 19 are higher enough to start a deep study of conditioning.

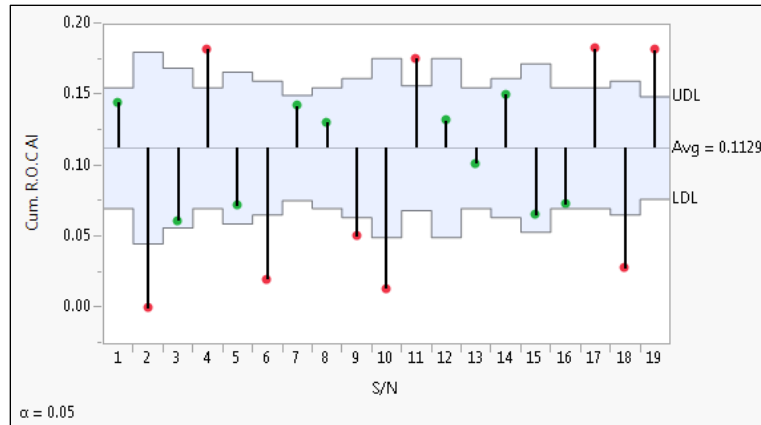


Figure 20 – Analysis of Means - Cum. R.O.C. of AI by S/N

Figure 21 exhibits the oneway analysis of the cumulative rate of contamination of Cr by serial number of the engine.

Engine number 5 is really different from the others, and it could demonstrate some problem that needs to be checked.

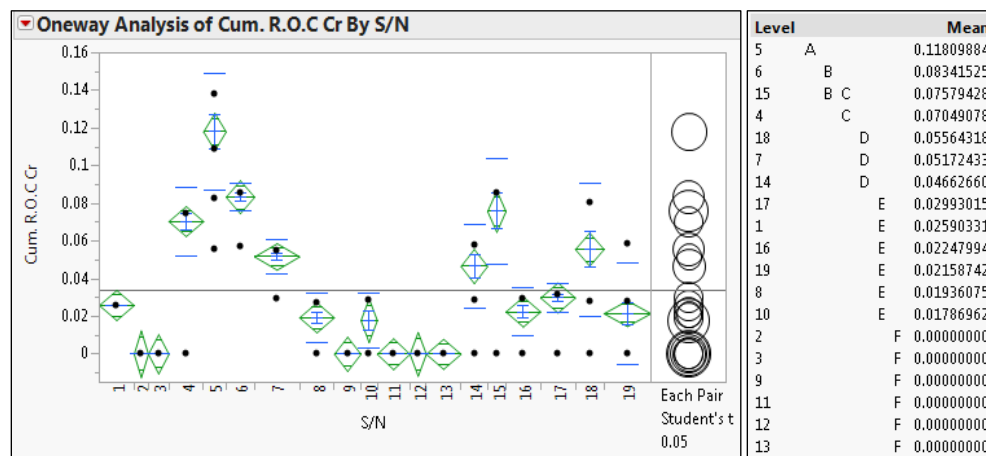


Figure 21 – Cumulative R.O.C. of Cr by S/N

Figure 22 features in a visual mode the difference in means among engines. The Avg = 0.0340 of every engine is three times smaller than the average Cum. R.O.C. of Cr in engine S/N 5.

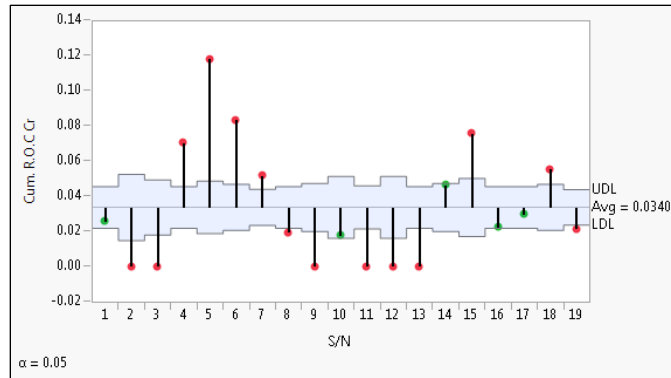


Figure 22 – Analysis of Means - Cum. R.O.C. of Cr by S/N

The same details demonstrate Figure 23 about cumulative rate of contamination of copper by serial number, all information that could be useful for determining some measure related to maintenance.

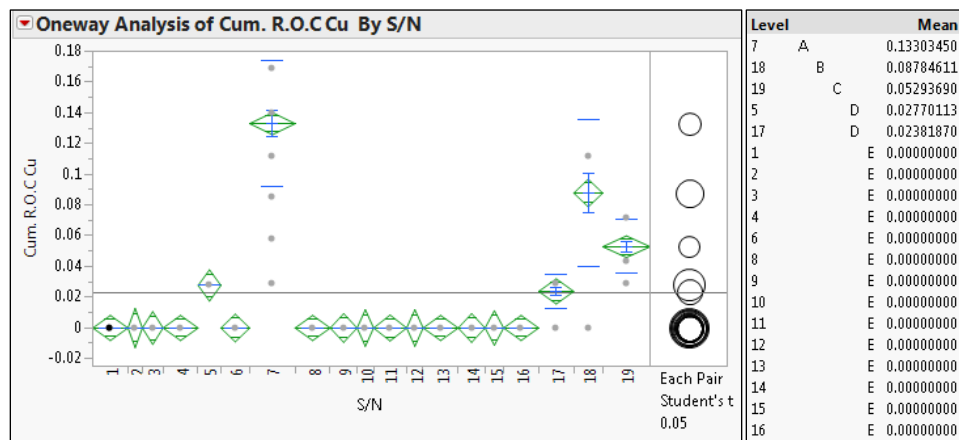


Figure 23 – Cumulative R.O.C. of Cu by S/N

Figure 24 exposes one engine (S/N 7) that has a cumulative value of Cu five times higher than the average value.

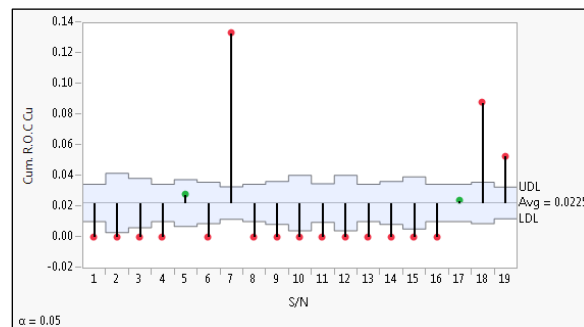


Figure 24 – Analysis of Means - Cum. R.O.C. of Cu by S/N

In Figure 25, the graph displays S/N 7, 9, and 19, that forms part of the same group, letter A, with significant differences related to the others. All analysis presented helps to evaluate, and make decisions, based on comparisons with other engines.

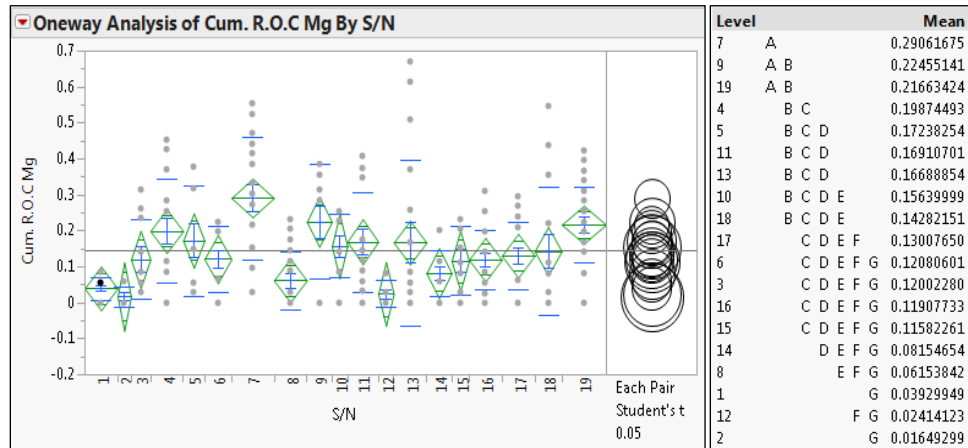


Figure 25 – Cumulative R.O.C. of Mg by S/N

Figure 26 presents engine number 7, another time, with a value of the mean cumulative of Mg close to double the mean of every other engine. This is another alarm for making decisions about the engine.

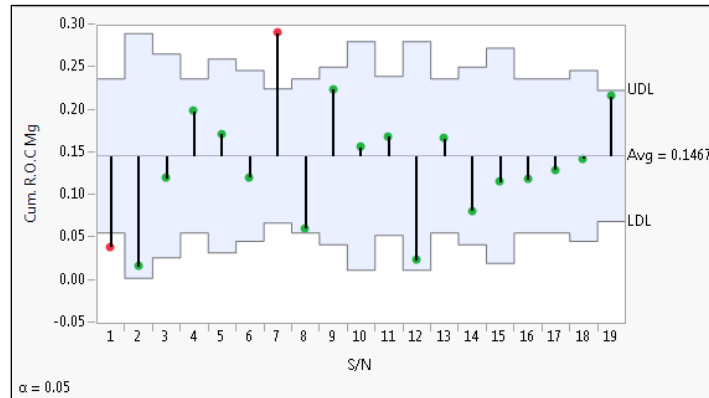


Figure 26 – Analysis of Means - Cum. R.O.C. of Mg by S/N

Applying the same method, Figure 27 and 28 exhibit engines S/N 4, 7, 18 and 19 in a group different from the others, and they have mean values of Ni higher, almost three times over the mean of the other fifteen engines.

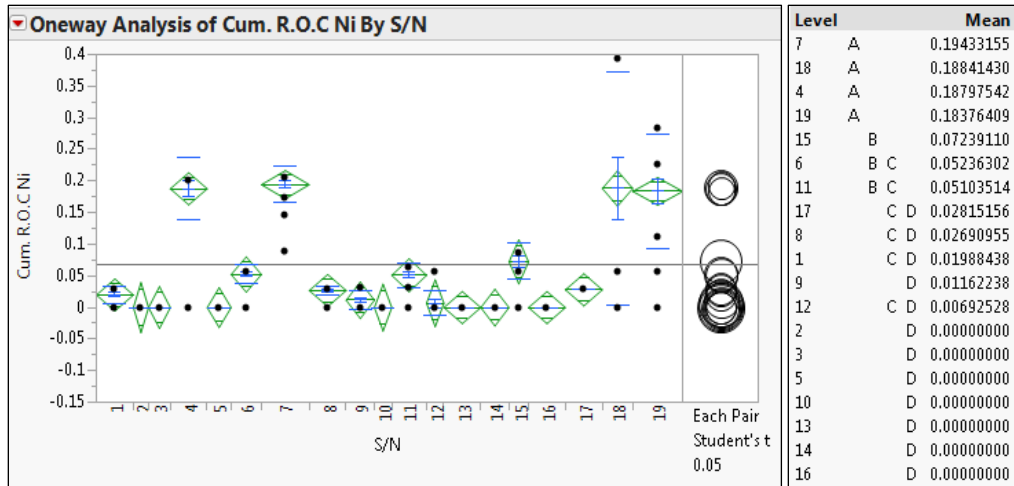


Figure 27 – Cumulative R.O.C. of Ni by S/N

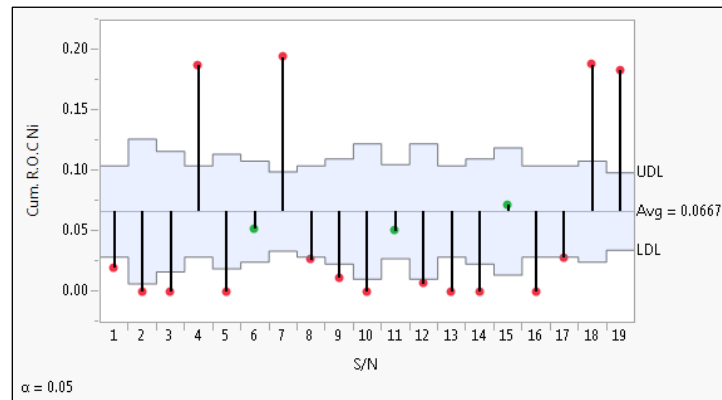


Figure 28 – Analysis of Means - Cum. R.O.C. of Ni by S/N

The last parameter analysed by the Air Force is Si, and Figure 29 demonstrates two engines S/N 1 and 4 with cumulative values of Si higher than the rest.

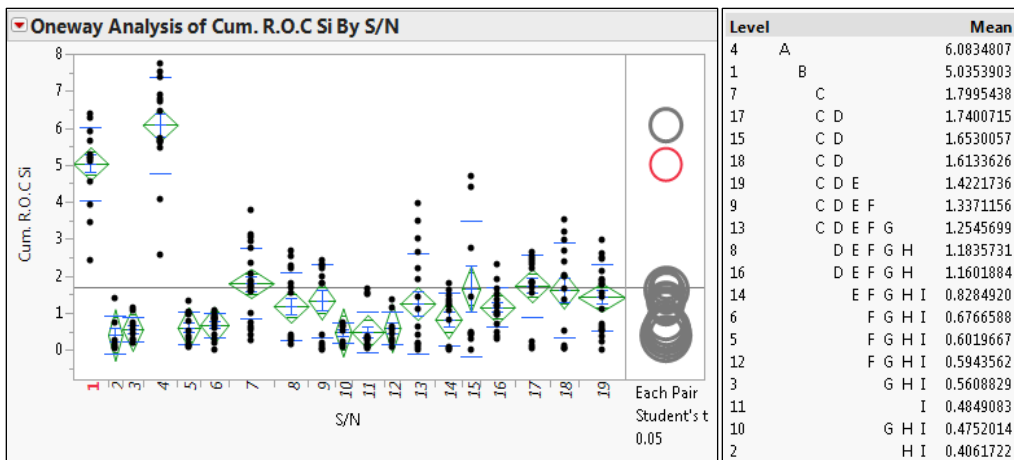


Figure 29 – Cumulative R.O.C. of Si by S/N

Figure 30 exhibits values of mean cumulative Si close to three times the average value of all other engines.

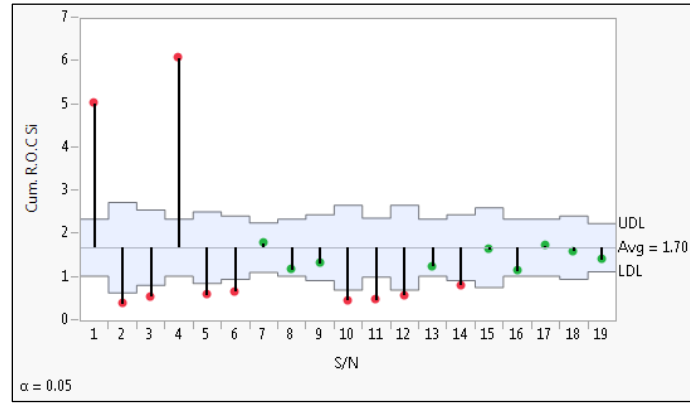


Figure 30 – Analysis of Means - Cum. R.O.C. of Si by S/N

All sets of figures were presented with a confidence interval of 95% with α equal 0.05.

Correlations

Another complementary method for analysing the results of samples was in making correlations among variables. In Figure 31, this presents the correlation of variables over the 270 tests and 19 engines.

Different variables were selected for obtaining relations among data extracted for results of oil analysis and seasonal variables over long or short periods of times, months, and so on.

“Date #” is the date of the testing result, and the value is in the increase within of the same engine, but it has no relation between engines.

“Month” is the number of the month when the result was obtained.

“Time between samples (Month)” is the number of months that passed between samples.

“Winter”, “Spring”, and “Fall” are dummy variables related to the season when the result was obtained.

“Long Time between Sample” is a dummy variable that assigns a 1 when the time between samples is more than 5 months.

“Oil Added Lts/Hr” is the quantity of oil added in liters per hour between samples.

“# of Refill” is how many times the make up was made between samples.

“Oil Added Lts” is the amount of oil added in liters.

“Time Since Last Repair” is the time in hours of operation since the last reparation/overhaul of the engine.

“Time Since New” is time in hours of operation since the engine was manufactured.

Every data presented as #DIV/0!, mean that the result of the tests have zero for all samples.

These correlations were made for seeing some details about general behavior of engines and procedures of maintenance.

Every correlation has a low values (Figure 31), no more than 0.30, and this is because it is an average value of the 19 engines. Likewise, this shows in the row “Time Since Last Repair” that in the columns Al, Cr, Ni and Si, there are negative values. This is an increase in hours of operation, corresponding to a decrease of the materials cited. It could be because of a poor process of reparation, by an incorrect process of cleaning or holding, for example.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	-0.070	#DIV/0!	-0.219	-0.239	-0.250	0.226	-0.106	0.092
<i>Month</i>	-0.011	#DIV/0!	0.091	0.017	0.054	0.154	0.004	0.137
<i>Time between samples (Month)</i>	0.027	#DIV/0!	-0.068	-0.049	0.021	-0.017	0.001	0.072
<i>winter</i>	-0.029	#DIV/0!	0.010	0.112	0.031	-0.012	0.102	0.138
<i>Spring</i>	0.018	#DIV/0!	0.120	-0.028	-0.023	0.054	-0.019	0.141
<i>Fall</i>	0.063	#DIV/0!	-0.174	-0.079	-0.039	0.056	-0.027	-0.114
<i>Long Time between Sample</i>	0.058	#DIV/0!	-0.023	0.029	0.059	0.008	0.015	0.039
<i>Oil added Lts/Hr</i>	-0.055	#DIV/0!	-0.057	0.042	-0.050	-0.025	-0.016	0.049
<i># of refills</i>	0.004	#DIV/0!	0.052	-0.098	-0.049	-0.008	-0.032	-0.201
<i>Oil added Lts</i>	0.000	#DIV/0!	0.029	-0.066	-0.046	-0.005	-0.043	-0.198
<i>Time Since last Repair</i>	0.008	#DIV/0!	-0.134	-0.185	0.036	0.127	-0.153	-0.150
<i>Time Since New</i>	-0.039	#DIV/0!	-0.158	-0.242	-0.130	0.142	-0.139	-0.087
<i>Fe</i>	1.000	#DIV/0!	0.154	0.000	0.210	0.153	-0.023	-0.061
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	0.198	0.000	-0.079	0.218	0.094
<i>Cr</i>				1.000	0.231	-0.091	0.308	0.158
<i>Cu</i>					1.000	-0.072	0.134	-0.020
<i>Mg</i>						1.000	-0.018	0.102
<i>Ni</i>							1.000	0.096
<i>Si</i>								1.000

Figure 31 – Correlations of 19 Engines and 270 Samples

The same procedure was applied for every engine.

For engine S/N 1, the procedure was performed, and the result is presented in Figure 32.

The values are higher than the correlation for 19 engines, and the table shows that S/N 1 could be one of the most influential ones responsible for the average values. As a consequence, S/N 1 could be one of the engines that received a bad procedure by maintenance.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	0.505	#DIV/0!	-0.105	-0.297	#DIV/0!	0.083	-0.151	-0.423
<i>Month</i>	-0.181	#DIV/0!	0.533	-0.127	#DIV/0!	-0.257	0.411	-0.122
<i>Time between samples (Month)</i>	0.063	#DIV/0!	-0.030	0.000	#DIV/0!	-0.132	0.009	-0.049
<i>winter</i>	0.182	#DIV/0!	-0.058	0.209	#DIV/0!	-0.178	-0.299	0.355
<i>Spring</i>	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Fall</i>	0.228	#DIV/0!	-0.319	-0.091	#DIV/0!	0.586	-0.091	-0.225
<i>Long Time between Sample</i>	0.033	#DIV/0!	0.343	0.265	#DIV/0!	-0.324	0.265	0.149
<i>Oil added Lts/Hr</i>	-0.138	#DIV/0!	-0.281	-0.030	#DIV/0!	-0.103	-0.090	-0.021
<i># of refills</i>	0.069	#DIV/0!	0.243	-0.375	#DIV/0!	0.057	0.125	-0.409
<i>Oil added Lts</i>	0.064	#DIV/0!	0.178	-0.384	#DIV/0!	0.040	0.076	-0.436
<i>Time Since last Repair</i>	0.508	#DIV/0!	-0.153	-0.377	#DIV/0!	0.080	-0.139	-0.569
<i>Time Since New</i>	0.508	#DIV/0!	-0.153	-0.377	#DIV/0!	0.080	-0.139	-0.569
<i>Fe</i>	1.000	#DIV/0!	0.202	-0.139	#DIV/0!	0.080	-0.139	-0.206
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	-0.219	#DIV/0!	-0.111	0.607	-0.162
<i>Cr</i>				1.000	#DIV/0!	-0.086	-0.063	0.882
<i>Cu</i>					1.000	#DIV/0!	#DIV/0!	#DIV/0!
<i>Mg</i>						1.000	-0.086	-0.145
<i>Ni</i>							1.000	-0.132
<i>Si</i>								1.000

Figure 32 – Correlations among variables for Engine S/N 1

In Figure 33, the graph shows a high concentration of Si in the first test, and it could be caused by a poor process of cleaning during the reparation or holding of parts.

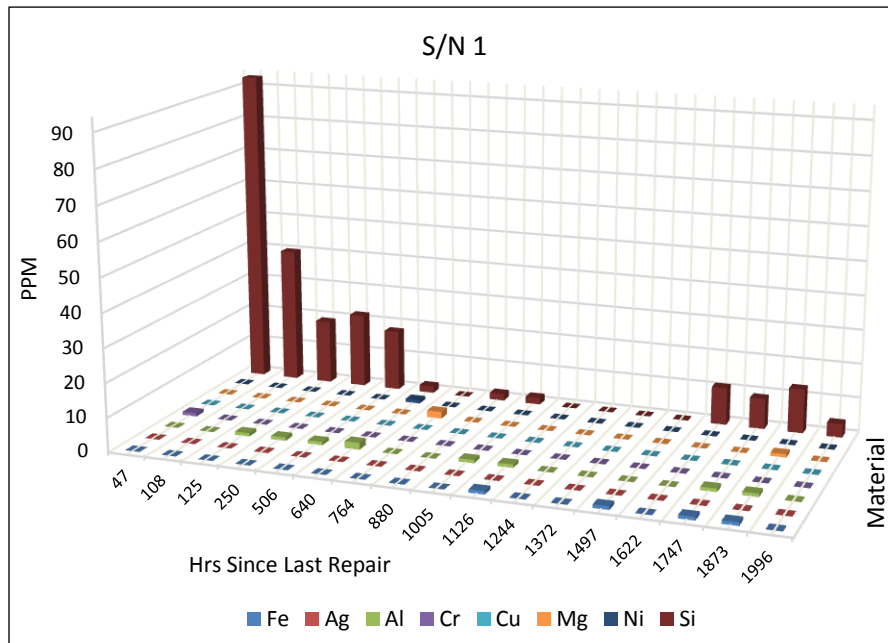


Figure 33 – PPM of material by Hours Since Last Repair S/N 1

For engine S/N 2, Figure 34 exhibits the results of correlations, and all the values are more logical than for the previous engine. For example, the values of Fe, Mg, and Si are directly proportional to the Time Since Last Reparation. In other words, the more time of operation of the engine, the more concentration. This shows that the repair was performed better, compared to the S/N 1 engine.

In the case of oil added, the more added, the less concentration of Fe and Si but the more concentration of Mg (although, it is so close to zero). It could be that the rate of increasing Fe and Si are less than the oil replenishment. “After filling up, the metal concentration drops because fresh oil has been added.” (Lotan, 1972, p. 2) Checking the values of correlations, it is possible to appreciate the high value of Si related to Time Since Last Repair. It is the highest value of all correlations, close to 0.8. It is important to remember that the S/N 2 is the engine with more variability in sampling (Figure 15 – Analysis of Means for Variances in Sampling).

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	0.239	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.472	#DIV/0!	0.746
<i>Month</i>	-0.058	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.000	#DIV/0!	-0.085
<i>Time between samples (Month)</i>	-0.335	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.260	#DIV/0!	-0.332
<i>winter</i>	0.766	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.471	#DIV/0!	0.672
<i>Spring</i>	0.167	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	-0.167	#DIV/0!	-0.238
<i>Fall</i>	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Long Time between Sample</i>	-0.194	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.645	#DIV/0!	0.061
<i>Oil added Lts/Hr</i>	-0.296	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.017	#DIV/0!	-0.387
<i># of refills</i>	-0.043	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.043	#DIV/0!	-0.434
<i>Oil added Lts</i>	-0.077	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.049	#DIV/0!	-0.481
<i>Time Since last Repair</i>	0.270	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.490	#DIV/0!	0.797
<i>Time Since New</i>	0.270	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.490	#DIV/0!	0.797
<i>Fe</i>	1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.167	#DIV/0!	0.771
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Cr</i>				1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Cu</i>					1.000	#DIV/0!	#DIV/0!	#DIV/0!
<i>Mg</i>						1.000	#DIV/0!	0.402
<i>Ni</i>							1.000	#DIV/0!
<i>Si</i>								1.000

Figure 34 – Correlations among variables for Engine S/N 2

The analysis of correlation needs to be carried out in a complementary mode with analysis of cumulative values, qualitative data, parts per million of concentration (for example, Figure 35), and different graphs that help to interpret what the behavior of the engine is and what type of maintenance it has received.

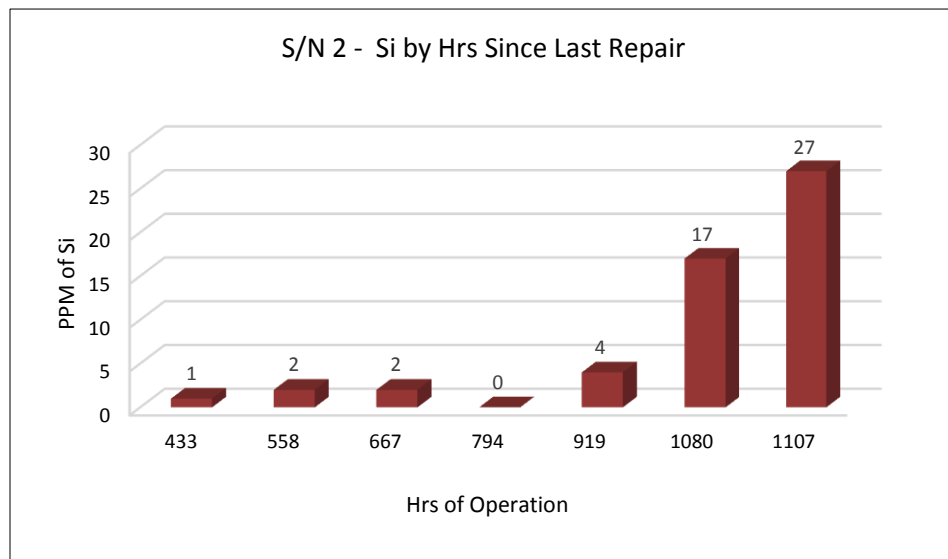


Figure 35 – PPM of Si by Hours of Operation

Figure 36 graphs the evolution of material in PPM in engine S/N 2 by hours since last repair.

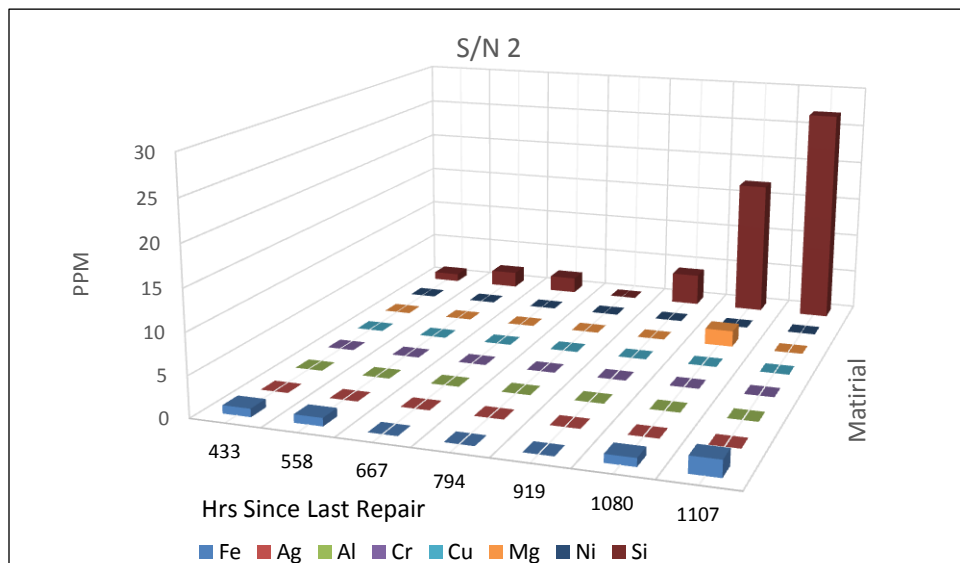


Figure 36 – PPM of material by Hours Since Last Repair S/N 2

The NAVAIR table (NAVY for PT-6A-25) (Figure 5) shows that 27 PPM of Si is a marginal range, and the engine can continue to operate. However, the same manual explains that the Air Force Logistics Center Depot has a guidance for engines T56-7/9/15 and G56-7/9/15 that the user needs to change oil when Si exceeds 20 PPM (NAVAIR 17-15-50.3 / TM 38-301-3 / T.O. 33-1-37-3 / CGTO 33-1-37-3, 2013, WP 004 00, p. 1). In this case, the criteria could be used in a complementary limitation for preserving the engine and reducing risks.

The correlations among variables in engine S/N 3 are presented in Figure 37. The higher values of correlations are Oil Added Lts/Hr by Si (-0.745), and Date # by Mg (0.738).

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	0.553	#DIV/0!	-0.437	#DIV/0!	#DIV/0!	0.738	#DIV/0!	0.281
<i>Month</i>	0.060	#DIV/0!	-0.208	#DIV/0!	#DIV/0!	0.525	#DIV/0!	-0.344
<i>Time between samples (Month)</i>	0.253	#DIV/0!	-0.272	#DIV/0!	#DIV/0!	0.260	#DIV/0!	0.042
<i>winter</i>	0.327	#DIV/0!	0.524	#DIV/0!	#DIV/0!	-0.069	#DIV/0!	0.230
<i>Spring</i>	0.167	#DIV/0!	-0.218	#DIV/0!	#DIV/0!	0.318	#DIV/0!	-0.200
<i>Fall</i>	0.250	#DIV/0!	0.218	#DIV/0!	#DIV/0!	-0.318	#DIV/0!	0.485
<i>Long Time between Sample</i>	0.000	#DIV/0!	-0.218	#DIV/0!	#DIV/0!	0.318	#DIV/0!	-0.143
<i>Oil added Lts/Hr</i>	-0.226	#DIV/0!	0.179	#DIV/0!	#DIV/0!	0.073	#DIV/0!	-0.745
<i># of refills</i>	0.102	#DIV/0!	-0.208	#DIV/0!	#DIV/0!	0.591	#DIV/0!	-0.016
<i>Oil added Lts</i>	0.158	#DIV/0!	-0.145	#DIV/0!	#DIV/0!	0.613	#DIV/0!	-0.154
<i>Time Since last Repair</i>	0.508	#DIV/0!	-0.431	#DIV/0!	#DIV/0!	0.692	#DIV/0!	0.256
<i>Time Since New</i>	0.508	#DIV/0!	-0.431	#DIV/0!	#DIV/0!	0.692	#DIV/0!	0.256
<i>Fe</i>	1.000	#DIV/0!	0.327	#DIV/0!	#DIV/0!	0.583	#DIV/0!	0.442
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	#DIV/0!	#DIV/0!	-0.301	#DIV/0!	0.044
<i>Cr</i>				1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Cu</i>					1.000	#DIV/0!	#DIV/0!	#DIV/0!
<i>Mg</i>						1.000	#DIV/0!	0.057
<i>Ni</i>							1.000	#DIV/0!
<i>Si</i>								1.000

Figure 37 – Correlations among variables for Engine S/N 3

For the first value, -0.745, with the help of Figure 38, the graph shows in about 4116 hrs a high increase in Oil Added (Lts) and a decrease in Si. For the second cited correlation, Date # by Mg, the graph demonstrates a similar shape for both variables.

For this last case, it could be important to analyse the property of the oil used, being that, Mg is an additive in the same type of oil, and as a consequence, the laboratory needs to add as a requirement that the user must send a sample of oil that has not been used.

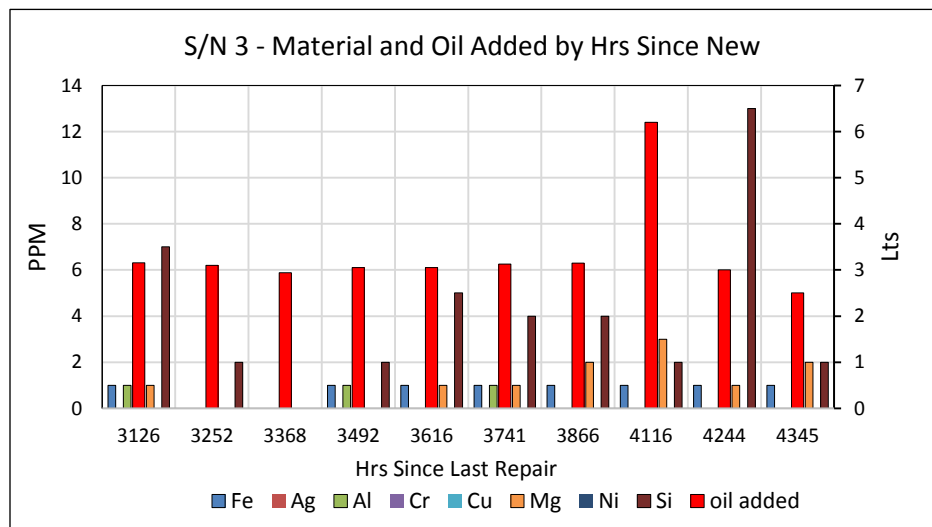


Figure 38 – Correlations among variables for Engine S/N 3

Figure 39 displays the evolution of material in PPM in engine S/N 3 by hours since the last repair.

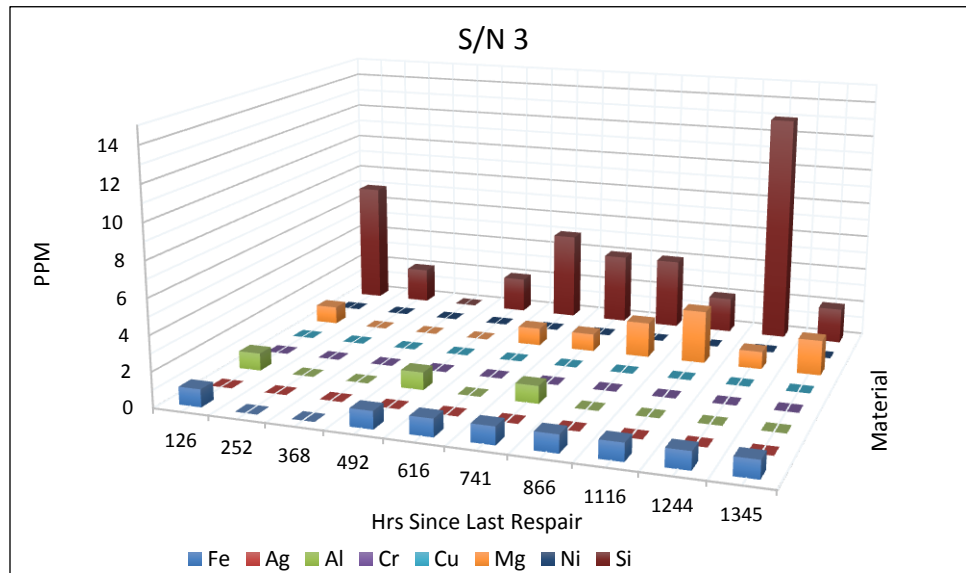


Figure 39 – PPM of material by Hours Since Last Repair S/N 3

The correlations among variables in engine S/N 4 are graphed in Figure 40. The highest value of correlations is Date # by Si (-0.573). This represents that the Si has high values at the beginning of use of the engine (first test), and the values decrease through time. It demonstrates contamination in oil, and/or the engine was preserved and when it was done maintenance work was done, the engine was not cleaned properly or it was operated in environments with powder in suspension.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	0.446	#DIV/0!	-0.264	-0.353	#DIV/0!	0.205	-0.353	-0.573
<i>Month</i>	0.142	#DIV/0!	-0.091	0.000	#DIV/0!	0.045	0.000	0.104
<i>Time between samples (Month)</i>	0.149	#DIV/0!	-0.147	-0.297	#DIV/0!	0.061	-0.297	-0.356
<i>winter</i>	-0.167	#DIV/0!	0.367	0.236	#DIV/0!	0.044	0.236	0.218
<i>Spring</i>	-0.161	#DIV/0!	-0.123	-0.063	#DIV/0!	-0.164	-0.063	0.350
<i>Fall</i>	0.165	#DIV/0!	-0.180	-0.091	#DIV/0!	0.142	-0.091	-0.191
<i>Long Time between Sample</i>	0.167	#DIV/0!	-0.070	-0.236	#DIV/0!	-0.044	-0.236	-0.111
<i>Oil added Lts/Hr</i>	0.120	#DIV/0!	0.069	-0.055	#DIV/0!	0.216	-0.055	0.170
<i># of refills</i>	0.057	#DIV/0!	-0.381	-0.522	#DIV/0!	0.180	-0.522	-0.412
<i>Oil added Lts</i>	0.083	#DIV/0!	-0.389	-0.546	#DIV/0!	0.182	-0.546	-0.391
<i>Time Since last Repair</i>	0.459	#DIV/0!	-0.252	-0.342	#DIV/0!	0.209	-0.342	-0.547
<i>Time Since New</i>	0.459	#DIV/0!	-0.252	-0.342	#DIV/0!	0.209	-0.342	-0.547
<i>Fe</i>	1.000	#DIV/0!	-0.102	-0.161	#DIV/0!	0.387	-0.161	-0.197
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	0.926	#DIV/0!	-0.152	0.926	0.472
<i>Cr</i>				1.000	#DIV/0!	-0.164	1.000	0.439
<i>Cu</i>					1.000	#DIV/0!	#DIV/0!	#DIV/0!
<i>Mg</i>						1.000	-0.164	-0.085
<i>Ni</i>							1.000	0.439
<i>Si</i>								1.000

Figure 40 – Correlations among variables for Engine S/N 4

Figure 41 shows a similar behavior of engine S/N 4 compared with engine S/N 1. Oil contamination in the firsts tests and reduced values in the following tests. According to the records, approximately one-third of the oil in the system is renewed between each test. As a consequence, the initially contaminated oil has reduced concentration with the progress of the trials.

Another important thing is the oscillation values of concentration and the absence of registered information about how many times the oil was refilled, as well as other important details of the engine performance.

The result of the first test would have to have been used to order the total oil change in the lubrication circuit, and it does not figure in the records.

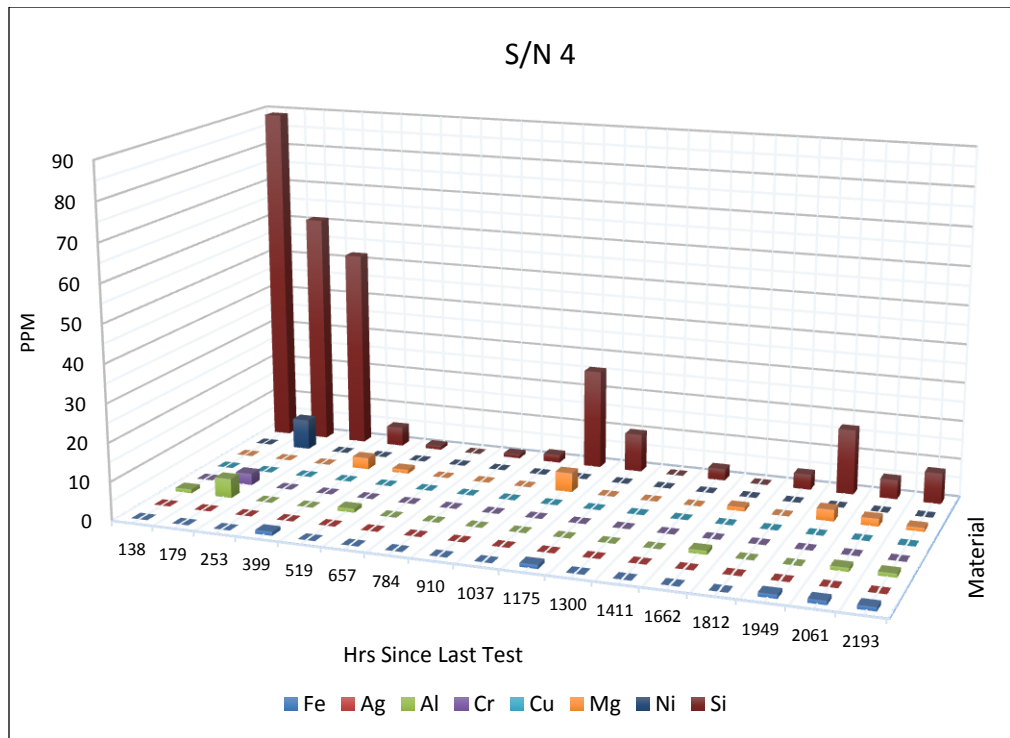


Figure 41 – PPM of material by Hours Since Last Repair S/N 4

The correlations of the remaining engines are presented in Appendix E (Engine Correlations from S/N 5 to S/N 19), in order to facilitate the reading of this thesis, although the procedure used is the same as for the first four engines.

Automation of NAVAIR Table

Possibly one of the first steps of the analysis of test results is knowing the values of concentration of wear material and tabulating them in an Excel sheet. An automatic procedure then obtains the conclusion in accordance with the NAVAIR Table. Figure 42 is displayed as an example of the complete file, and it is only about Si for engine S/N 1, with modification using different colors for each stage. In the table, it is possible to observe in the first column the concentration of Si in PPM for every test of the engine. The second and third columns are the result of the formula applied in accordance with the Technical Report of the FAA (The second column is coincident with the NAVAIR table

also for 10 hours of operation). The fourth to the eighth columns show the limitations in each division of concentration. The ninth column is a conditional formula that shows the “Normal Trend” in green (less value than the reference), the “Abnormal Increase” in red (equal or higher value than the reference), and the “Decrease” in sky blue (negative trend). The tenth column could be the “Normal Range” in green color (less than the maximum value of the reference), the “Marginal Range” in yellow (less than or equal to the maximum value of the reference but more than the normal range), the “High Range” in amber (less than or equal to the maximum value of the reference but more than the marginal range), or the “Abnormal” in red (equal to or higher value than the reference), in accordance with the values in each case for each material. (rows 7, 8, 9 and 10 in column 1 were modified for demonstrating the different legends and colors).

Si	Trend	Concentration of atmosphere	Abnormal Trend	Normal Range	Marginal Range	High Range	Abnormal	Reference of	Concentration of
93	20.39	2.41	3	27	30	34	35	Abnormal_Increase_Si	Abnormal_Range_Si
40	-8.60	1.04	3	27	30	34	35	Decrease_Si	Abnormal_Range_Si
19	-12.35	0.48	3	27	30	34	35	Decrease_Si	Normal_Range_Si
22	0.24	0.62	3	27	30	34	35	Normal_Trend_Si	Normal_Range_Si
18	-0.16	0.56	3	27	30	34	35	Decrease_Si	Normal_Range_Si
27	0.67	0.76	3	27	30	34	35	Normal_Trend_Si	Normal_Range_Si
30	0.24	0.83	3	27	30	34	35	Normal_Trend_Si	Marginal_Range_Si
34	0.34	0.94	3	27	30	34	35	Normal_Trend_Si	High_Range_Si
35	0.08	0.98	3	27	30	34	35	Normal_Trend_Si	Abnormal_Range_Si
0	-2.89	0.00	3	27	30	34	35	Decrease_Si	Normal_Range_Si
0	0.00	0.00	3	27	30	34	35	Normal_Trend_Si	Normal_Range_Si

Figure 42 – Example of Automation of NAVAIR Table

Regressions

Another type of analysis could be performed to demonstrate a manner for predicting the next result. This is done through a regression analysis, and the software Excel was used because it is common in all maintenance groups of the Air Force. The same situation does not happen with JMP for example. It is not commonly available.

The data selected were cumulative concentrations of each wear material in Parts Per Million (PPM) (y-axis) in relation to Hours Since Last Repair (Hrs) (x-axis)(Figure 43 – Example of Regression).

Every material was graphed with selected trendline giving the option to select what polynomial order was convenient and to forecast the next result by selecting 125 hours as the option (Forward 125.0 periods, Figure 44). Another option selected was the presentation of the formula for making predictions (Display Equation on chart) and the R Square of each regression (Display R-squared value on chart, Figure 44 – Options selected in Excel).

The difference between the forecast value and the last cumulative value will define whether the engine is at risk and whether it continues to operate or not.

The coefficient of determination (R Square) is a key for defining if the value is a reasonable value for taking into account the result of the prediction or not.

Another consideration is that as the cumulative value of material is always more than or equal to the previous value, the prediction value must be more than or equal to the previous one.

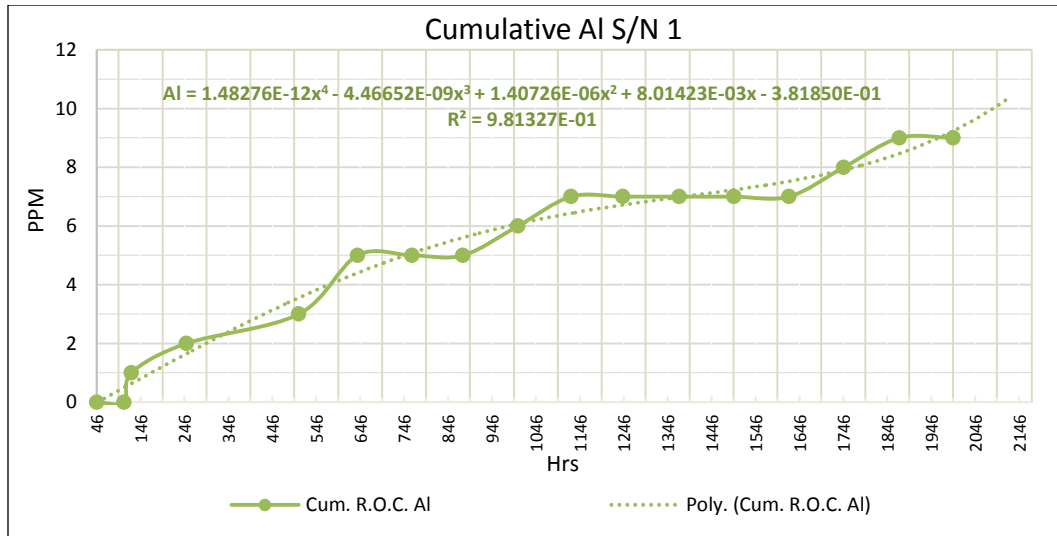


Figure 43 – Example of Regression

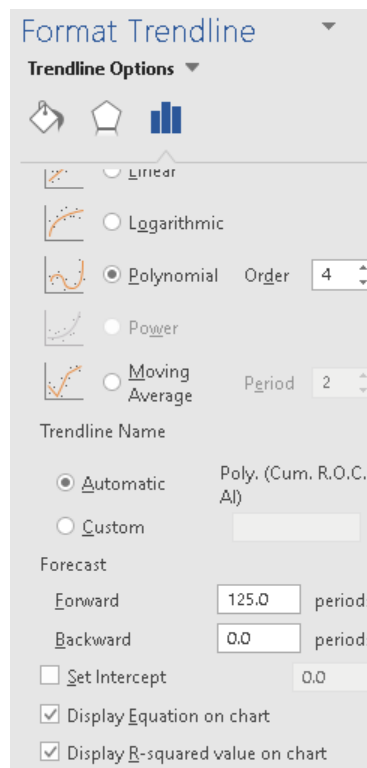


Figure 44 – Options selected in Excel

The regression for engine S/N 1 was divided into two graphs because the larger values of Si do not permit the other regressions with smaller values to be observed.

Figure 45 shows the prediction formula and R Square of Si for polynomial order 5 in engine S/N 1.

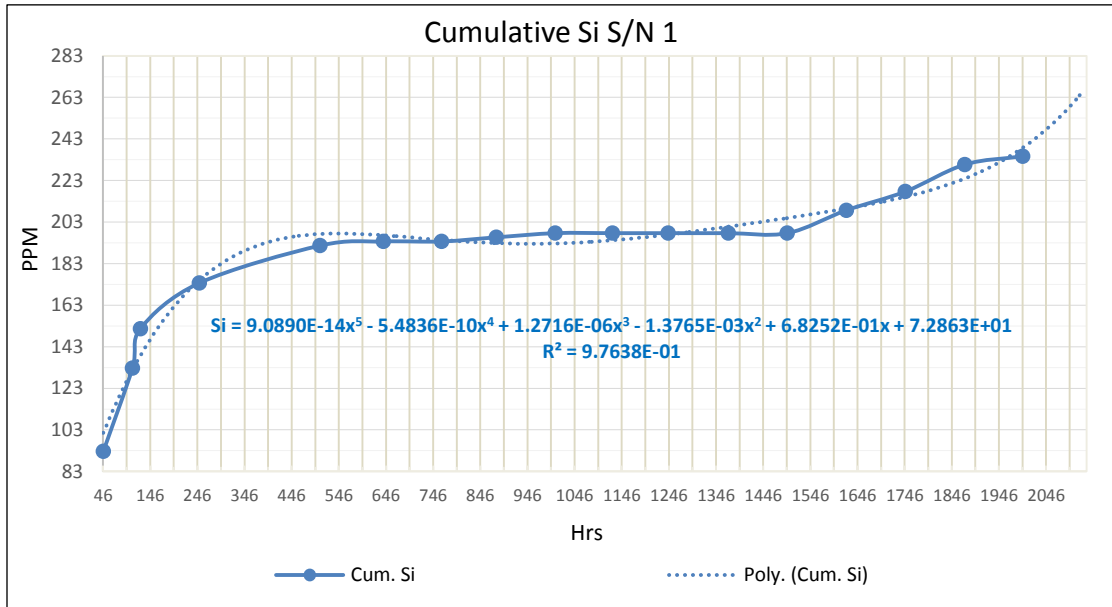


Figure 45 – Regression of Cumulative Si - S/N 1

The increase of cumulative Si, in accordance with the prediction, is 30 PPM, but the previous test shows that Si is 3 PPM, as a result the measurement was not required.

For the other materials the selected regression polynomial was order 4 (Figure 46). Nothing presents a risk until the next test if the condition of operation is managed in the same way. Cumulative Cr was not shown since the cumulative value is constant in 1 PPM from the first test until the last one.

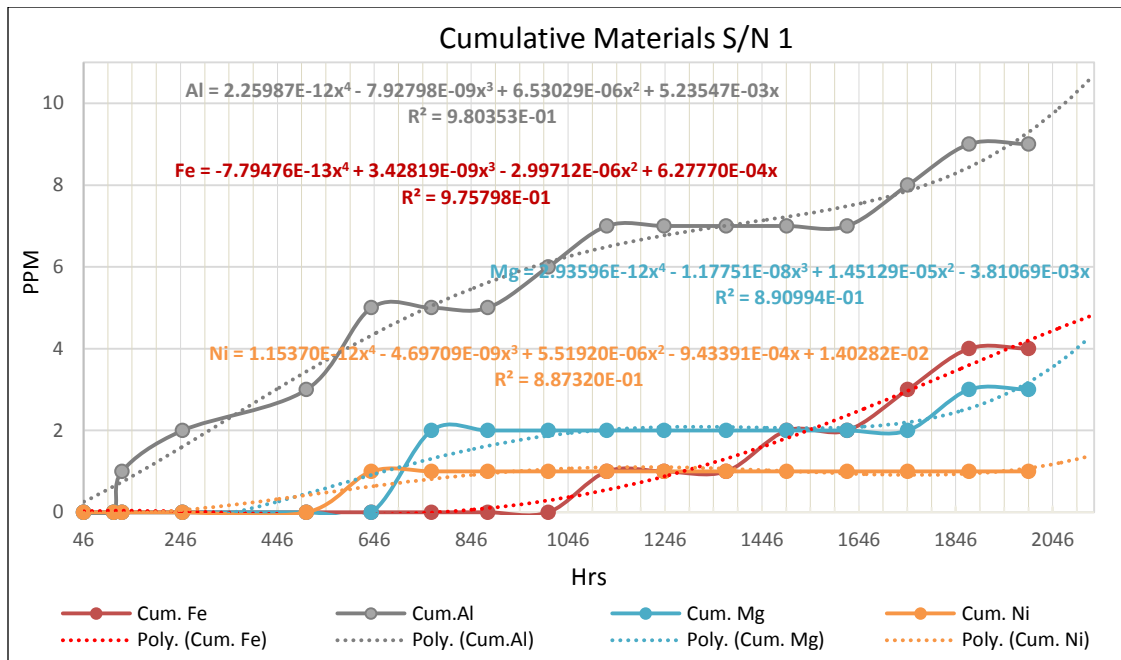


Figure 46 – Regression of Cumulative Fe, Al, Mg, and Ni - S/N 1

The same procedure was used for engine S/N 2. First cumulative Si was presented (Figure 47) and then the rest of the materials (Figure 48). For the cumulative value of Si (Figure 47), the determination could be to change the oil before continuing to operate, because the predicted value tends to be higher than the limit. In addition, the last result was 27 PPM.

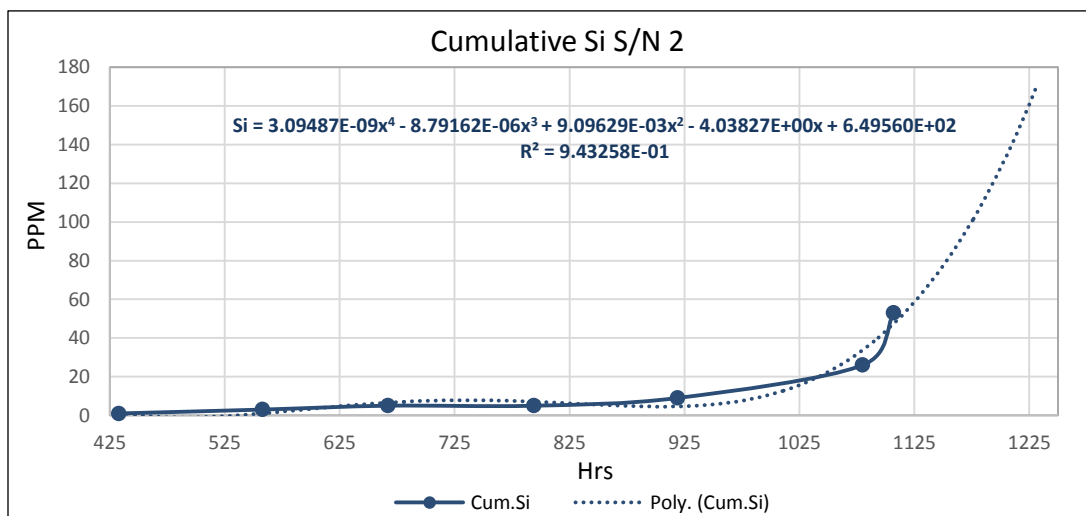


Figure 47 – Regression of Cumulative Si - S/N 2

Figure 48 exhibits the regression of cumulative Fe and Mg, the others having a cumulative value equal to zero. For Fe, it shows that the predicted value could be 13 PPM and this means that the increment is 8 PPM. In accordance with the NAVAIR table, the Normal Range is between 0-11 PPM in Fe. As a result, the engine can continue to operate, but the maintenance personnel need to be alert for trouble, such as changes in performance, and/or they can reduce the time between samples for more precision in determining the advancement of wear materials.

The predicted value for cumulative Mg is 6 PPM and the previous cumulative is 2 PPM. The difference is 4 PPM of increment, as a consequence Mg is within the parameter (Normal Range) of the NAVAIR table.

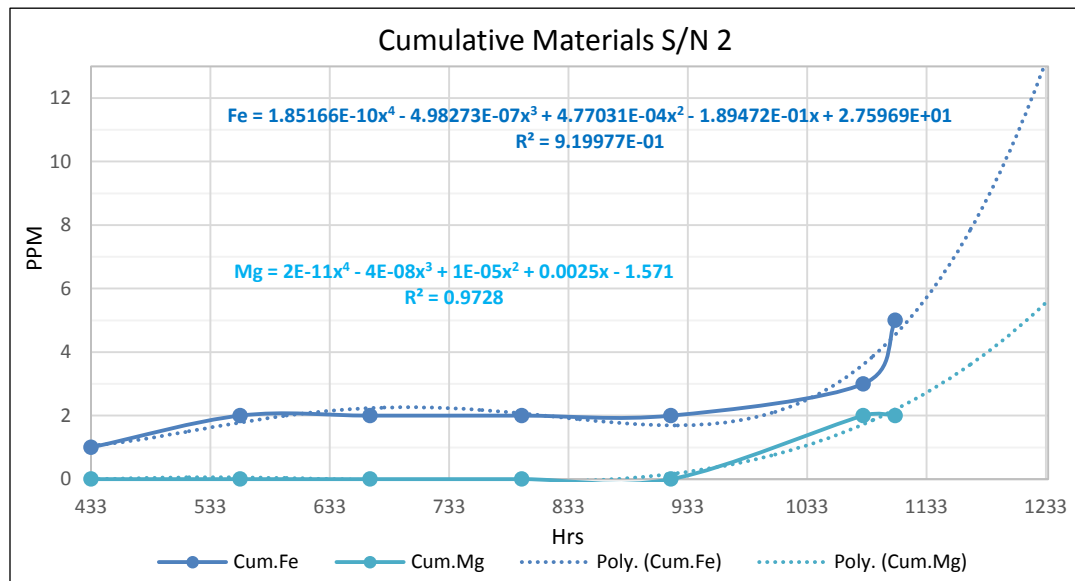


Figure 48 – Regression of Cumulative Fe and Mg - S/N 2

For engine S/N 3, cumulative Fe, Si, Mg and Al and their regressions were presented in Figure 49.

The forecast for the next sample does not exhibit large changes. The increase of Si could be 13 PPM, as a result, it is not a concern.

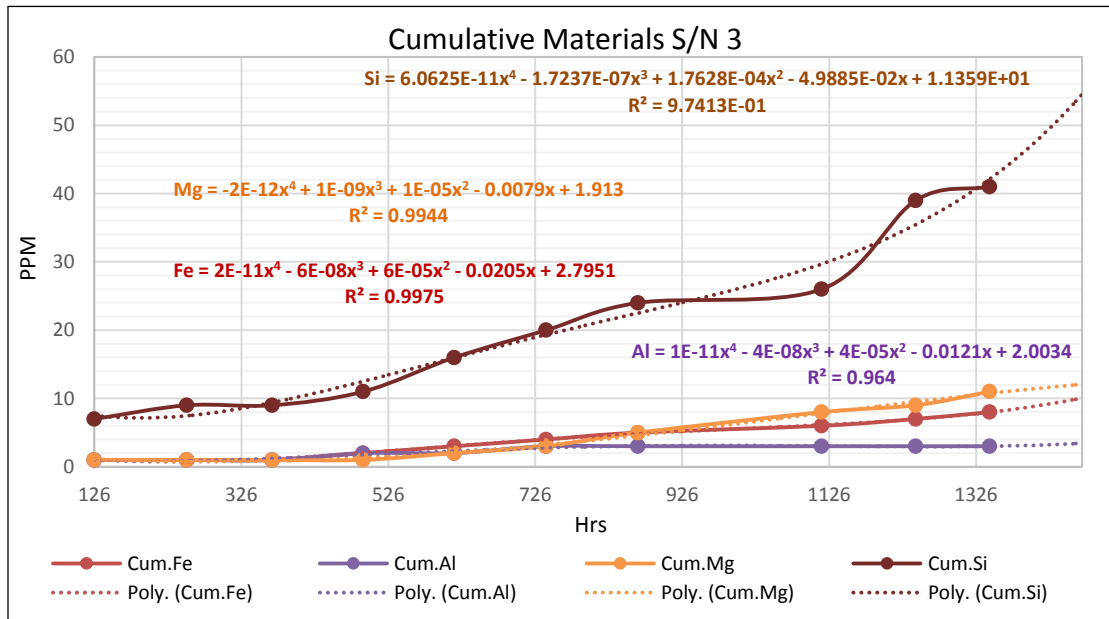


Figure 49 – Regression of Cumulative Fe, Al, Mg and Si - S/N 3

In engine S/N 4, the material was divided into two graphs, Figure 50 for cumulative Si and Figure 51 for the rest.

The predicted value for Si could be 20 PPM and this does not present a risk for the engine. It is important to remember that Si is a contaminant in oil, and the last result of Si was 8 PPM (not enough concentration of Si for changing the oil).

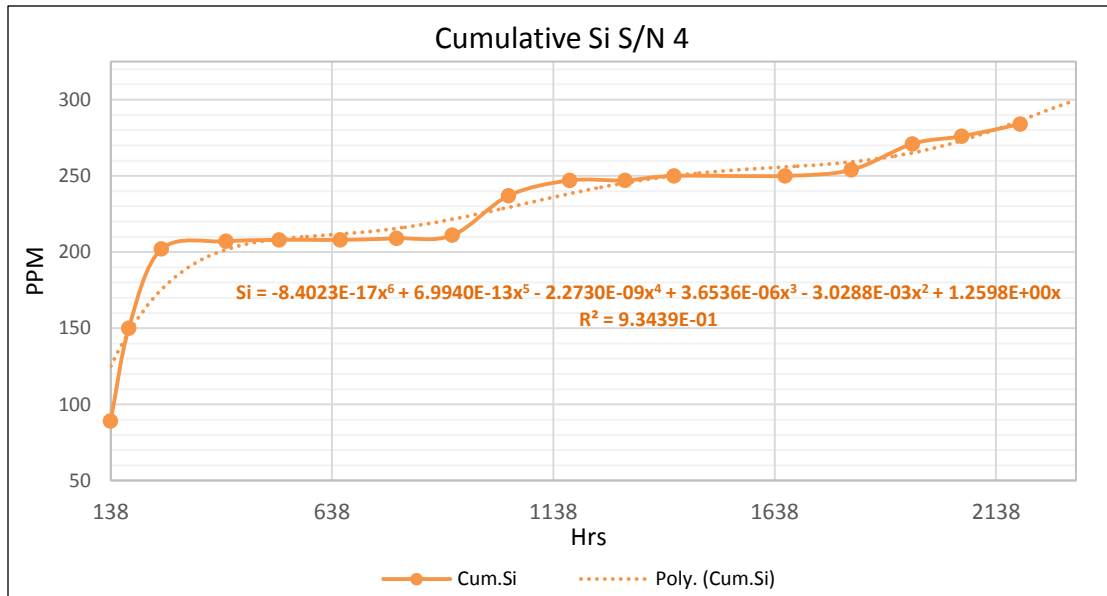


Figure 50 – Regression of Cumulative Si - S/N 4

Figure 51 demonstrates the regressions for the other materials and R Square for Mg (0.95), Al (0.83), Fe (0.964) are acceptable but for Ni (0.59) and Cr (0.59) are low values. Nothing looks like a problem for the next result if the conditions of operation are kept in the same way.

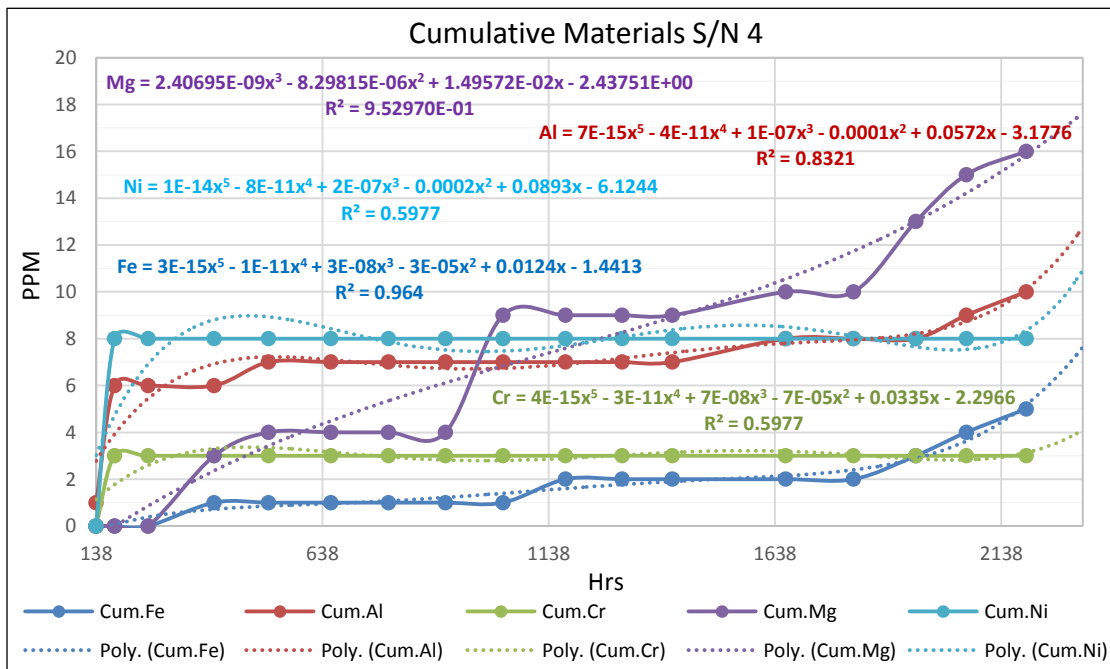


Figure 51 – Regression of Cumulative Fe, Al, Cr, Mg, and Ni - S/N 4

In the same way as in Correlations, the regressions of the following 15 engines are presented in Appendix F (Engine Regressions from S/N 5 to S/N 19).

Results

The results obtained in this chapter are useful for improving the program of spectrometric oil analysis. A lot of work needs to be applied for improving processes, starting with designing optimal procedures and applying them correctly, and continuing without finishing the processes for improvement.

For reducing variability, it is necessary to make the complete program in accordance with the procedures, and then, using the knowledge and tools to evaluate in different ways the trends, rate of contamination, correlations, regressions and so on, for taking advantage of the data and reducing the risks.

Chapter Summary

However sophisticated the spectrometric analysis program, simple analyses should never be ruled out. It is always useful to superimpose analysis with different approaches and ways of presenting data. The way in which these are presented helps to make a better interpretation of the data and can help to reduce risks in the management of the analysed material.

V. Conclusions and Recommendations

Chapter Overview

In this chapter, the conclusions of this research are presented and recapitulated in different ways so the program can enhance itself for reducing risks in operation and management.

In the same way, the significance of this research reinforces the idea that analysis of data is very important, but all the gears need to be aligned for obtaining correct results, since if simpler steps are poorly performed, the most useful and complex program can be ruined. In order to make improvements in the program of spectrometric oil analysis, some recommendations are presented, which can open opportunities for new research.

Discussion

The answers to the Research Questions (RQ) and Investigative Questions (IQ) are possible to summarize as follows:

- 1) RQ1: Are the data extracted enough to fulfill the requirement of predicting the next result for the sample of oil, avoiding unnecessary risk management and operational risk? The response is that the data are enough, although it is important to assure the minimum variation possible in the procedure of extraction.
- 2) RQ2: Do the data extracted meet the quality to fulfill the requirement for predicting the next result for the oil sample? The data do not meet the optimal quality, but in the same way the prediction reach high values of Coefficient of

Determination (R Square), being that, a good signal for using the prediction for avoiding risks.

- 3) RQ3: Is it possible to change or optimize the system of spectrometric oil analysis applied in the FAA? It is possible to optimize the oil spectrometric analysis program as long as the recommendations written below are complied with.
- 4) RQ4: Does the technical report require some type of upgrade? The technical report requires actualization, correction of the formulas and the end user needs to do its own procedure of extraction and analysis of results.

The responses to the Investigative Questions are:

- 1) IQ1: In what mode is the Technical Report of spectrometric analysis applied in the weapon systems today? It is applied in a preventive manner today. The result is compared with the NAVAIR table if the values are within parameter the engine continues to operate.
- 2) IQ2: Has the process been updated with the development over the years? Never the technical report was updated since 1986.
- 3) IQ3: How does the engine user process the information once the laboratory results are received? The end user only compares the test result with the NAVAIR table.
- 4) IQ4: Has the user developed an alarm system in case of unfavorable results? The user has not developed an alarm system and it is a necessity for controlling the evolution of the engine.

- 5) IQ5: Has the user a written procedure of spectrometric oil analysis in this type of engine? The user does not have a written procedure, as a consequence they introduce variability in the process of extraction of samples.
- 6) IQ6: Is the communication between the testing laboratory and the end user proactive? The communication is not proactive and it needs to be improved for taking advantage of this powerful program.
- 7) IQ7: Are qualitative data recorded in addition to the quantitative data in the oil analysis program? The qualitative data are scarce, almost null, and this type of information collection needs to be empowered.

Conclusions of this research

The conclusions of this research are that one program never will function well if it is viewed only as an obligation and there is no control of the program's advancement and evolution. The oil analysis program was implemented in 1987, and the first data for making this research is from 2003. About 30 years passed and no one reviewed the program's status. This is the clear message of the method analyzed. As a result, the technical report needs to be updated and the formulas used in it corrected.

The lack of written procedures about how the sample needs to be extracted is another problem that needs to be addressed to ensure proper oil sampling. Once the procedures have been established, it is necessary to ensure that it is performed correctly, in a standard way to minimize variability and thus obtain significant results. Solving this problem will require the proper training of the personnel that extract samples.

The analysis of the data is very important for knowing the reasons why the sample has variation, and then corrections made in a timely manner. Also, the correct recording of oil consumption and changes are critical and the number of times it is refilled.

All other engine maintenance information needs to be recorded to find correlations between issues of components, appearance of higher particle concentration, oil misalignment, or operation in unusual conditions, for example, with unpaved runways and so on.

The evaluation for comparison of wear is a useful tool to apply because it can reveal irregularities among engines. Although each engine is a unique element, with different background, different wear, subject to different requirements, it is important to do the analysis and then find explanations for these variations. This may be to stop operating the engine, disassemble the engine, or simply inspect more deeply or extract oil samples more frequently.

The correlations combined with graphs are useful for making conclusions about the advancement of the program of spectrometry and the relations among variables. The analysis of correlations gives values, and the graphs, as the popular saying goes, "a picture is worth more than a thousand words", are very useful for appreciating in a visual way the engine status, and this evaluation can lead to positive conclusions as well.

Advancing in the same way as in the development of this thesis, the next step was the automation of the reference NAVAIR table for this engine. After receiving the results of the sample, the first thing to do is to load the data in the Excel sheet, record the results of the test, and develop an alarm system to notify the user when contamination exceeds the maximum values for each material.

Finally, a very important procedure is the regression for predicting the next result of the sample. This could be adjusted by selecting the quantity of cycles that the manager likes forecast in two ways--either using the formula of the regression presented in each graph of Excel or selecting the trendline format when the graph is configured.

In this analysis, the value of R Square is really important, since a value close to 1 means that the formula obtained to make the prediction fits closely to the real data. The prediction then will be perfect, as long as the preconditions remain unchanged in the future.

Every analysis proposed is complementary and contributed to reduced risks in operation and management. As a consequence, all together form a package that is necessary to apply with the only intention to reduce risks. No less important is to work together, the laboratory and the user, in the same direction with the same goal, applying improvement processes to reduce risk, and costs.

Significances

When the risk exists, and the evaluation of the potential impact is high, the only thing that can be done is develop a plan to mitigate the risk, “Risk Management Framework” (Chase, et al., 2014, p. 40). As a result, every measure destined to mitigate risk can be significant for an organization with scarce resources.

The incorporation of this analysis in the program of spectrometric oil analysis will spur a revitalization in the method, in predicted tools, in written procedures and in reporting issues, and it will be useful as a tool to defend technical decisions that are not always simple.

Recommendations

For being successful in the improvement of the predictive program of spectrometric oil analysis, the Air Force will need to make the following changes:

- 1) To update Technical Report C.T. FA42B2-1-2 in accordance with the methods used in this research.
- 2) To require a written procedure for extracting sample, in consideration of the laboratory requirements.
- 3) To train the personnel that work in this area, for assuring a reduced variability in the extraction.
- 4) To establish a written data collection and management procedures for registering oil added, lot number of the oil, quantity, number of times that it was added, personnel that worked, and if the engine was washed. This needs to be per engine in relation to its time of operation.
- 5) To keep all data until engine is no long in service for the FAA.

Future Research

This research opens the opportunity for making future improvements in predictive maintenance, promoting all measures that management can take for reducing the risk of disruption in processes that must be taken immediately. Other research with better records than currently exist could be repeated but not with hours of flight of the engine, trying with periodic time between samples as independent variable, for evaluating the influence of the operation, seasonal variation, pollution, salt in the air, and so on.

To the extent that the prediction tools increase reliability and gain a place in the Air Force, the spectrum of use is widened, although for that to occur it is necessary to ensure the recording of useful data to be able to make future predictions in maintenance.

Appendix A - Decision Making

(NAVAIR 17-15-50.3/TM 38-301-3/T.O. 33-1-37-3/CGTO 33-1-37-3 - WP 002 00, 2013, p. 1)

RANGE THIS SAMPLE	RANGE PREVIOUS SAMPLE	TREND	RECOMMENDATIONS	
			CATEGORY I	CATEGORY II
Normal		Normal	routine	N/A
	Normal	Abnormal	resample or surveillance required	surveillance required
	Marginal	N/A	routine or resample required	surveillance X 2 required
	High	N/A	routine or resample required	surveillance X 2 required
	Abnormal	N/A	routine or resample required	surveillance X 2 required
Marginal		Normal	routine or resample required	surveillance required
	Normal	Abnormal	resample required	surveillance required
		Normal	routine	N/A
	Marginal	Abnormal	resample required	surveillance required
	High	N/A	routine or resample required	surveillance X 2 required
High		Normal	resample required	surveillance required
	Normal	Abnormal	resample required	resample or inspection
		Normal	surveillance required	surveillance required
	Marginal	Abnormal	resample required	resample or inspection
		Normal	surveillance required	surveillance required
	High	Abnormal	resample required	resample or inspection
	Abnormal	N/A	resample or surveillance required	surveillance X 2 required
Abnormal		Normal	resample required	surveillance required
	Normal	Abnormal	resample required	resample or inspection
		Normal	surveillance required	surveillance required
	Marginal	Abnormal	resample required	resample or inspection
		Normal	surveillance required	surveillance required
	High	Abnormal	resample required	resample or inspection
		Normal	resample required	resample or inspection
	Abnormal	Abnormal	inspection required	inspection required
Routine samples: A				
Resample required: B, F, P - use most applicable				
Surveillance required: C, E - use most applicable				
Inspection required: H, R, T - use most applicable				
Self-explanatory: G, J, Q,W, Z				
NOTE: Two C codes should follow a J code to establish a new baseline.				
For all routine samples, recommendation in the Category I column will be used. For all laboratory requested special/verification samples, recommendation in Category II will be used.				

Appendix B - TABLE 203, Material Specification (Engine Components)

(Pratt & Whitney Canada, 2012, p. 223-227)

Specification	Material	Nomenclature	Engine Location
AMS 2412	Silver Plating	Cage, No. 1 Brg	GG
		Cage, No. 2 Brg	GG
		Cage, No. 3 Brg	PT
		Cage, No. 4 Brg	PT
		Cage, No. 5 Brg	RGB
		Cage, No. 6 Brg	RGB
		Cage, No. 7 Brg	RGB
		Cage, FCU Drive Brg	AGB
		Cage, Start-Gen Drive Brg	AGB
AMS 4082, 4150	Alum (AA6061)	Sleeve, First-stage, Carrier	RGB
AMS 4117, 4127, 4150	Alum (AA6061)	Stator, No. 1 Brg Air Seal	GG
AMS 4214	Alum (Alloy 355)	Breather, Impeller	AGB
		Body, Main Scavenge Oil Pump	AGB
		Housing, Main Scavenge Oil Pump	AGB
		Cover, Main Scavenge Oil Pump	AGB
		Housing, External Scavenge Oil Pump	AGB
		Spacer, External Scavenge Oil Pump	AGB
		Cover Housing, Scavenge Oil Pump	AGB
AMS 4260	Alum. (Alloy 356)	Cover, Main Oil Pressure Pump	AGB
AMS 4275	Alum. (Alloy 750)	Brgs, Main Oil Pump Gear	AGB
		Sleeve, Accessory Drive Gears	RGB
AMS 4439	Magnesium (ZE41E)	Housing, Front	RGB
		Housing, Rear	RGB
		Housing, Main Oil Pressure Pump	RGB

		Diaphragm	AGB
		Housing	AGB
AMS 4212	Alum (Alloy 355)	Compressor Inlet Case	GG
AMS 4616	Bronze	Cage, FCU Drive Brgs	AGB
		Cage, Start- Gen Drive Brg	AGB
		Cage, Vacuum Pump Drive Brg	AGB
		Cage, External Scavenge Oil Pump Drive Brg	AGB
		Cage, Coupling Shaft Brg	RGB
AMS 5315	Steel	Sleeve, Propeller, Oil Transfer	RGB
AMS 5613	SST (X51410)	No. 1 Brg Front Air Seal	GG
		No. 2 Brg Front Stator, Air Stator	GG
		No. 2 Brg Front Rotor Air Seal	GG
		No. 2 Brg Rear Stator Air Seal	GG
		No. 2 Brg Rear Rotor Air Seal	GG
		No. 3 Brg Stator Air Seal ,	PT
AMS 5645, 5646	SST (30321)	Sleeve, AGB Coupling Shaft Brg	AGB
AMS 5671	SST (Inconel X750)	Seal, No. 3 Brg, Front Labyrinth, Air	PT
AMS 5732	SST (A286)	Housing, No. 1 Brg, Outer	GG
AMS 6260	Steel (9310)	Gear, Main Oil Scavenge Pump	AGB
AMS 6265	Steel (9310)	Gear, Accessory Drive, Front	RGB
		Gear, Second-stage Planet	RGB
		Carrier, Second-stage Planet Gear	RGB
		Shaft, Second-stage Planet Gear	RGB
		Gear, Ng Tacho Drive	RGB
		Gear, Propeller and O/S Governor Drive	RGB
		Coupling, Propeller Governor Drive	RGB
		Gear, Second-stage, Ring	RGB
		Gear, First-stage, Ring	RGB
		Gear, Second-stage, Sun	RGB
		Coupling, Second-stage Sun Gear	RGB
		Adapter, Second-stage Sun Gear	RGB
		Carrier, First-stage Planet Gear	RGB
		Gear, First-stage, Planet	RGB
		Gear, First-stage, Sun	RGB
		Coupling, AGB Drive	GG
		Coupling, First-stage Sun Gear	PT

		Shaft, AGB Coupling	AGB
		Gear, FCU, Drive	AGB
		Gear, Start- Gen Drive	AGB
		Gear, Vacuum Pump Drive	AGB
		Gear, Hydraulic Pump Drive	AGB
		Gear, Main Oil Pump Drive	AGB
		Gear, External Scavenge Pump Drive	AGB
		Gear, Oil Pressure Pump	AGB
		Gear, External Oil Scavenge Pump	AGB
		Gear, Scavenge Oil Pump	AGB
		Shaft, Vacuum Pump Drive	AGB
		Shaft, External Scavenge Pump Drive,	AGB
		Coupling, Oil Pump Drive	AGB
AMS 6322	Steel (8740)	Sleeve, Second-stage Sun Gear	RGB
		Shaft, First-stage Planet Gear	RGB
AMS 6414	Steel (4340)	Cage, No. 7 Roller Brg	RGB
		Torque Piston	RGB
		Inner Housing No. 1 Brg	GG
		Cage, No. 1 Brg	GG
		Cage, No. 2 Brg	GG
		Cage, No. 3 Brg	PT
		Cage, No. 4 Brg	PT
		Coupling, Main Oil Pump Drive Gear	AGB
AMS 6415	Steel (4340)	Shaft, Propeller	RGB
		Cage, No. 6 Brg	RGB
		Cage, No. 5 Brg	RGB
		Locating Pin, Second-stage Planet Gear Carrier,	RGB
		Torque Cylinder,	RGB
		Shaft, Impeller	GG
AMS 6440/ 6444	Steel (52100)	Roller, AGB Coupling Shaft Brg	AGB
		Roller, Start-Gen Drive Brg	AGB
		Roller, Hydraulic Pump Drive Brg	AGB
		Roller, Vacuum Pump Drive Brg	AGB
		Roller, External Scavenge Pump Drive Brg	AGB
		No. 7 Brg, Roller and Rings	RGB
		No. 6 Brg, Ball and Rings	RGB
		No. 5 Brg, Roller and Rings	RGB
		First-stage Planet Gearshaft	RGB
		Rings, AGB Coupling Shaft Brg	AGB

		Rings, FCU Drive Brg	AGB
		Rings, Start-Gen Drive Brg	AGB
		Rings, Hydraulic Pump Drive Brg	AGB
		Rings, Vacuum Pump Drive Brg	AGB
		Rings, External Scavenge Pump Drive Brg	AGB
AMS 6490	Steel (M50)	No. 2 Brg, Rings and Rollers	GG
		No. 3 Brg Rings and Rollers	PT
AMS 6491	Steel (M50)	No. 1 Brg Rings and Balls,	GG
		PT Shaft	PT
		PT Shaft Coupling	PT
		No. 4 Brg Rings and Balls,	PT
AMS6265/6444	Steel	Shaft, Second-stage Planet Gear	RGB
		Shaft, First-stage Planet Gear	RGB
AMS 4928	Titanium Alloy	Compressor, First-stage	GG
		Stubshaft, First-stage Compressor	GG
	Molybdenum	Coating, No. 2 Brg, Labyrinth, Seals, Air	GG

Appendix C - TABLE 204, Common Contaminants – Non-organic Material

(Pratt & Whitney Canada, 2012, p. 227)

Contaminant Detected	Main Elements	Cause of Contaminants
Alumina	Al_2O_3	Manufacturing
Black Magnetic	Fe_3O_4	Anaerobic decomposition of shaft material, can look like carbon is a corrosive product.
Calcium Oxide	CaO	Environment
Rust, Non-magnetic	Fe_2O_3	Rust
Sand	SiO_2	Manufacturing/Environment
Silicon Carbide (Black, Shiny, Angular)	SiC	Manufacturing/Blasting
Zirconia	ZrSiO_4	Manufacturing
	MoS_2	Common as a trace, could combine with Fe (Iron) to indicate bearing alloy. Usually found in new or overhauled engines.
Calcium Chloride (Salt)	CaCl_2	Environment
Sodium Chloride (Salt)	NaCl	Environment
Calcium Sulphate (Salt)	CaSO_4	Environment

Appendix D - Sheet Engine Data

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million													
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn		
01	19-Jun-08	45.60	1.15	46.60	3046.60	0	0	0	1	0	0	0	93	-	-	-	-		
01	28-Jun-08	61.66	1.536	108.26	3108.26	0	0	0	0	0	0	0	40	-	-	-	-		
01	19-Aug-08	17.00	0.425	125.26	3125.26	0	0	1	0	0	0	0	19	-	-	-	-		
01	25-Nov-08	125.00	3.13	250.26	3250.26	0	0	1	0	0	0	0	22	-	-	-	-		
01	11-Jun-09	256.00	6.3	506.26	3506.26	0	0	1	0	0	0	0	18	-	-	-	-		
01	10-Dec-09	134.00	3.337	640.26	3640.26	0	0	2	0	0	0	1	2	-	-	-	-		
01	15-Apr-10	124.00	3.087	764.26	3764.26	0	0	0	0	0	2	0	0	-	-	-	-		
01	7-Jun-10	116.00	2.905	880.26	3880.26	0	0	0	0	0	0	0	2	-	-	-	-		
01	5-Nov-10	125.00	3.123	1005.26	4005.26	0	0	1	0	0	0	0	2	-	-	-	-		
01	11-Aug-11	121.00	3.025	1126.26	4126.26	1	0	1	0	0	0	0	0	-	-	-	-		
01	31-Aug-11	118.00	2.935	1244.26	4244.26	0	0	0	0	0	0	0	0	-	-	-	-		
01	14-Dec-11	128.00	3.185	1372.26	4372.26	0	0	0	0	0	0	0	0	-	-	-	-		
01	20-Apr-12	125.00	3.13	1497.26	4497.26	1	0	0	0	0	0	0	0	-	-	-	-		
01	4-Aug-14	125.00	3.8	1622.26	4622.26	0	0	0	0	0	0	0	11	-	-	-	-		
01	17-Jun-15	125.00	3.125	1747.26	4747.26	1	0	1	0	0	0	0	9	-	-	-	-		
01	18-Aug-15	126.20	3.175	1873.46	4873.46	1	0	1	0	0	1	0	13	-	-	-	-		
01	25-Feb-16	123.00	3.25	1996.46	4996.46	0	0	0	0	0	0	0	4	-	-	-	-		

Figure 52 - Sheet Engine S/N 01

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million													
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn		
02	7-Jun-10	376.00	9.1	433.00	3432.00	1	0	0	0	0	0	0	1	-	-	-	-		
02	27-Sep-10	125.00	3.25	558.00	3557.00	1	0	0	0	0	0	0	2	-	-	-	-		
02	15-Dec-10	109.00	2.725	667.00	3666.00	0	0	0	0	0	0	0	2	-	-	-	-		
02	6-Dec-11	127.00	3.1	794.00	3793.00	0	0	0	0	0	0	0	0	-	-	-	-		
02	11-Jan-12	125.00	3.15	919.00	3918.00	0	0	0	0	0	0	0	4	-	-	-	-		
02	1-Aug-12	161.00	4	1080.00	4079.00	1	0	0	0	0	2	0	17	-	-	-	-		
02	27-Aug-12	27.00	0.65	1107.00	4106.00	2	0	0	0	0	0	0	27	-	-	-	-		

Figure 53 - Sheet Engine S/N 02

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million													
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn		
03	22-Jun-10	126.00	3.16	126.00	3126.00	1	0	1	0	0	1	0	7	-	-	-	-		
03	15-Dec-10	126.00	3.10	252.00	3252.00	0	0	0	0	0	0	0	2	-	-	-	-		
03	8-Feb-11	116.00	2.94	368.00	3368.00	0	0	0	0	0	0	0	0	-	-	-	-		
03	26-May-11	124.00	3.05	492.00	3492.00	1	0	1	0	0	0	0	2	-	-	-	-		
03	12-Jun-13	124.00	3.05	616.00	3616.00	1	0	0	0	0	1	0	5	-	-	-	-		
03	28-Aug-13	125.00	3.13	741.00	3741.00	1	0	1	0	0	1	0	4	-	-	-	-		
03	11-Nov-13	125.00	3.15	866.00	3866.00	1	0	0	0	0	2	0	4	-	-	-	-		
03	25-Nov-14	250.00	6.20	1116.00	4116.00	1	0	0	0	0	3	0	2	-	-	-	-		
03	25-Mar-15	128.00	3.00	1244.00	4244.00	1	0	0	0	0	1	0	13	-	-	-	-		
03	21-Oct-15	100.66	2.50	1344.66	4344.66	1	0	0	0	0	2	0	2	-	-	-	-		

Figure 54 - Sheet Engine S/N 03

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part per Million													
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn		
4	18-Jun-09	138.00	3.50	138.00	3055.00	0	0	1	0	0	0	0	89	-	-	-	-		
4	31-Jul-09	41.00	1.00	179.00	3096.00	0	0	5	3	0	0	8	61	-	-	-	-		
4	4-Sep-09	74.00	1.85	253.00	3170.00	0	0	0	0	0	0	0	52	-	-	-	-		
4	15-Apr-10	146.00	3.66	399.00	3316.00	1	0	0	0	0	3	0	5	-	-	-	-		
4	21-Jul-10	120.00	3.05	519.00	3436.00	0	0	1	0	0	1	0	1	-	-	-	-		
4	31-Aug-11	138.00	3.34	657.00	3574.00	0	0	0	0	0	0	0	0	-	-	-	-		
4	14-Dec-11	127.00	3.15	784.00	3701.00	0	0	0	0	0	0	0	1	-	-	-	-		
4	15-Apr-12	126.00	3.15	910.00	3827.00	0	0	0	0	0	0	0	2	-	-	-	-		
4	27-Aug-12	127.00	3.15	1037.00	3954.00	0	0	0	0	0	5	0	26	-	-	-	-		
4	8-Nov-12	138.00	3.34	1175.00	4092.00	1	0	0	0	0	0	0	10	-	-	-	-		
4	4-Jan-13	125.00	3.10	1300.00	4217.00	0	0	0	0	0	0	0	0	-	-	-	-		
4	12-Jun-13	111.00	2.76	1411.00	4328.00	0	0	0	0	0	0	0	3	-	-	-	-		
4	13-May-14	250.50	6.26	1661.50	4578.50	0	0	1	0	0	1	0	0	-	-	-	-		
4	4-Aug-14	150.00	3.13	1811.50	4728.50	0	0	0	0	0	0	0	4	-	-	-	-		
4	25-Nov-14	137.50	3.43	1949.00	4866.00	1	0	0	0	0	3	0	17	-	-	-	-		
4	17-Jun-15	111.66	2.78	2060.66	4977.66	1	0	1	0	0	2	0	5	-	-	-	-		
4	10-Jun-16	132.20	3.30	2192.86	5109.86	1	0	1	0	0	1	0	8	-	-	-	-		

Figure 55 - Sheet Engine S/N 04

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million													
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn		
05	26-Jun-06	125.00	3.10	714.00	2284.00	2	0	1	2	1	1	0	3	-	-	-	-		
05	3-Sep-06	118.00	2.90	832.00	2402.00	1	0	1	1	0	1	0	1	-	-	-	-		
05	1-Aug-07	51.00	1.25	883.00	2453.00	0	0	0	0	0	0	0	1	-	-	-	-		
05	3-Nov-08	53.00	1.35	936.00	2506.00	0	0	0	1	0	0	0	6	-	-	-	-		
05	19-Jun-08	159.00	4.00	1095.00	2665.00	0	0	0	1	0	0	0	3	-	-	-	-		
05	10-Oct-08	126.00	3.13	1221.00	2791.00	0	0	1	0	0	0	0	5	-	-	-	-		
05	9-Apr-09	223.00	5.57	1444.00	3014.00	1	0	0	0	0	3	0	8	-	-	-	-		
05	5-Apr-10	125.00	3.18	1569.00	3139.00	1	0	0	0	0	6	0	7	-	-	-	-		
05	21-Jul-10	136.00	3.45	1705.00	3275.00	0	0	0	0	0	2	0	1	-	-	-	-		
05	2-Aug-11	115.00	2.75	1820.00	3390.00	1	0	1	0	0	0	0	1	-	-	-	-		
05	6-Oct-16	124.10	3.15	1944.10	3514.10	1	0	0	0	0	0	0	11	-	-	-	-		

Figure 56 - Sheet Engine S/N 05

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million												
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn	
06	31-Jan-08	121.00	3.10	121.00	3124.00	0	0	0	2	0	0	0	0	-	-	-	-	
06	12-May-08	125.00	3.15	246.00	3249.00	1	0	0	1	0	0	2	7	-	-	-	-	
06	28-Jul-08	137.00	3.50	383.00	3386.00	0	0	0	0	0	0	0	4	-	-	-	-	
06	24-Apr-09	250.00	6.40	633.00	3636.00	1	0	0	0	0	2	0	3	-	-	-	-	
06	25-Aug-09	126.00	3.20	759.00	3762.00	0	0	1	0	0	0	0	7	-	-	-	-	
06	7-Jun-10	119.00	3.00	878.00	3881.00	0	0	0	0	0	0	0	3	-	-	-	-	
06	27-Sep-10	125.00	3.15	1003.00	4006.00	0	0	0	0	0	0	0	4	-	-	-	-	
06	27-Aug-12	41.00	1.05	1044.00	4047.00	0	0	0	0	0	5	0	1	-	-	-	-	
06	19-Apr-13	125.00	3.15	1169.00	4172.00	0	0	0	0	0	0	0	1	-	-	-	-	
06	12-Jun-13	113.00	2.90	1282.00	4285.00	1	0	0	0	0	0	0	1	-	-	-	-	
06	8-Dec-13	125.25	3.20	1407.25	4410.25	1	0	0	0	0	0	0	1	-	-	-	-	
06	13-May-14	126.75	3.16	1534.00	4537.00	0	0	0	0	0	0	0	0	-	-	-	-	
06	25-Nov-14	137.50	3.43	1671.50	4674.50	1	0	0	0	0	1	0	1	-	-	-	-	
06	18-Aug-15	112.66	2.80	1784.16	4787.16	0	0	0	0	0	0	0	4	-	-	-	-	

Figure 57 - Sheet Engine S/N 06

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million												
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn	
07	13-Dec-04	128.00	3.30	128.00	3128.00	1	0	0	1	1	1	3	9	-	-	-	-	
07	21-Apr-05	134.00	3.38	262.00	3262.00	1	0	0	0	1	0	2	5	-	-	-	-	
07	6-Jul-05	125.00	3.10	387.00	3387.00	1	0	0	0	1	0	1	5	-	-	-	-	
07	24-Nov-05	116.00	2.75	503.00	3503.00	1	0	0	1	1	0	0	3	-	-	-	-	
07	22-Sep-06	264.00	6.80	767.00	3767.00	1	0	2	0	0	2	1	4	-	-	-	-	
07	15-Oct-07	125.00	3.16	892.00	3892.00	1	0	1	0	0	2	0	9	-	-	-	-	
07	25-Nov-08	262.00	6.40	1154.00	4154.00	1	0	1	0	0	2	0	18	-	-	-	-	
07	24-Apr-09	100.00	2.70	1254.00	4254.00	0	0	0	0	0	2	0	2	-	-	-	-	
07	18-Jun-09	123.00	3.10	1377.00	4377.00	0	0	0	0	0	1	0	3	-	-	-	-	
07	21-Jul-10	128.00	3.30	1505.00	4505.00	1	0	0	0	0	0	0	1	-	-	-	-	
07	26-May-11	126.00	3.20	1631.00	4631.00	0	0	1	0	1	0	0	3	-	-	-	-	
07	31-Aug-11	126.00	3.20	1757.00	4757.00	0	0	0	0	0	0	0	0	-	-	-	-	
07	6-Dec-11	130.00	3.35	1887.00	4887.00	1	0	1	0	1	1	0	0	-	-	-	-	
07	11-Jan-12	112.00	2.90	1999.00	4999.00	0	0	0	0	0	0	0	2	-	-	-	-	
07	4-Jan-13	142.00	3.35	2141.00	5141.00	0	0	1	0	0	0	0	0	-	-	-	-	
07	19-Apr-13	113.00	2.75	2254.00	5254.00	2	0	0	0	0	2	0	7	-	-	-	-	
07	28-Aug-13	125.00	3.20	2379.00	5379.00	1	0	0	0	0	1	0	10	-	-	-	-	
07	11-Nov-13	125.00	3.15	2504.00	5504.00	1	0	0	0	0	1	0	14	-	-	-	-	
07	12-Jun-14	137.00	3.40	2641.00	5641.00	1	0	1	0	0	1	0	6	-	-	-	-	
07	25-Nov-14	113.00	2.80	2754.00	5754.00	1	0	0	0	0	2	0	5	-	-	-	-	
07	25-Mar-15	133.60	3.40	2887.60	5887.60	1	0	0	0	0	1	0	2	-	-	-	-	
07	17-Jun-15	129.30	3.30	3016.90	6016.90	0	0	0	0	0	0	0	23	-	-	-	-	

Figure 58 - Sheet Engine S/N 07

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million													
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn		
08	28-Aug-08	125.00	3.15	330.00	3332.00	1	0	2	0	0	0	0	6	-	-	-	-		
08	25-Nov-08	126.00	3.20	456.00	3458.00	0	0	1	0	0	0	1	3	-	-	-	-		
08	2-Feb-09	162.00	4.00	618.00	3620.00	0	0	0	0	0	0	0	0	-	-	-	-		
08	8-Feb-11	215.00	5.40	833.00	3835.00	0	0	0	0	0	0	0	0	-	-	-	-		
08	26-Apr-11	126.00	3.25	959.00	3961.00	0	0	0	0	0	0	0	0	-	-	-	-		
08	11-Aug-11	124.00	3.05	1083.00	4085.00	0	0	0	1	0	0	0	3	-	-	-	-		
08	6-Dec-11	124.00	3.05	1207.00	4209.00	0	0	1	0	0	0	0	0	-	-	-	-		
08	20-Apr-12	127.00	3.25	1334.00	4336.00	0	0	1	0	0	0	0	2	-	-	-	-		
08	17-Oct-12	125.00	3.25	1459.00	4461.00	0	0	0	0	0	1	0	40	-	-	-	-		
08	4-Jan-13	124.00	3.00	1583.00	4585.00	0	0	1	0	0	0	0	0	-	-	-	-		
08	19-Apr-13	125.00	3.20	1708.00	4710.00	0	0	0	0	0	0	0	0	-	-	-	-		
08	11-Nov-13	126.00	3.25	1834.00	4836.00	1	0	0	0	0	2	0	4	-	-	-	-		
08	15-Mar-14	125.00	3.15	1959.00	4961.00	1	0	0	0	0	1	0	5	-	-	-	-		
08	13-Jun-14	125.00	3.18	2084.00	5086.00	0	0	0	0	0	1	0	13	-	-	-	-		
08	25-Nov-14	125.00	3.25	2209.00	5211.00	0	0	0	0	0	1	0	3	-	-	-	-		
08	18-Aug-15	263.00	6.60	2472.00	5474.00	0	0	0	0	0	1	0	8	-	-	-	-		
08	10-Jun-16	112.66	2.80	2584.66	5586.66	0	0	0	0	0	1	0	5	-	-	-	-		

Figure 59 - Sheet Engine S/N 08

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million													
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn		
09	26-Apr-11	58.00	1.50	58.00	3054.00	0	0	0	0	0	0	0	0	-	-	-	-		
09	31-Aug-11	126.00	3.25	184.00	3180.00	0	0	0	0	0	0	0	2	-	-	-	-		
09	20-Jan-12	125.00	3.25	309.00	3305.00	0	0	0	0	0	0	0	2	-	-	-	-		
09	20-Apr-12	125.00	3.20	434.00	3430.00	0	0	0	0	0	0	0	2	-	-	-	-		
09	27-Aug-12	125.00	3.15	559.00	3555.00	0	0	0	0	0	10	0	9	-	-	-	-		
09	17-Oct-10	53.00	3.15	612.00	3608.00	0	0	0	0	0	0	0	21	-	-	-	-		
09	4-Jan-13	85.00	1.33	697.00	3693.00	1	0	1	0	0	0	0	0	-	-	-	-		
09	19-Apr-13	210.00	2.13	907.00	3903.00	1	0	1	0	0	0	0	2	-	-	-	-		
09	12-Jun-13	120.00	3.23	1027.00	4023.00	1	0	1	0	0	1	1	5	-	-	-	-		
09	2-Oct-13	77.00	3.03	1104.00	4100.00	1	0	1	0	0	1	0	5	-	-	-	-		
09	12-Jun-14	80.00	3.10	1184.00	4180.00	1	0	1	0	0	0	0	2	-	-	-	-		
09	25-Nov-14	137.50	3.43	1321.50	4317.50	0	0	0	0	0	1	0	2	-	-	-	-		
09	17-Jun-15	108.80	2.70	1430.30	4426.30	1	0	1	0	0	0	0	3	-	-	-	-		

Figure 60 - Sheet Engine S/N 09

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million													
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn		
10	15-Jan-07	288.00	7.10	1164.00	4166.00	0	0	0	0	0	0	0	3	-	-	-	-		
10	13-Jun-07	125.00	3.20	1289.00	4291.00	0	0	0	0	0	3	0	2	-	-	-	-		
10	10-Dec-07	118.00	3.00	1407.00	4409.00	0	0	0	0	0	2	0	3	-	-	-	-		
10	25-Jun-08	126.00	3.20	1533.00	4535.00	0	0	0	1	0	0	0	10	-	-	-	-		
10	25-Nov-08	126.00	3.10	1659.00	4661.00	0	0	1	0	0	0	0	4	-	-	-	-		
10	4-May-09	122.00	3.10	1781.00	4783.00	0	0	0	0	0	3	0	1	-	-	-	-		
10	18-Jun-09	48.00	1.25	1829.00	4831.00	0	0	0	0	0	1	0	3	-	-	-	-		
10	6-Dec-11	233.00	6.00	2062.00	5064.00	0	0	0	0	0	0	0	0	-	-	-	-		

Figure 61 - Sheet Engine S/N 10

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million												
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn	
11	10-May-06	254.00	6.40	754.00	3754.00	0	0	0	0	0	0	0	1	-	-	-	-	
11	22-Sep-06	208.00	5.30	962.00	3962.00	1	0	3	0	0	1	1	2	-	-	-	-	
11	17-May-07	43.00	1.10	1005.00	4005.00	1	0	0	0	0	1	0	1	-	-	-	-	
11	11-Nov-07	125.00	3.20	1130.00	4130.00	1	0	1	0	0	0	0	0	-	-	-	-	
11	7-Apr-08	139.00	3.60	1269.00	4269.00	1	0	1	0	0	0	0	1	-	-	-	-	
11	25-Jun-08	237.00	6.00	1506.00	4506.00	1	0	0	0	0	1	1	3	-	-	-	-	
11	2-Feb-09	138.00	3.50	1644.00	4644.00	0	0	0	0	0	0	0	0	-	-	-	-	
11	18-Jun-09	125.00	3.20	1769.00	4769.00	1	0	1	0	0	1	0	2	-	-	-	-	
11	25-Aug-09	127.00	3.20	1896.00	4896.00	1	0	1	0	0	1	0	1	-	-	-	-	
11	6-Dec-11	124.00	3.20	2020.00	5020.00	1	0	1	0	0	1	0	0	-	-	-	-	
11	15-Apr-12	126.00	3.20	2146.00	5146.00	0	0	0	0	0	0	0	0	-	-	-	-	
11	11-Jun-12	125.00	3.20	2271.00	5271.00	0	0	0	0	0	0	0	1	-	-	-	-	
11	27-Aug-12	126.00	3.20	2397.00	5397.00	1	0	0	0	0	6	0	0	-	-	-	-	
11	11-Nov-13	126.00	3.10	2523.00	5523.00	0	0	0	0	0	1	0	42	-	-	-	-	
11	24-Mar-14	250.00	6.40	2773.00	5773.00	0	0	0	0	0	1	0	1	-	-	-	-	
11	4-Aug-14	123.33	3.05	2896.33	5896.33	0	0	0	0	0	0	0	4	-	-	-	-	

Figure 62 - Sheet Engine S/N 11

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part per Million												
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn	
12	15-Jan-07	245.00	6.20	2031.00	2031.00	0	0	1	0	0	0	0	3	-	-	-	-	
12	17-May-07	138.00	3.60	2169.00	2169.00	1	0	1	0	0	0	0	4	-	-	-	-	
12	20-Nov-07	116.00	3.00	2285.00	2285.00	1	0	1	0	0	0	0	3	-	-	-	-	
12	7-Apr-08	126.00	3.20	2411.00	2411.00	1	0	1	0	0	0	0	5	-	-	-	-	
12	10-Jul-08	124.00	3.15	2535.00	2535.00	1	0	1	0	0	0	0	4	-	-	-	-	
12	19-Sep-08	124.00	3.05	2659.00	2659.00	0	0	1	0	0	1	0	3	-	-	-	-	
12	25-Nov-08	130.00	3.2	2789.00	2789.00	1	0	1	0	0	2	0	18	-	-	-	-	
12	11-Jun-12	125.00	3.10	2914.00	2914.00	1	0	1	0	0	0	2	8	-	-	-	-	

Figure 63 - Sheet Engine S/N 12

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million												
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn	
13	25-Jun-07	141.00	3.10	141.00	3141.00	0	0	0	0	0	0	0	0	-	-	-	-	
13	22-Nov-07	137.00	3.43	278.00	3278.00	0	0	0	0	0	0	0	0	-	-	-	-	
13	11-Mar-08	123.00	2.08	401.00	3401.00	1	0	1	0	0	0	0	1	-	-	-	-	
13	10-Oct-08	245.00	6.13	646.00	3646.00	1	0	1	0	0	0	0	2	-	-	-	-	
13	2-Feb-09	125.00	3.13	771.00	3771.00	0	0	1	0	0	0	0	0	-	-	-	-	
13	22-Jun-10	125.00	3.13	896.00	3896.00	0	0	0	0	0	1	0	3	-	-	-	-	
13	15-Dec-10	111.00	2.78	1007.00	4007.00	0	0	0	0	0	0	0	1	-	-	-	-	
13	2-Jul-12	138.00	3.45	1145.00	4145.00	1	0	0	0	0	0	0	8	-	-	-	-	
13	4-Jan-13	112.00	2.80	1257.00	4257.00	0	0	1	0	0	0	0	7	-	-	-	-	
13	28-Jun-13	138.00	3.45	1395.00	4395.00	1	0	1	0	0	1	0	17	-	-	-	-	
13	11-Sep-13	105.00	2.63	1500.00	4500.00	0	0	0	0	0	1	0	13	-	-	-	-	
13	11-Dec-13	137.75	3.43	1637.75	4637.75	1	0	0	0	0	3	0	16	-	-	-	-	
13	25-Nov-14	113.40	2.33	1751.15	4751.15	1	0	0	0	0	4	0	14	-	-	-	-	
13	20-Mar-15	125.66	3.13	1876.81	4876.81	1	0	0	0	0	4	0	15	-	-	-	-	
13	18-Aug-15	112.60	2.83	1989.41	4989.41	1	0	1	0	0	5	0	13	-	-	-	-	
13	5-Feb-16	44.79	1.50	2034.20	5034.20	1	0	1	0	0	3	0	14	-	-	-	-	
13	10-Jun-16	137.80	3.45	2172.00	5172.00	1	0	1	0	0	2	0	17	-	-	-	-	

Figure 64 - Sheet Engine S/N 13

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million													
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn		
14	17-May-07	125.00	3.13	125.00	3125.00	1	0	1	0	0	0	0	0	-	-	-	-		
14	8-Jul-07	141.00	3.20	266.00	3266.00	1	0	1	0	0	0	0	0	-	-	-	-		
14	1-Nov-07	126.00	3.25	392.00	3392.00	2	0	1	1	0	0	0	0	-	-	-	-		
14	19-Jun-08	121.00	3.10	513.00	3513.00	1	0	1	1	0	0	0	2	-	-	-	-		
14	25-Nov-08	127.00	3.25	640.00	3640.00	1	0	1	0	0	2	0	1	-	-	-	-		
14	18-Jun-09	127.00	3.20	767.00	3767.00	1	0	1	0	0	2	0	25	-	-	-	-		
14	25-Aug-09	125.00	3.10	892.00	3892.00	1	0	1	0	0	0	0	10	-	-	-	-		
14	21-Jul-10	109.00	2.78	1001.00	4001.00	1	0	0	0	0	0	0	5	-	-	-	-		
14	2-Feb-11	127.00	3.25	1128.00	4128.00	1	0	0	0	0	0	0	3	-	-	-	-		
14	7-Mar-12	125.00	3.05	1253.00	4253.00	1	0	0	0	0	0	0	2	-	-	-	-		
14	9-Apr-13	123.00	3.20	1376.00	4376.00	1	0	0	0	0	0	0	4	-	-	-	-		
14	15-Mar-14	132.00	3.25	1508.00	4508.00	1	0	0	0	0	0	0	5	-	-	-	-		
14	25-Nov-14	137.66	3.50	1645.66	4645.66	1	0	0	0	0	3	0	7	-	-	-	-		

Figure 65 - Sheet Engine S/N 14

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million													
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn		
15	2-Feb-09	78.00	2.00	339.00	3328.00	0	0	0	0	0	0	0	0	-	-	-	-		
15	31-Jul-09	124.00	3.15	463.00	3452.00	0	0	0	3	0	0	2	10	-	-	-	-		
15	10-Dec-09	121.00	3.05	584.00	3573.00	0	0	3	0	0	1	1	4	-	-	-	-		
15	4-May-10	70.00	1.80	654.00	3643.00	0	0	0	0	0	2	0	2	-	-	-	-		
15	21-Jul-10	52.00	1.35	706.00	3695.00	0	0	0	0	0	1	0	1	-	-	-	-		
15	20-Sep-14	1.50	0.03	707.50	3696.50	1	0	0	0	0	2	0	44	-	-	-	-		
15	25-Nov-14	59.80	1.48	767.30	3756.30	0	0	0	0	0	2	0	51	-	-	-	-		
15	18-Aug-15	126.20	3.15	893.50	3882.50	0	0	0	0	0	1	0	59	-	-	-	-		
15	10-Jun-16	137.50	3.43	1031.00	4020.00	0	0	0	0	0	0	0	10	-	-	-	-		

Figure 66 - Sheet Engine S/N 15

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million												
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn	
16	15-Jan-07	125.00	3.25	292.00	3292.00	1	0	1	0	0	0	0	10	-	-	-	-	
16	25-Jul-07	125.00	3.10	417.00	3417.00	1	0	0	0	0	0	0	3	-	-	-	-	
16	22-Nov-07	120.00	2.85	537.00	3537.00	1	0	0	0	0	1	0	4	-	-	-	-	
16	7-Apr-08	127.00	3.25	664.00	3664.00	1	0	0	0	0	1	0	8	-	-	-	-	
16	25-Jun-08	122.00	3.20	786.00	3786.00	1	0	0	1	0	1	0	8	-	-	-	-	
16	2-Feb-09	136.00	3.45	922.00	3922.00	0	0	1	0	0	0	0	1	-	-	-	-	
16	16-Feb-09	127.00	3.15	1049.00	4049.00	0	0	0	0	0	0	0	2	-	-	-	-	
16	4-Sep-09	130.00	3.30	1179.00	4179.00	0	0	0	0	0	0	0	5	-	-	-	-	
16	15-Apr-10	115.00	2.90	1294.00	4294.00	1	0	0	0	0	2	0	0	-	-	-	-	
16	5-Nov-10	125.00	3.20	1419.00	4419.00	0	0	1	0	0	0	0	2	-	-	-	-	
16	8-Feb-11	114.00	2.90	1533.00	4533.00	0	0	0	0	0	0	0	0	-	-	-	-	
16	26-May-11	124.00	3.20	1657.00	4657.00	1	0	1	0	0	0	0	4	-	-	-	-	
16	31-Aug-11	125.00	3.15	1782.00	4782.00	0	0	0	0	0	0	0	0	-	-	-	-	
16	4-Aug-14	128.00	3.25	1910.00	4910.00	0	0	0	0	0	0	0	6	-	-	-	-	
16	25-Nov-14	122.10	3.10	2032.10	5032.10	1	0	0	0	0	2	0	5	-	-	-	-	
16	11-Oct-15	127.00	3.20	2159.10	5159.10	1	0	0	0	0	2	0	9	-	-	-	-	
16	6-Oct-16	122.90	3.10	2282.00	5282.00	1	0	0	0	0	2	0	14	-	-	-	-	

Figure 67 - Sheet Engine S/N 16

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million												
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn	
17	19-Apr-06	123.00	3.10	623.00	3623.00	1	0	0	0	0	0	1	1	-	-	-	-	
17	22-Sep-06	232.00	5.90	855.00	3855.00	0	0	3	1	0	2	0	3	-	-	-	-	
17	17-May-07	128.00	3.30	983.00	3983.00	1	0	1	0	0	0	0	3	-	-	-	-	
17	10-Oct-08	124.00	3.20	1107.00	4107.00	0	0	1	0	1	0	0	46	-	-	-	-	
17	15-Dec-10	138.00	3.50	1245.00	4245.00	0	0	1	0	0	0	0	5	-	-	-	-	
17	26-May-11	118.00	3.00	1363.00	4363.00	0	0	0	0	0	0	0	4	-	-	-	-	
17	11-Aug-11	123.00	3.10	1486.00	4486.00	0	0	0	0	0	0	0	0	-	-	-	-	
17	22-Sep-11	106.00	2.70	1592.00	4592.00	1	0	1	0	0	0	0	0	-	-	-	-	
17	15-Apr-12	125.00	3.20	1717.00	4717.00	0	0	0	0	0	0	0	1	-	-	-	-	
17	11-Jun-12	125.00	3.20	1842.00	4842.00	0	0	0	0	0	0	0	1	-	-	-	-	
17	27-Aug-12	125.00	3.25	1967.00	4967.00	0	0	0	0	0	5	0	12	-	-	-	-	
17	12-Jun-13	251.00	6.35	2218.00	5218.00	0	0	0	0	0	0	0	3	-	-	-	-	
17	28-Aug-13	126.00	3.20	2344.00	5344.00	0	0	0	0	0	0	0	3	-	-	-	-	
17	13-May-14	122.33	3.06	2466.33	5466.33	0	0	0	0	0	0	0	0	-	-	-	-	
17	25-Mar-15	125.00	3.20	2591.33	5591.33	0	0	0	0	0	1	0	2	-	-	-	-	
17	18-Aug-15	147.10	3.75	2738.43	5738.43	1	0	1	0	0	1	0	3	-	-	-	-	
17	10-Jun-16	108.20	2.70	2846.63	5846.63	1	0	1	0	0	1	0	4	-	-	-	-	

Figure 68 - Sheet Engine S/N 17

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million												
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn	
18	12-Jan-03	126.00	3.15	2613.00	2613.00	1	0	1	0	0	0	0	1	-	-	-	-	
18	29-Jun-04	126.00	3.20	2739.00	2739.00	1	0	0	0	0	0	0	0	-	-	-	-	
18	27-Sep-04	132.00	3.25	2871.00	2871.00	0	0	0	0	0	1	0	1	-	-	-	-	
18	2-Aug-05	123.00	3.08	2994.00	2994.00	1	0	0	1	4	0	2	2	-	-	-	-	
18	14-Dec-11	17.00	0.42	17.00	3011.00	0	0	0	0	0	0	0	17	-	-	-	-	
18	20-Apr-12	137.33	5.85	154.33	3148.33	0	0	0	1	0	0	0	16	-	-	-	-	
18	27-Aug-12	112.00	2.85	266.33	3260.33	0	0	0	0	0	0	0	10	-	-	-	-	
18	25-Sep-12	122.00	2.95	388.33	3382.33	0	0	0	0	0	2	0	13	-	-	-	-	
18	12-Jun-13	126.00	3.15	514.33	3508.33	0	0	0	0	0	1	12	1	-	-	-	-	
18	28-Aug-13	125.00	3.13	639.33	3633.33	0	0	0	0	0	0	0	13	-	-	-	-	
18	28-Nov-13	125.50	3.10	764.83	3758.83	0	0	0	0	0	4	0	10	-	-	-	-	
18	23-Apr-14	124.15	3.00	888.98	3882.98	1	0	0	0	0	5	0	12	-	-	-	-	
18	25-Nov-14	125.00	3.13	1013.98	4007.98	1	0	0	0	0	3	0	7	-	-	-	-	
18	28-Oct-15	124.90	3.00	1138.88	4132.88	1	0	0	0	0	4	0	13	-	-	-	-	

Figure 69 - Sheet Engine S/N 18

S/N	Date	Hrs. since last test	Oil added	Engine		Concentration in Part Per Million												
			Lts	Time Since last Repair	Time Since New	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si	Ti	Sn	B	Zn	
19	10-Jan-06	125.00	3.20	125.00	3125.00	6	0	0	0	1	0	0	0	-	-	-	-	
19	23-May-06	125.00	3.10	250.00	3250.00	2	0	2	0	0	3	2	8	-	-	-	-	
19	22-Sep-06	125.00	3.15	375.00	3375.00	1	0	0	0	0	2	2	6	-	-	-	-	
19	15-Jan-07	113.00	2.85	488.00	3488.00	1	0	1	0	0	0	0	5	-	-	-	-	
19	13-Jun-07	35.00	0.50	523.00	3523.00	1	0	1	0	1	0	0	3	-	-	-	-	
19	31-Jan-08	124.00	3.00	647.00	3647.00	0	0	0	0	0	0	0	0	-	-	-	-	
19	24-Apr-08	124.00	3.10	771.00	3771.00	0	0	0	0	0	0	0	0	-	-	-	-	
19	25-Jun-08	125.00	3.25	896.00	3896.00	0	0	1	0	0	0	0	2	-	-	-	-	
19	10-Oct-08	125.00	3.15	1021.00	4021.00	0	0	1	0	0	0	0	3	-	-	-	-	
19	18-Jun-09	124.00	3.20	1145.00	4145.00	1	0	0	0	0	1	0	14	-	-	-	-	
19	4-Sep-09	137.00	3.45	1282.00	4282.00	1	0	1	0	0	0	0	11	-	-	-	-	
19	21-Jul-10	126.00	3.20	1408.00	4408.00	0	0	0	0	0	1	4	4	-	-	-	-	
19	8-Feb-11	127.00	3.18	1535.00	4535.00	0	0	1	0	0	1	0	8	-	-	-	-	
19	6-Dec-11	118.00	3.00	1653.00	4653.00	1	0	1	1	1	1	0	0	-	-	-	-	
19	11-Jan-12	125.00	3.20	1778.00	4778.00	0	0	0	0	0	0	0	1	-	-	-	-	
19	28-Mar-12	125.00	3.15	1903.00	4903.00	0	0	0	0	0	0	2	3	-	-	-	-	
19	13-Jun-12	109.50	3.00	2012.50	5012.50	0	0	0	1	0	1	0	1	-	-	-	-	
19	12-Jun-13	163.50	6.80	2176.00	5176.00	1	0	0	0	0	0	0	4	-	-	-	-	
19	28-Aug-13	114.00	2.84	2290.00	5290.00	2	0	1	0	0	1	0	12	-	-	-	-	
19	21-Nov-13	124.25	3.10	2414.25	5414.25	1	0	1	0	0	1	0	2	-	-	-	-	
19	20-Mar-14	125.00	3.10	2539.25	5539.25	1	0	0	0	0	1	0	0	-	-	-	-	
19	18-Nov-14	125.00	3.10	2664.25	5664.25	0	0	0	0	0	1	0	3	-	-	-	-	
19	12-Jun-15	125.20	3.10	2789.45	5789.45	1	0	1	0	0	1	0	14	-	-	-	-	

Figure 70 - Sheet Engine S/N 19

Appendix E - Engine Correlations from S/N 5 to S/N 19

Continuing with Correlations, the next engine analyzed is engine S/N 5.

It is shown in Figure 71, and another time, it exhibits variations in the results.

Negative correlations are shown for Date # by Al, Cr, Cu, and Mg, and positive correlations for Fe and Si.

The first time a positive correlation appears is among Fe by Cu, Mg, and Al. This could be in accordance with NAVAIR Table (Figure 5) for novelty in “Accessory bushing bearing turning in magnesium housing”.

Other details for the first test were made 714 hours after the last repair of the engine, and this was done at an unscheduled time (1570 hrs since new), being that, the schedule time for an overhaul is each 3000 hours of operation.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	0.028	#DIV/0!	-0.330	-0.555	-0.358	-0.014	#DIV/0!	0.604
<i>Month</i>	-0.362	#DIV/0!	0.235	0.017	-0.215	-0.736	#DIV/0!	-0.008
<i>Time between samples (Month)</i>	0.287	#DIV/0!	-0.217	-0.207	0.000	-0.155	#DIV/0!	0.622
<i>winter</i>	-0.052	#DIV/0!	0.069	0.203	0.346	-0.295	#DIV/0!	-0.695
<i>Spring</i>	0.029	#DIV/0!	0.386	-0.113	-0.194	-0.289	#DIV/0!	0.263
<i>Fall</i>	0.267	#DIV/0!	-0.356	-0.327	-0.149	0.869	#DIV/0!	0.468
<i>Long Time between Sample</i>	0.454	#DIV/0!	-0.214	-0.052	0.239	0.181	#DIV/0!	0.238
<i>Oil added Lts/Hr</i>	-0.221	#DIV/0!	-0.688	0.024	-0.099	0.369	#DIV/0!	0.588
<i># of refills</i>	0.128	#DIV/0!	-0.053	-0.157	-0.071	0.291	#DIV/0!	0.224
<i>Oil added Lts</i>	0.282	#DIV/0!	-0.072	-0.115	0.007	0.395	#DIV/0!	0.309
<i>Time Since last Repair</i>	0.008	#DIV/0!	-0.259	-0.724	-0.441	0.241	#DIV/0!	0.394
<i>Time Since New</i>	0.008	#DIV/0!	-0.259	-0.724	-0.441	0.241	#DIV/0!	0.394
<i>Fe</i>	1.000	#DIV/0!	0.428	0.392	0.671	0.293	#DIV/0!	0.178
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	0.341	0.418	-0.286	#DIV/0!	-0.412
<i>Cr</i>				1.000	0.745	-0.224	#DIV/0!	-0.229
<i>Cu</i>					1.000	-0.032	#DIV/0!	-0.124
<i>Mg</i>						1.000	#DIV/0!	0.256
<i>Ni</i>							1.000	#DIV/0!
<i>Si</i>								1.000

Figure 71 – Correlations among variables for Engine S/N 5

Figure 72 reveals that the engine starts the oil analysis program five periods later than it should be, after an overhaul or a reparation.

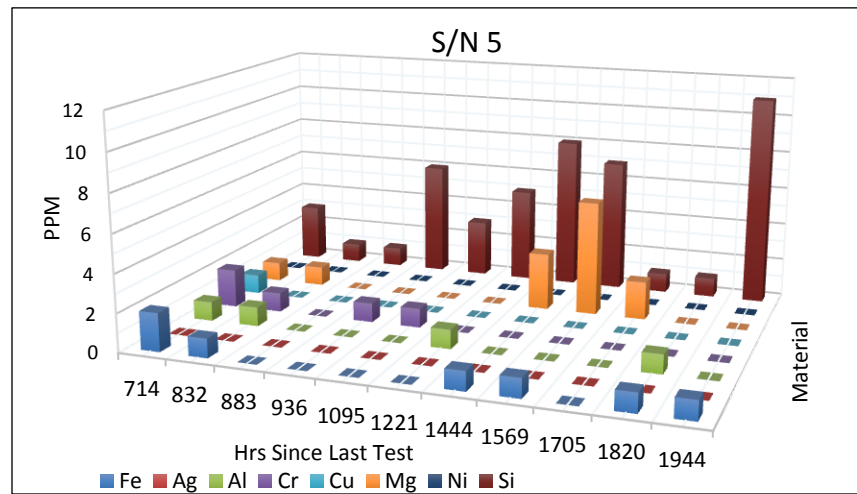


Figure 72 – PPM of material by Hours Since Last Repair S/N 5

Figure 73 displays the correlation among variables for engine S/N 6 and it exhibits positive correlation among Time Since Last Repair with Fe, and Mg, and negative correlation with Al, Cr, Ni, and Si. The correlation between Time Since Last Repair and Cr (-0.634) is one of the highest absolute values. This means that the concentration of Cr decreased with increases in the time of operation.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	0.094	#DIV/0!	-0.220	-0.527	#DIV/0!	0.072	-0.360	-0.479
<i>Month</i>	0.235	#DIV/0!	0.127	-0.598	#DIV/0!	0.100	-0.169	0.108
<i>Time between samples (Month)</i>	-0.279	#DIV/0!	-0.172	-0.097	#DIV/0!	0.869	-0.210	-0.335
<i>winter</i>	-0.344	#DIV/0!	0.320	-0.333	#DIV/0!	0.168	-0.240	0.265
<i>Spring</i>	-0.207	#DIV/0!	-0.077	-0.107	#DIV/0!	-0.118	-0.077	0.167
<i>Fall</i>	0.122	#DIV/0!	-0.113	-0.157	#DIV/0!	0.130	-0.113	-0.116
<i>Long Time between Sample</i>	-0.067	#DIV/0!	-0.372	0.019	#DIV/0!	0.316	-0.372	-0.647
<i>Oil added Lts/Hr</i>	0.170	#DIV/0!	0.076	0.221	#DIV/0!	0.305	-0.122	-0.108
<i># of refills</i>	0.421	#DIV/0!	0.087	-0.121	#DIV/0!	-0.266	-0.087	0.129
<i>Oil added Lts</i>	0.419	#DIV/0!	-0.007	-0.041	#DIV/0!	-0.220	-0.021	0.144
<i>Time Since last Repair</i>	0.080	#DIV/0!	-0.129	-0.634	#DIV/0!	0.022	-0.412	-0.374
<i>Time Since New</i>	0.080	#DIV/0!	-0.129	-0.634	#DIV/0!	0.022	-0.412	-0.374
<i>Fe</i>	1.000	#DIV/0!	-0.207	-0.019	#DIV/0!	0.016	0.372	-0.014
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	-0.107	#DIV/0!	-0.118	-0.077	0.536
<i>Cr</i>				1.000	#DIV/0!	-0.163	0.391	-0.053
<i>Cu</i>					1.000	#DIV/0!	#DIV/0!	#DIV/0!
<i>Mg</i>						1.000	-0.118	-0.215
<i>Ni</i>							1.000	0.536
<i>Si</i>								1.000

Figure 73 – Correlations among variables Engine S/N 6

In Figure 74, Si has 7 PPM as the highest value, and in general, the graph presents a great amount of variation in every parameter. This is not a good indicator of the procedure, nor for the program.

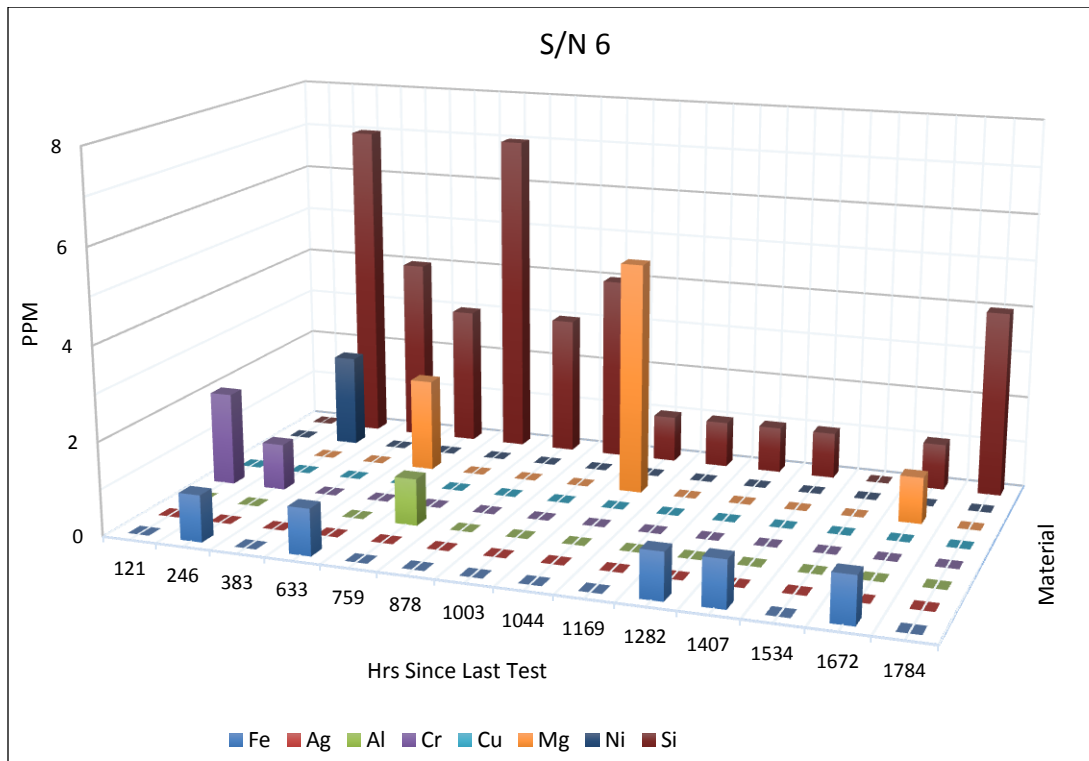


Figure 74 – PPM of material by Hours Since Last Repair S/N 6

The correlation in engine S/N 7 (Figure 75) has values similar to the engine S/N 6 with two differences. These are that Fe has a negative correlation with respect to Date # (positive in engine S/N 6) and that Si has a positive correlation (negative in S/N 6).

The variation in the concentration looks similar too. While S/N 6 has 14 tests (1784 hrs of operation), engine S/N 7 has 22, and it completed 3000 hours of operation, the maximum time of operation between overhauls.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
Date #	-0.121	#DIV/0!	-0.109	-0.491	-0.577	0.036	-0.653	0.136
Month	0.396	#DIV/0!	0.140	0.409	0.247	0.338	0.178	0.305
Time between samples (Month)	0.059	#DIV/0!	0.617	-0.059	-0.150	0.192	-0.053	0.012
winter	-0.198	#DIV/0!	-0.266	-0.216	-0.199	-0.365	-0.157	0.106
Spring	0.160	#DIV/0!	0.633	-0.100	-0.194	0.441	0.075	0.030
Fall	0.239	#DIV/0!	-0.302	-0.149	-0.024	0.224	0.112	-0.158
Long Time between Sample	-0.046	#DIV/0!	0.541	0.029	-0.149	0.377	0.098	-0.040
Oil added Lts/Hr	-0.272	#DIV/0!	-0.099	-0.201	-0.084	0.144	0.149	-0.067
# of refills	0.136	#DIV/0!	0.680	-0.085	-0.104	0.259	0.152	0.249
Oil added Lts	0.143	#DIV/0!	0.693	-0.133	-0.165	0.355	0.139	0.264
Time Since last Repair	-0.105	#DIV/0!	-0.114	-0.481	-0.591	0.051	-0.646	0.174
Time Since New	-0.105	#DIV/0!	-0.114	-0.481	-0.591	0.051	-0.646	0.174
Fe	1.000	#DIV/0!	0.027	0.160	0.121	0.434	0.212	0.141
Ag		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Al			1.000	-0.203	-0.033	0.304	-0.057	-0.050
Cr				1.000	0.516	-0.141	0.490	0.002
Cu					1.000	-0.399	0.548	-0.188
Mg						1.000	-0.077	0.200
Ni							1.000	0.044
Si								1.000

Figure 75 – Correlations among variables for Engine S/N 7

Figure 76 exhibits the performance of the engine S/N 7 in a complete period of operation between overhaul and overhaul (repair to repair), 3000 hours of flight, with high values of Si (within of parameter), and with low values of the others.

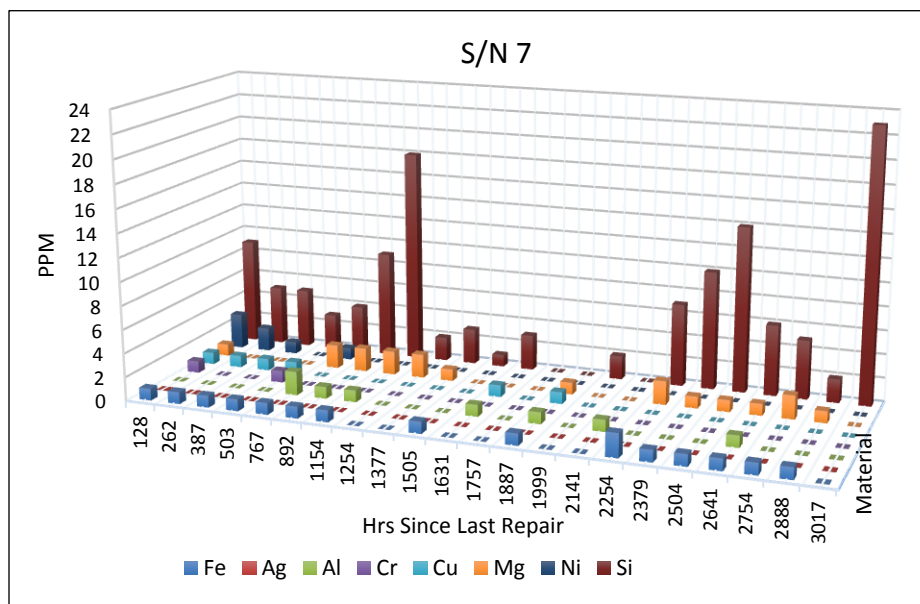


Figure 76 – PPM of material by Hours Since Last Repair S/N 7

Figure 77 demonstrates correlations in engine S/N 8 and shows similar correlations to S/N 7, positive with Date # / Mg, and Date # / Si, and negative correlations for the rest.

The highest correlation is Time Sence New related to Mg and the value is 0.7.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	-0.066	#DIV/0!	-0.534	-0.107	#DIV/0!	0.683	-0.410	0.172
<i>Month</i>	0.105	#DIV/0!	0.137	0.104	#DIV/0!	0.378	0.316	0.316
<i>Time between samples (Month)</i>	-0.026	#DIV/0!	-0.189	-0.115	#DIV/0!	0.071	-0.144	-0.021
<i>winter</i>	0.040	#DIV/0!	0.052	0.387	#DIV/0!	0.138	-0.161	0.110
<i>Spring</i>	0.107	#DIV/0!	-0.097	-0.139	#DIV/0!	0.485	0.451	0.423
<i>Fall</i>	0.107	#DIV/0!	-0.097	-0.139	#DIV/0!	-0.202	-0.139	-0.219
<i>Long Time between Sample</i>	0.240	#DIV/0!	-0.096	-0.209	#DIV/0!	0.534	-0.209	0.362
<i>Oil added Lts/Hr</i>	0.138	#DIV/0!	-0.251	-0.315	#DIV/0!	0.419	0.074	0.403
<i># of refills</i>	-0.173	#DIV/0!	-0.224	-0.145	#DIV/0!	0.028	0.009	-0.115
<i>Oil added Lts</i>	-0.169	#DIV/0!	-0.250	-0.126	#DIV/0!	0.049	-0.087	-0.027
<i>Time Since last Repair</i>	-0.055	#DIV/0!	-0.522	-0.139	#DIV/0!	0.700	-0.374	0.165
<i>Time Since New</i>	-0.055	#DIV/0!	-0.522	-0.139	#DIV/0!	0.700	-0.374	0.165
<i>Fe</i>	1.000	#DIV/0!	0.247	-0.116	#DIV/0!	0.405	-0.116	-0.021
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	-0.150	#DIV/0!	-0.466	0.275	-0.166
<i>Cr</i>				1.000	#DIV/0!	-0.194	-0.063	-0.065
<i>Cu</i>					1.000	#DIV/0!	#DIV/0!	#DIV/0!
<i>Mg</i>						1.000	-0.194	0.405
<i>Ni</i>							1.000	-0.065
<i>Si</i>								1.000

Figure 77 – Correlations among variables for Engine S/N 8

The explanation for such a correlation seems to be that magnesium tends to stabilize over time (Figure 78) while the others continue to have oscilations.

The largest amount of silicon was 40 parts per million (1459 hrs) and at no time was the oil change registered in the engine. Only oil added was recorded and that did not exceed 0.026 Ltr/hr.

The large change in the amount of silicon in the sample of 1459 hours (40 PPM) and 1583 hours (0 PPM) is not reflected in any register and this shows a great deficiency in the application of the program.

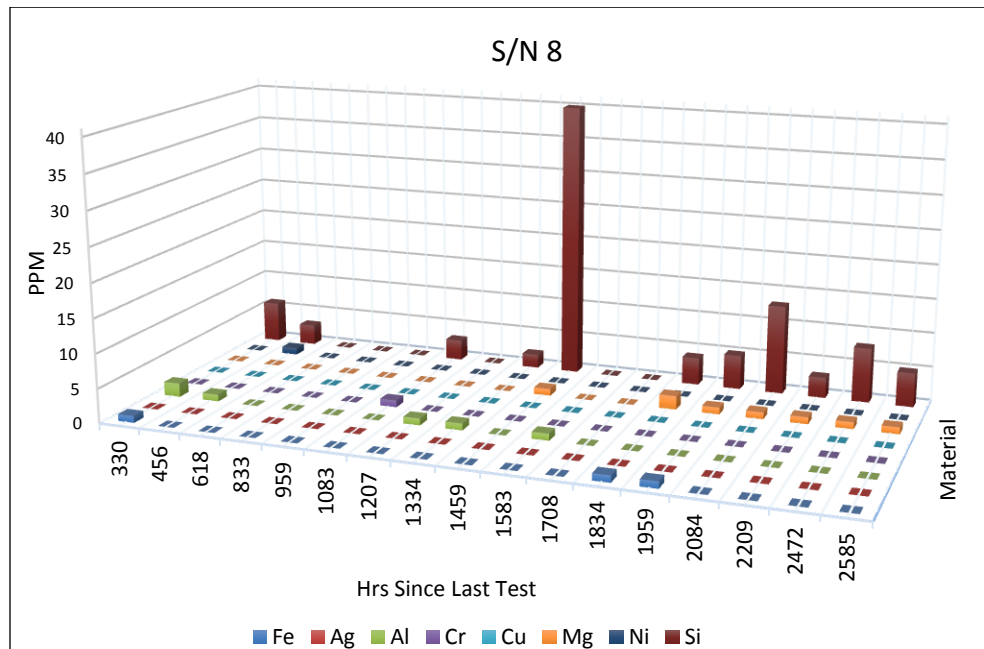


Figure 78 – PPM of material by Hours Since Last Repair S/N 8

Figure 79 presents the correlations for engine S/N 9, and one detail could be the correlation between Oil Added Lts/Hr and Si that is 0.774. The reason for this could be the short time between samples (in test 6 - 58 hrs) and the large amount of oil added (0.0594 Lts/Hr) and Si (21 PPM) too.

In this case, the mix variability in sampling and the lack of a record of the activities performed on the engine are presented. The variability of the samples in some cases are justified by issues in the results, and others are not.

This is not exclusive to this engine; it is applicable to the entire program.

The correlation between Spring and Si (0.699) is difficult to explain since, the program will need to require periodic sampling to define if some pattern of seasonality exists. On average, the sample is taken every seven months, and for defining the season relationships, it is necessary to make samples more frequently.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	0.615	#DIV/0!	0.615	#DIV/0!	#DIV/0!	-0.010	0.094	-0.375
<i>Month</i>	-0.171	#DIV/0!	-0.171	#DIV/0!	#DIV/0!	0.262	-0.007	0.523
<i>Time between samples (Month)</i>	0.142	#DIV/0!	0.142	#DIV/0!	#DIV/0!	-0.009	-0.380	-0.392
<i>winter</i>	0.220	#DIV/0!	0.220	#DIV/0!	#DIV/0!	0.361	0.365	-0.005
<i>Spring</i>	0.033	#DIV/0!	0.033	#DIV/0!	#DIV/0!	-0.081	-0.123	0.699
<i>Fall</i>	-0.141	#DIV/0!	-0.141	#DIV/0!	#DIV/0!	-0.208	-0.158	-0.297
<i>Long Time between Sample</i>	0.225	#DIV/0!	0.225	#DIV/0!	#DIV/0!	-0.139	-0.158	-0.194
<i>Oil added Lts/Hr</i>	-0.193	#DIV/0!	-0.193	#DIV/0!	#DIV/0!	-0.063	-0.035	0.774
<i># of refills</i>	0.151	#DIV/0!	0.151	#DIV/0!	#DIV/0!	0.020	0.015	-0.316
<i>Oil added Lts</i>	-0.301	#DIV/0!	-0.301	#DIV/0!	#DIV/0!	0.207	0.185	0.352
<i>Time Since last Repair</i>	0.657	#DIV/0!	0.657	#DIV/0!	#DIV/0!	-0.054	0.184	-0.002
<i>Time Since New</i>	0.657	#DIV/0!	0.657	#DIV/0!	#DIV/0!	-0.054	0.184	-0.002
<i>Fe</i>	1.000	#DIV/0!	1.000	#DIV/0!	#DIV/0!	-0.235	0.312	-0.242
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	#DIV/0!	#DIV/0!	-0.235	0.312	-0.242
<i>Cr</i>				1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Cu</i>					1.000	#DIV/0!	#DIV/0!	#DIV/0!
<i>Mg</i>						1.000	0.000	0.257
<i>Ni</i>							1.000	0.041
<i>Si</i>								1.000

Figure 79 – Correlations among variables for Engine S/N 9

According to the Air Force Logistics Center Depot for some engines with more than 20 PPM, the user would have to have changed oil when Si reached 21 PPM (Figure 80).

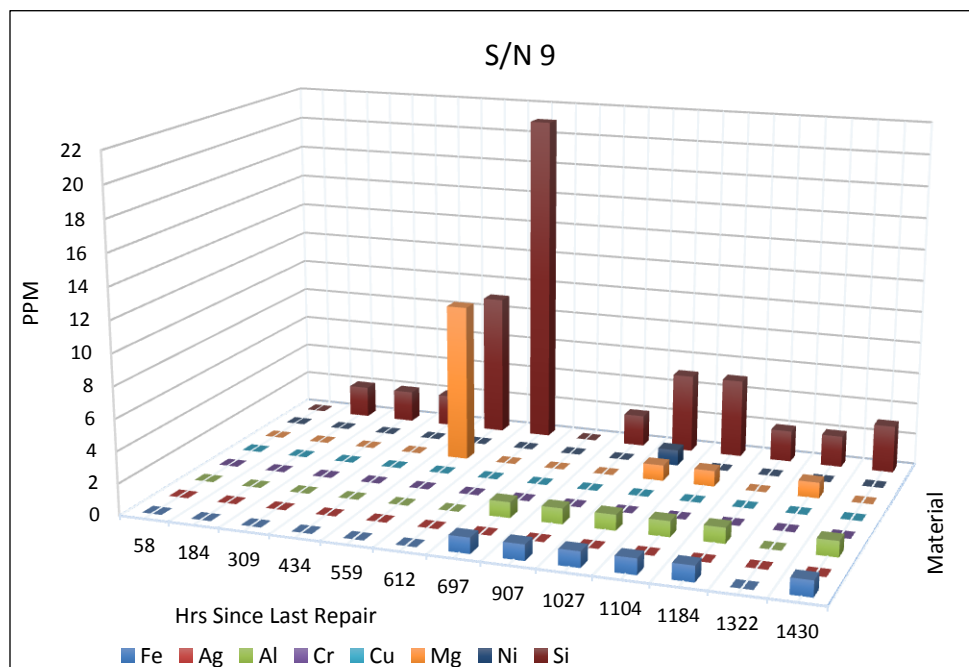


Figure 80 – PPM of material by Hours Since Last Repair S/N 9

Figure 81 – Correlations among variables for engine S/N 10 shows the highest value between Si and Cr (0.906) and this is because the higher silicon value matches with the higher Cr value (Figure 82).

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	#DIV/0!	#DIV/0!	0.022	-0.089	#DIV/0!	-0.252	#DIV/0!	-0.350
<i>Month</i>	#DIV/0!	#DIV/0!	0.373	-0.142	#DIV/0!	-0.091	#DIV/0!	-0.166
<i>Time between samples (Month)</i>	#DIV/0!	#DIV/0!	-0.154	-0.086	#DIV/0!	-0.380	#DIV/0!	-0.380
<i>winter</i>	#DIV/0!	#DIV/0!	-0.293	0.488	#DIV/0!	0.127	#DIV/0!	0.481
<i>Spring</i>	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Fall</i>	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Long Time between Sample</i>	#DIV/0!	#DIV/0!	0.218	0.218	#DIV/0!	-0.398	#DIV/0!	0.154
<i>Oil added Lts/Hr</i>	#DIV/0!	#DIV/0!	-0.610	0.030	#DIV/0!	0.353	#DIV/0!	-0.191
<i># of refills</i>	#DIV/0!	#DIV/0!	-0.048	-0.048	#DIV/0!	-0.513	#DIV/0!	-0.146
<i>Oil added Lts</i>	#DIV/0!	#DIV/0!	-0.139	-0.117	#DIV/0!	-0.424	#DIV/0!	-0.238
<i>Time Since last Repair</i>	#DIV/0!	#DIV/0!	0.092	-0.077	#DIV/0!	-0.162	#DIV/0!	-0.289
<i>Time Since New</i>	#DIV/0!	#DIV/0!	0.092	-0.077	#DIV/0!	-0.162	#DIV/0!	-0.289
<i>Fe</i>	1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	-0.143	#DIV/0!	-0.335	#DIV/0!	0.101
<i>Cr</i>				1.000	#DIV/0!	-0.335	#DIV/0!	0.906
<i>Cu</i>					1.000	#DIV/0!	#DIV/0!	#DIV/0!
<i>Mg</i>						1.000	#DIV/0!	-0.393
<i>Ni</i>							1.000	#DIV/0!
<i>Si</i>								1.000

Figure 81 – Correlations among variables for Engine S/N 10

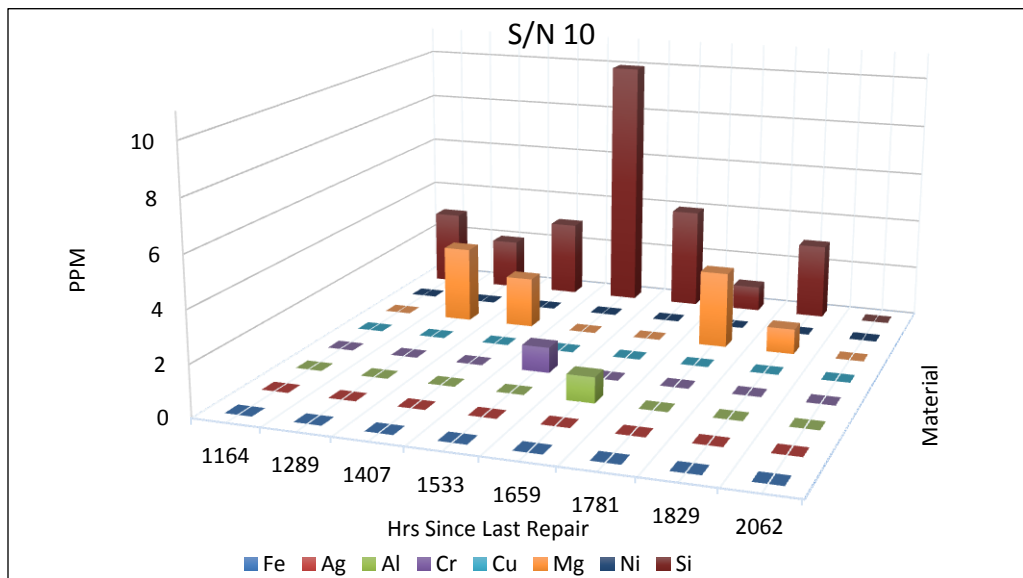


Figure 82 – PPM of material by Hours Since Last Repair S/N 10

S/N 10 is the second engine with more variability in sampling (Figure 15).

The correlation in engine S/N 11 is shown in Figure 83. It does not demonstrate clear correlations, only negative correlations among Date # and Fe, Al, and Ni, and positive correlations with Mg, and Si. The explanation is that the last two correlations presented have higher values in the last part of samples.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	-0.494	#DIV/0!	-0.449	#DIV/0!	#DIV/0!	0.215	-0.382	0.343
<i>Month</i>	0.361	#DIV/0!	0.384	#DIV/0!	#DIV/0!	0.208	0.098	0.381
<i>Time between samples (Month)</i>	0.058	#DIV/0!	0.070	#DIV/0!	#DIV/0!	-0.068	-0.190	0.299
<i>winter</i>	0.163	#DIV/0!	-0.163	#DIV/0!	#DIV/0!	0.344	0.098	-0.144
<i>Spring</i>	0.228	#DIV/0!	0.816	#DIV/0!	#DIV/0!	0.023	0.683	-0.044
<i>Fall</i>	-0.222	#DIV/0!	-0.101	#DIV/0!	#DIV/0!	-0.185	-0.182	-0.146
<i>Long Time between Sample</i>	-0.098	#DIV/0!	-0.163	#DIV/0!	#DIV/0!	-0.206	-0.293	0.284
<i>Oil added Lts/Hr</i>	0.489	#DIV/0!	0.322	#DIV/0!	#DIV/0!	-0.001	0.001	-0.658
<i># of refills</i>	-0.217	#DIV/0!	0.086	#DIV/0!	#DIV/0!	-0.022	0.505	-0.027
<i>Oil added Lts</i>	-0.200	#DIV/0!	0.105	#DIV/0!	#DIV/0!	-0.080	0.497	-0.103
<i>Time Since last Repair</i>	-0.455	#DIV/0!	-0.429	#DIV/0!	#DIV/0!	0.240	-0.337	0.298
<i>Time Since New</i>	-0.455	#DIV/0!	-0.429	#DIV/0!	#DIV/0!	0.240	-0.337	0.298
<i>Fe</i>	1.000	#DIV/0!	0.558	#DIV/0!	#DIV/0!	0.369	0.333	-0.293
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	#DIV/0!	#DIV/0!	-0.056	0.478	-0.155
<i>Cr</i>				1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Cu</i>					1.000	#DIV/0!	#DIV/0!	#DIV/0!
<i>Mg</i>						1.000	0.034	0.002
<i>Ni</i>							1.000	-0.045
<i>Si</i>								1.000

Figure 83 – Correlations among variables for Engine S/N 11

It is very important to note that S/N 11 is the third engine with more variability in sampling (Figure 15).

It does not present large values in general (Figure 84), although the Si reaches 42 PPM in 2523 Hours since the last repair. Nowhere is there registered the changing of oil; only refill was registered.

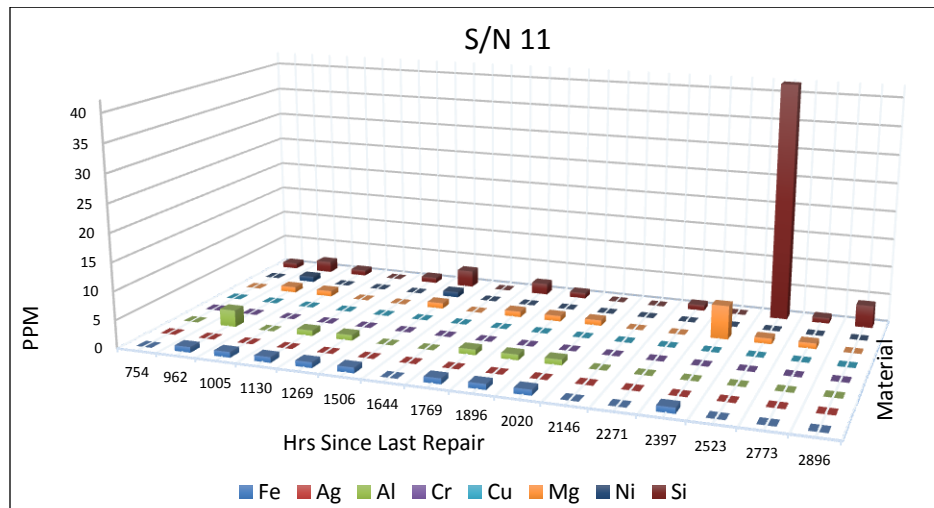


Figure 84 – PPM of material by Hours Since Last Repair S/N 11

Engine S/N 12 (Figure 85) has all positive correlations among Date # and every material, and this is a good sign that the procedure was applied to the program.

It had a good procedure of sampling, exactly in the average value (Figure 15 – Analysis of Means for Variances in Sampling).

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	0.283	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.068	0.922	0.346
<i>Month</i>	0.309	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.591	-0.087	0.423
<i>Time between samples (Month)</i>	0.157	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	-0.297	0.985	0.081
<i>winter</i>	0.333	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	-0.311	0.655	0.000
<i>Spring</i>	-0.655	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.339	-0.143	-0.236
<i>Fall</i>	0.218	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	-0.204	-0.143	-0.079
<i>Long Time between Sample</i>	-0.149	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	-0.417	0.488	-0.215
<i>Oil added Lts/Hr</i>	0.341	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	-0.674	-0.334	-0.537
<i># of refills</i>	-0.548	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	-0.114	-0.239	-0.099
<i>Oil added Lts</i>	-0.607	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	-0.220	-0.173	-0.228
<i>Time Since last Repair</i>	-0.106	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	-0.363	-0.186	-0.353
<i>Time Since New</i>	0.260	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.509	0.579	0.595
<i>Fe</i>	1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	-0.104	0.218	0.361
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Cr</i>				1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Cu</i>					1.000	#DIV/0!	#DIV/0!	#DIV/0!
<i>Mg</i>						1.000	-0.204	0.786
<i>Ni</i>							1.000	0.158
<i>Si</i>								1.000

Figure 85 – Correlations among variables for Engine S/N 12

The procedure looks good considering the variability of sampling but it starts late (Figure 86) after about 2031 hours of operation.

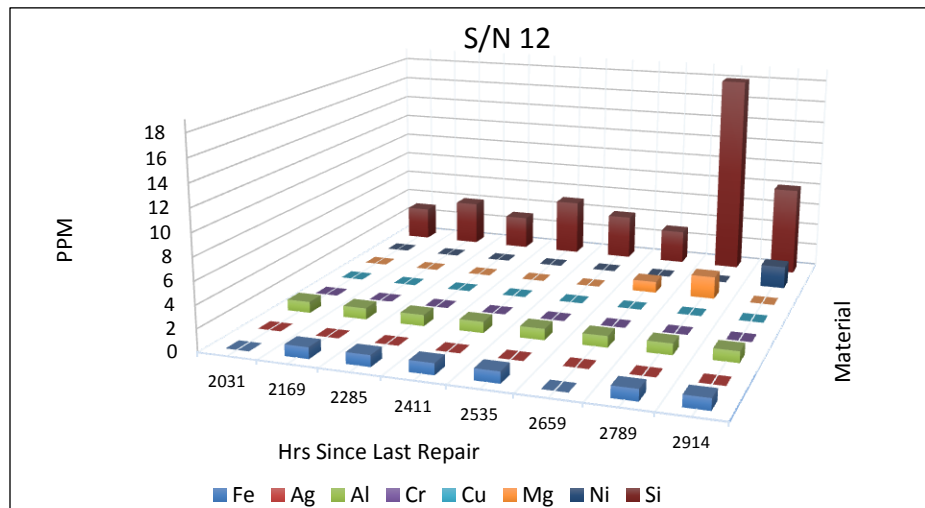


Figure 86 – PPM of material by Hours Since Last Repair S/N 12

Engine S/N 13 has correlations (Figure 87) similar to S/N 12, with values higher in Si and Mg than the previous engine.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	0.518	#DIV/0!	0.116	#DIV/0!	#DIV/0!	0.771	#DIV/0!	0.924
<i>Month</i>	0.012	#DIV/0!	-0.532	#DIV/0!	#DIV/0!	0.085	#DIV/0!	0.015
<i>Time between samples (Month)</i>	0.015	#DIV/0!	-0.342	#DIV/0!	#DIV/0!	-0.133	#DIV/0!	-0.152
<i>winter</i>	0.118	#DIV/0!	0.044	#DIV/0!	#DIV/0!	0.039	#DIV/0!	0.153
<i>Spring</i>	-0.065	#DIV/0!	0.022	#DIV/0!	#DIV/0!	-0.198	#DIV/0!	-0.044
<i>Fall</i>	0.306	#DIV/0!	0.022	#DIV/0!	#DIV/0!	0.128	#DIV/0!	-0.016
<i>Long Time between Sample</i>	-0.118	#DIV/0!	-0.044	#DIV/0!	#DIV/0!	-0.112	#DIV/0!	-0.227
<i>Oil added Lts/Hr</i>	0.001	#DIV/0!	0.148	#DIV/0!	#DIV/0!	0.195	#DIV/0!	0.303
<i># of refills</i>	0.140	#DIV/0!	-0.019	#DIV/0!	#DIV/0!	-0.280	#DIV/0!	-0.204
<i>Oil added Lts</i>	0.096	#DIV/0!	0.069	#DIV/0!	#DIV/0!	-0.290	#DIV/0!	-0.195
<i>Time Since last Repair</i>	0.530	#DIV/0!	0.158	#DIV/0!	#DIV/0!	0.794	#DIV/0!	0.904
<i>Time Since New</i>	0.530	#DIV/0!	0.158	#DIV/0!	#DIV/0!	0.794	#DIV/0!	0.904
<i>Fe</i>	1.000	#DIV/0!	0.310	#DIV/0!	#DIV/0!	0.560	#DIV/0!	0.614
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	#DIV/0!	#DIV/0!	-0.021	#DIV/0!	0.083
<i>Cr</i>				1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Cu</i>					1.000	#DIV/0!	#DIV/0!	#DIV/0!
<i>Mg</i>						1.000	#DIV/0!	0.733
<i>Ni</i>							1.000	#DIV/0!
<i>Si</i>								1.000

Figure 87 – Correlations among variables for Engine S/N 13

Figure 88 presents the evolution of the wear material, with all values less than the limit permitted, and an increased value of Si in the last seven tests with oscillation possibly due to the oil added between samples.

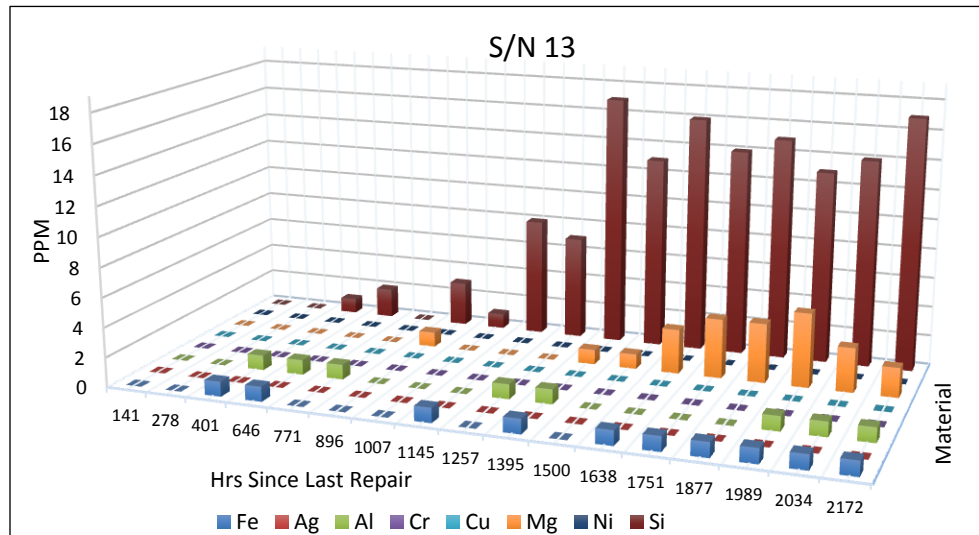


Figure 88 – PPM of material by Hours Since Last Repair S/N 13

Engine S/N 14 has the second best sampling procedure with 13 samples and the table of correlations (Figure 89) does not show high values and Date # by Fe, Al, and Cr are negative correlations, while Date # by Mg and Si are positives.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	-0.304	#DIV/0!	-0.863	-0.394	#DIV/0!	0.265	#DIV/0!	0.151
<i>Month</i>	0.436	#DIV/0!	0.451	0.289	#DIV/0!	0.553	#DIV/0!	-0.022
<i>Time between samples (Month)</i>	-0.297	#DIV/0!	-0.763	-0.215	#DIV/0!	-0.077	#DIV/0!	-0.013
<i>winter</i>	-0.228	#DIV/0!	0.415	0.101	#DIV/0!	-0.109	#DIV/0!	0.425
<i>Spring</i>	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Fall</i>	-0.158	#DIV/0!	-0.592	-0.234	#DIV/0!	-0.292	#DIV/0!	-0.106
<i>Long Time between Sample</i>	-0.527	#DIV/0!	-0.507	-0.272	#DIV/0!	0.292	#DIV/0!	0.135
<i>Oil added Lts/Hr</i>	0.243	#DIV/0!	-0.182	0.314	#DIV/0!	0.200	#DIV/0!	0.098
<i># of refills</i>	0.267	#DIV/0!	0.071	-0.033	#DIV/0!	0.494	#DIV/0!	0.156
<i>Oil added Lts</i>	0.142	#DIV/0!	0.011	0.004	#DIV/0!	0.580	#DIV/0!	0.050
<i>Time Since last Repair</i>	-0.305	#DIV/0!	-0.860	-0.395	#DIV/0!	0.254	#DIV/0!	0.219
<i>Time Since New</i>	-0.305	#DIV/0!	-0.860	-0.395	#DIV/0!	0.254	#DIV/0!	0.219
<i>Fe</i>	1.000	#DIV/0!	0.267	0.677	#DIV/0!	-0.154	#DIV/0!	-0.220
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	0.395	#DIV/0!	0.035	#DIV/0!	0.084
<i>Cr</i>				1.000	#DIV/0!	-0.228	#DIV/0!	-0.259
<i>Cu</i>					1.000	#DIV/0!	#DIV/0!	#DIV/0!
<i>Mg</i>						1.000	#DIV/0!	0.455
<i>Ni</i>							1.000	#DIV/0!
<i>Si</i>								1.000

Figure 89 – Correlations among variables for Engine S/N 14

Figure 90 graphs a high increase in Si in the sample of 767 hours and important decrease in the next test. The registered data does not have any change of oil, only 3.1 Lts added between samples (1/3 part of the tank capacity).

In another case, the procedure could have been to change all the oil in the lubrication circuit.

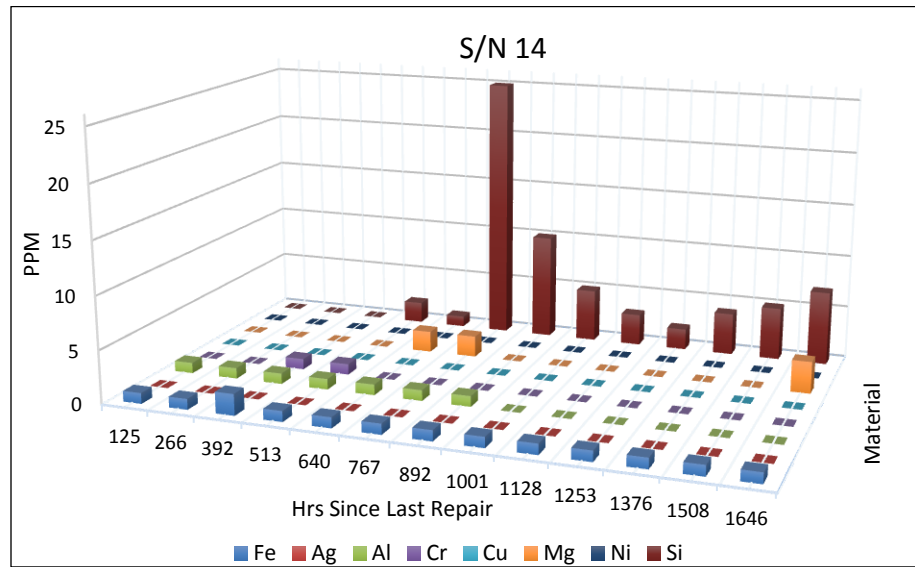


Figure 90 – PPM of material by Hours Since Last Repair S/N 14

Figure 91 - Correlations among variables for Engine S/N 15 present similar behavior as that for the previous engine, with the highest value of 0.521 of correlation between Date # and Si.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	-0.050	#DIV/0!	-0.229	-0.177	#DIV/0!	0.441	-0.152	0.521
<i>Month</i>	-0.027	#DIV/0!	0.248	-0.035	#DIV/0!	0.339	0.124	0.253
<i>Time between samples (Month)</i>	0.128	#DIV/0!	-0.143	-0.087	#DIV/0!	0.156	-0.085	0.356
<i>winter</i>	-0.234	#DIV/0!	-0.275	0.384	#DIV/0!	-0.311	0.212	0.088
<i>Spring</i>	0.282	#DIV/0!	-0.176	-0.109	#DIV/0!	0.368	-0.116	0.218
<i>Fall</i>	0.337	#DIV/0!	-0.119	-0.074	#DIV/0!	0.249	-0.079	-0.113
<i>Long Time between Sample</i>	0.078	#DIV/0!	-0.176	0.128	#DIV/0!	-0.091	0.091	0.204
<i>Oil added Lts/Hr</i>	-0.186	#DIV/0!	0.150	0.131	#DIV/0!	-0.300	0.052	-0.496
<i># of refills</i>	-0.048	#DIV/0!	0.090	0.025	#DIV/0!	-0.448	0.027	-0.322
<i>Oil added Lts</i>	0.030	#DIV/0!	0.193	0.115	#DIV/0!	-0.463	0.107	-0.416
<i>Time Since last Repair</i>	0.128	#DIV/0!	-0.153	-0.235	#DIV/0!	0.186	-0.270	-0.133
<i>Time Since New</i>	0.131	#DIV/0!	-0.153	-0.236	#DIV/0!	0.183	-0.272	-0.137
<i>Fe</i>	1.000	#DIV/0!	-0.114	-0.090	#DIV/0!	0.418	-0.234	-0.009
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	-0.105	#DIV/0!	-0.166	0.305	-0.158
<i>Cr</i>				1.000	#DIV/0!	-0.157	0.838	-0.010
<i>Cu</i>					1.000	#DIV/0!	#DIV/0!	#DIV/0!
<i>Mg</i>						1.000	-0.140	0.389
<i>Ni</i>							1.000	-0.037
<i>Si</i>								1.000

Figure 91 – Correlations among variables for Engine S/N 15

Figure 92 displays two hours of differences between samples (706 and 708 Hrs), but the explanation of the reasons is not present in the registers, although the engine was unused for more than four years. The increase may then be linked to improper preservation of the engine, or if it was inhibited, it was done in a negative way or the process for return to service was poor.

The oil added covers the consumption between samples, not change of oil for this engine.

The increase of Si was from 1 to 44 PPM (706 / 708 Hrs), 44 to 51 PPM (708 / 767 hrs) and 51 to 59 PPM (767 / 894 Hrs), and the oil was never changed completely because of contamination.

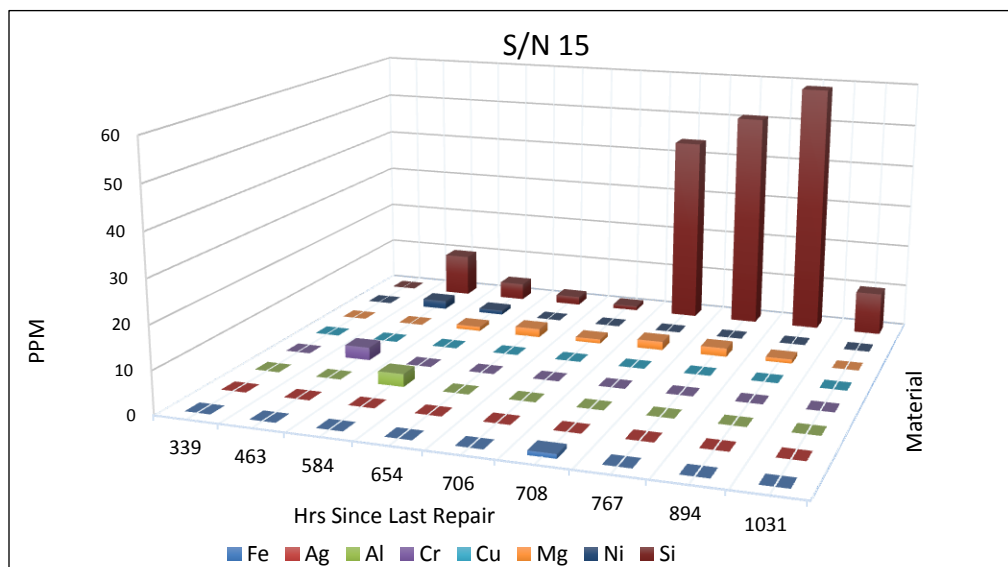


Figure 92 – PPM of material by Hours Since Last Repair S/N 15

The most stable process of sampling was done in engine S/N 16 and the correlation is presented in Figure 93.

The highest value of correlation is Spring by Si (0.546), but this indicator is not a good reference in an engine sampled every 7 months on average. Negative correlations

are between Date # / Al, and Date # / Cr, and positive correlations are among Date # / Ni, and Date # / Si.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	0.000	#DIV/0!	-0.247	-0.201	#DIV/0!	0.502	#DIV/0!	0.324
<i>Month</i>	-0.056	#DIV/0!	-0.010	-0.078	#DIV/0!	0.276	#DIV/0!	0.081
<i>Time between samples (Month)</i>	-0.184	#DIV/0!	-0.138	-0.158	#DIV/0!	-0.022	#DIV/0!	0.277
<i>winter</i>	-0.099	#DIV/0!	-0.308	0.451	#DIV/0!	-0.263	#DIV/0!	-0.074
<i>Spring</i>	0.074	#DIV/0!	-0.257	-0.116	#DIV/0!	0.380	#DIV/0!	0.546
<i>Fall</i>	0.306	#DIV/0!	-0.203	-0.091	#DIV/0!	0.373	#DIV/0!	-0.072
<i>Long Time between Sample</i>	0.070	#DIV/0!	0.033	-0.236	#DIV/0!	0.116	#DIV/0!	0.331
<i>Oil added Lts/Hr</i>	0.008	#DIV/0!	0.395	0.431	#DIV/0!	-0.115	#DIV/0!	0.253
<i># of refills</i>	-0.383	#DIV/0!	-0.119	-0.185	#DIV/0!	-0.130	#DIV/0!	0.077
<i>Oil added Lts</i>	-0.282	#DIV/0!	0.467	0.084	#DIV/0!	-0.355	#DIV/0!	0.235
<i>Time Since last Repair</i>	-0.151	#DIV/0!	-0.197	-0.207	#DIV/0!	0.386	#DIV/0!	0.122
<i>Time Since New</i>	-0.151	#DIV/0!	-0.197	-0.207	#DIV/0!	0.386	#DIV/0!	0.122
<i>Fe</i>	1.000	#DIV/0!	-0.099	0.209	#DIV/0!	0.648	#DIV/0!	0.535
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	-0.139	#DIV/0!	-0.429	#DIV/0!	-0.074
<i>Cr</i>				1.000	#DIV/0!	0.106	#DIV/0!	0.209
<i>Cu</i>					1.000	#DIV/0!	#DIV/0!	#DIV/0!
<i>Mg</i>						1.000	#DIV/0!	0.428
<i>Ni</i>							1.000	#DIV/0!
<i>Si</i>								1.000

Figure 93 – Correlations among variables for Engine S/N 16

Figure 94 demonstrates oscillations in concentrations between samples, and it could probably reflect the refilling of clean oil of approximately one third the total among samples.

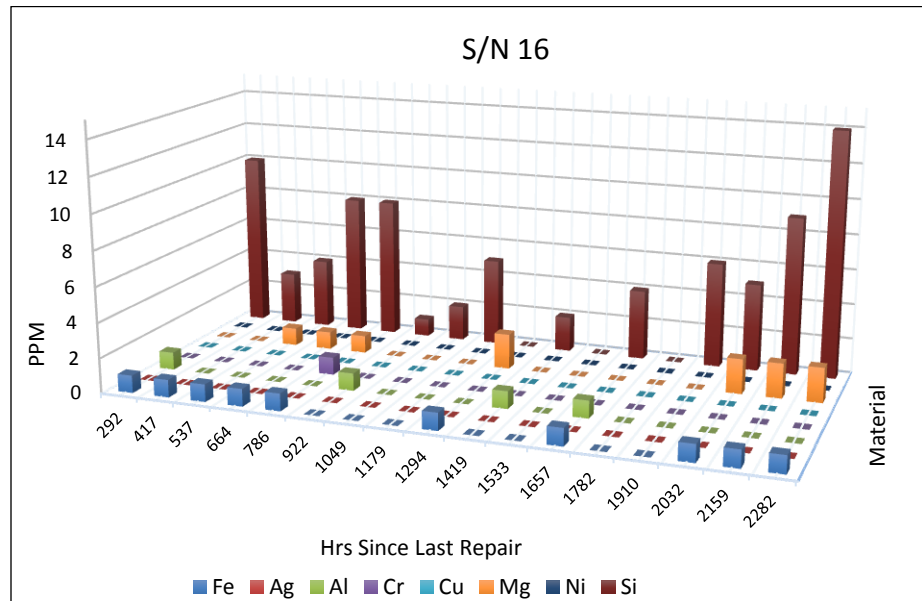


Figure 94 – PPM of material by Hours Since Last Repair S/N 16

Correlations among variables in engine S/N 17 are shown in Figure 95, and only one correlation is positive with Date #, which is Date # in relation to Mg, and the value is close to zero.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	-0.072	#DIV/0!	-0.395	-0.432	-0.259	0.093	-0.469	-0.232
<i>Month</i>	-0.116	#DIV/0!	0.501	0.231	0.337	0.136	-0.299	0.396
<i>Time between samples (Month)</i>	-0.144	#DIV/0!	0.171	-0.103	0.383	-0.223	0.000	0.399
<i>winter</i>	-0.015	#DIV/0!	-0.263	-0.209	-0.209	0.278	-0.209	-0.130
<i>Spring</i>	0.040	#DIV/0!	0.678	0.540	0.540	0.029	-0.116	0.483
<i>Fall</i>	0.040	#DIV/0!	-0.316	-0.116	-0.116	-0.095	0.540	-0.177
<i>Long Time between Sample</i>	-0.064	#DIV/0!	0.187	0.185	0.185	-0.245	0.185	0.153
<i>Oil added Lts/Hr</i>	-0.159	#DIV/0!	0.039	-0.015	0.333	0.429	-0.226	0.446
<i># of refills</i>	-0.178	#DIV/0!	0.437	0.590	-0.126	0.059	-0.126	-0.107
<i>Oil added Lts</i>	-0.263	#DIV/0!	0.403	0.605	-0.079	0.124	-0.104	-0.055
<i>Time Since last Repair</i>	-0.007	#DIV/0!	-0.317	-0.340	-0.246	0.148	-0.427	-0.219
<i>Time Since New</i>	-0.007	#DIV/0!	-0.317	-0.340	-0.246	0.148	-0.427	-0.219
<i>Fe</i>	1.000	#DIV/0!	0.225	-0.161	-0.161	-0.098	0.387	-0.193
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	0.796	0.152	0.165	-0.171	0.157
<i>Cr</i>				1.000	-0.063	0.285	-0.063	-0.056
<i>Cu</i>					1.000	-0.119	-0.063	0.966
<i>Mg</i>						1.000	-0.119	0.097
<i>Ni</i>							1.000	-0.103
<i>Si</i>								1.000

Figure 95 – Correlations among variables for Engine S/N 17

Figure 96 graphs the maximum value of Si (46 PPM) in the test of 1107 hours and no change of oil is recorded. The others have values inside of the parameters and they do not present issues for the engine.

The program in this engine started 5 periods later (623 hours) after the last repair.

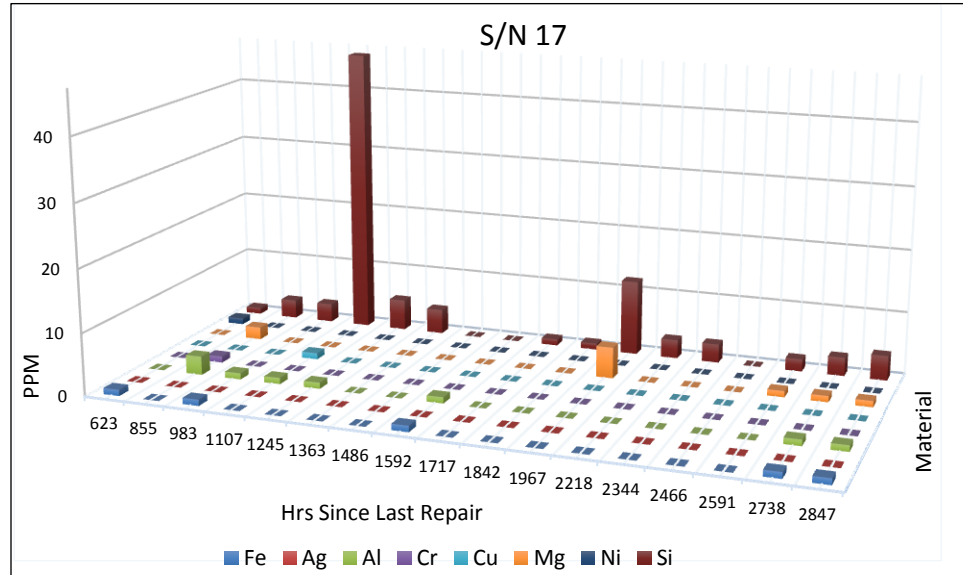


Figure 96 – PPM of material by Hours Since Last Repair S/N 17

The table of correlations for engine S/N 18 is presented in Figure 97. Positive correlations are in Date # with Mg, Ni, and Si, and negative correlations in Date # by Fe, Al, Cr, and Cu.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
Date #	-0.260	#DIV/0!	-0.517	-0.194	-0.351	0.567	0.103	0.710
Month	-0.280	#DIV/0!	-0.611	-0.222	0.033	0.231	-0.146	0.318
Time between samples (Month)	-0.066	#DIV/0!	0.000	-0.102	-0.025	-0.266	-0.053	0.267
winter	-0.043	#DIV/0!	-0.207	0.122	0.372	-0.520	0.434	-0.388
Spring	-0.101	#DIV/0!	-0.145	-0.213	-0.145	0.268	-0.169	0.063
Fall	0.059	#DIV/0!	-0.113	0.417	-0.113	0.248	-0.132	0.394
Long Time between Sample	0.577	#DIV/0!	0.277	0.000	0.277	-0.162	0.323	-0.410
Oil added Lts/Hr	-0.243	#DIV/0!	-0.064	0.688	-0.062	-0.287	-0.074	0.317
# of refills	0.132	#DIV/0!	0.191	0.117	-0.032	0.102	0.185	-0.538
Oil added Lts	0.003	#DIV/0!	0.016	0.545	-0.002	-0.028	0.016	-0.077
Time Since last Repair	0.562	#DIV/0!	0.369	0.140	0.469	-0.194	-0.106	-0.801
Time Since New	0.078	#DIV/0!	-0.441	-0.247	-0.214	0.791	0.057	0.449
Fe	1.000	#DIV/0!	0.320	0.059	0.320	0.281	-0.187	-0.359
Ag		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Al			1.000	-0.113	-0.077	-0.225	-0.090	-0.341
Cr				1.000	0.679	-0.331	0.000	0.049
Cu					1.000	-0.225	0.090	-0.294
Mg						1.000	-0.105	0.242
Ni							1.000	-0.390
Si								1.000

Figure 97 – Correlations among variables for Engine S/N 18

Figure 98 (Correlations among variables for Engine S/N 18) indicates the presence of silicon higher than the rest of the materials. Although nickel is the component to which more attention is necessary, seeing that the limit value (abnormal range) for Ni is more than 9 PPM and the value in the test of 514 hours since last repair is 12 PPM. No record of this issue is displayed anywhere.

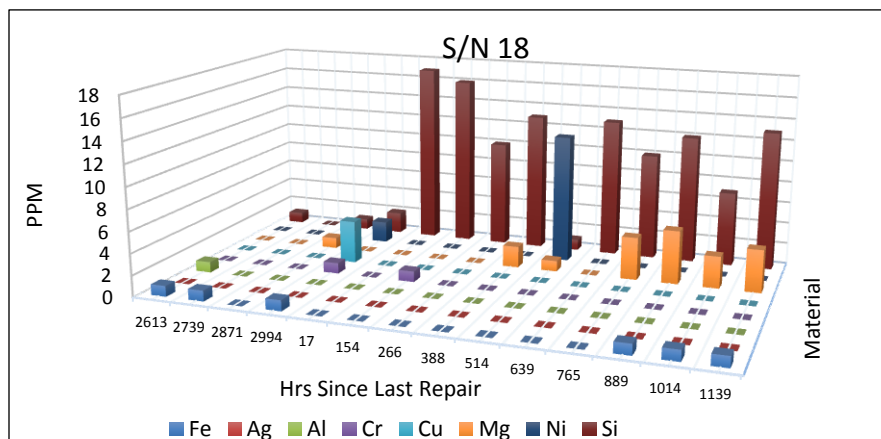


Figure 98 – PPM of material by Hours Since Last Repair S/N 18

The third engine with the best procedure of extracting is S/N 19, and the correlation is shown in Figure 99.

While in an ideal condition of operation and wear, the correlation should be positive between Date # and each wear material analyzed, (for longer operating time, greater concentration of particles in the oil circuit), in the case of most of the engines, alternate positive and negative values of correlations are presented for Date # with Fe, Al, Cu and Si being negatives, while positive values for Cr, Mg and Si are presented.

	Fe	Ag	Al	Cr	Cu	Mg	Ni	Si
<i>Date #</i>	-0.301	#DIV/0!	-0.160	0.177	-0.278	0.044	-0.185	0.117
<i>Month</i>	-0.158	#DIV/0!	0.246	0.289	0.058	0.298	0.047	0.159
<i>Time between samples (Month)</i>	0.008	#DIV/0!	-0.192	0.113	0.198	0.115	0.183	0.085
<i>winter</i>	-0.069	#DIV/0!	-0.027	0.099	-0.012	-0.026	0.047	0.366
<i>Spring</i>	-0.062	#DIV/0!	0.097	-0.120	-0.150	0.007	0.089	0.187
<i>Fall</i>	-0.165	#DIV/0!	-0.348	-0.120	-0.150	-0.163	0.089	-0.307
<i>Long Time between Sample</i>	0.154	#DIV/0!	-0.260	0.069	0.219	0.015	0.008	0.126
<i>Oil added Lts/Hr</i>	0.003	#DIV/0!	-0.278	0.068	-0.349	-0.060	-0.031	-0.001
<i># of refills</i>	-0.065	#DIV/0!	-0.138	-0.047	-0.515	0.070	0.136	0.258
<i>Oil added Lts</i>	0.003	#DIV/0!	-0.262	-0.053	-0.379	-0.061	-0.001	0.035
<i>Time Since last Repair</i>	-0.306	#DIV/0!	-0.154	0.157	-0.312	0.045	-0.186	0.132
<i>Time Since New</i>	-0.306	#DIV/0!	-0.154	0.157	-0.312	0.045	-0.186	0.132
<i>Fe</i>	1.000	#DIV/0!	0.093	-0.090	0.552	0.089	-0.092	0.066
<i>Ag</i>		1.000	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
<i>Al</i>			1.000	-0.012	0.097	0.314	-0.090	0.367
<i>Cr</i>				1.000	0.339	0.142	-0.132	-0.279
<i>Cu</i>					1.000	-0.163	-0.166	-0.307
<i>Mg</i>						1.000	0.423	0.338
<i>Ni</i>							1.000	0.046
<i>Si</i>								1.000

Figure 99 – Correlations among variables for Engine S/N 19

In Figure 100, the x-axis (Hrs Since Last Repair) shows almost a complete period between overhaul and all the values are low enough for continuing to operate. The concentration of particles in the first two tests is a result of waste from the previous repair.

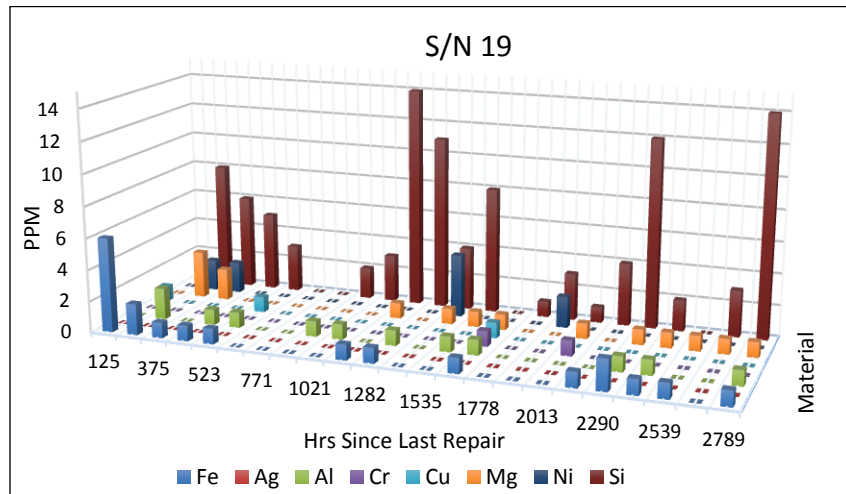


Figure 100 – PPM of material by Hours Since Last Repair S/N 19

Appendix F - Engine Regressions from S/N 5 to S/N 19

Continuing with Regressions, the next engine analyzed is engine S/N 5.

Figure 101 displays cumulative wear materials for engine S/N 5. All the regressions have R Square with good percentages between 99.07 and 90.62 % and they represent how well the regression adjusts to the real data.

Although the cumulative value of Ni is different to zero in this engine, it was discarded being that the value of 1 PPM is constant from the first sample to the last sample. As a result, it does not make a change in the prediction.

The next result of Si is about 11 PPM (in accordance with the prediction), of Mg is about 4 PPM, of Fe is 3 PPM, and 1 PPM for Ni, Cr, and Al.

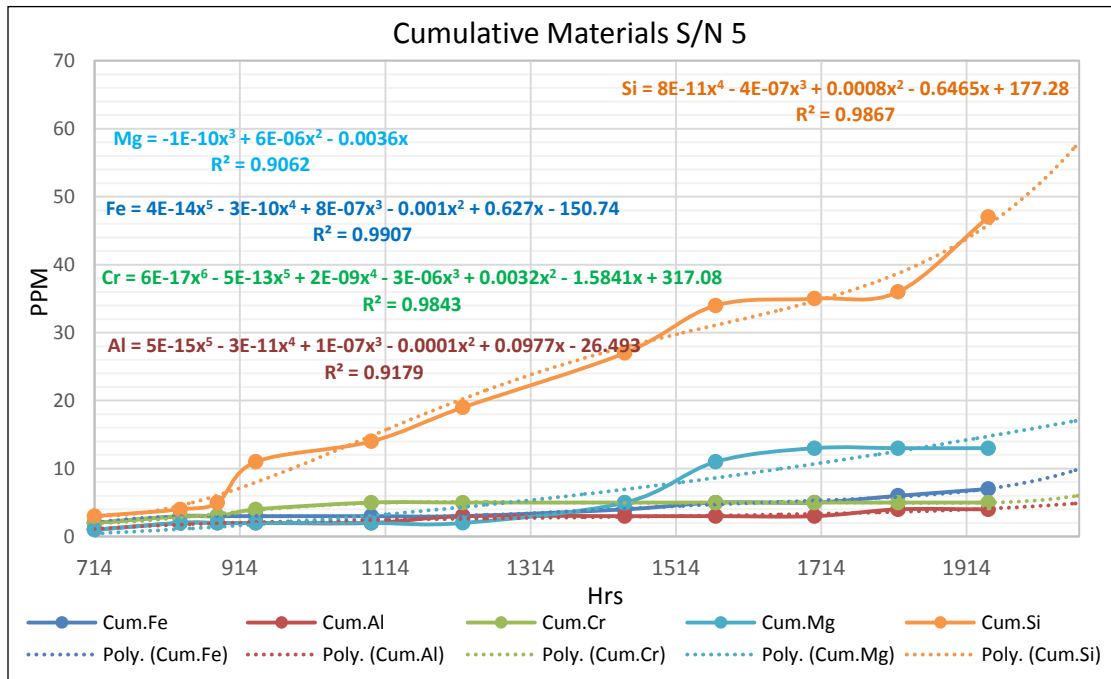


Figure 101 – Regression of Cumulative Fe, Al, Cr, Mg, and Si - S/N 5

Figure 102 presents the cumulative values of the different wear materials and their regressions. The forecast of each material does not show large changes. For Si, the next

result could be 13 PPM, for Mg 2 PPM, Fe 2 PPM, Ni 1 PPM, and zero for Al, and Cr, with everything within parameters for continuing to operate.

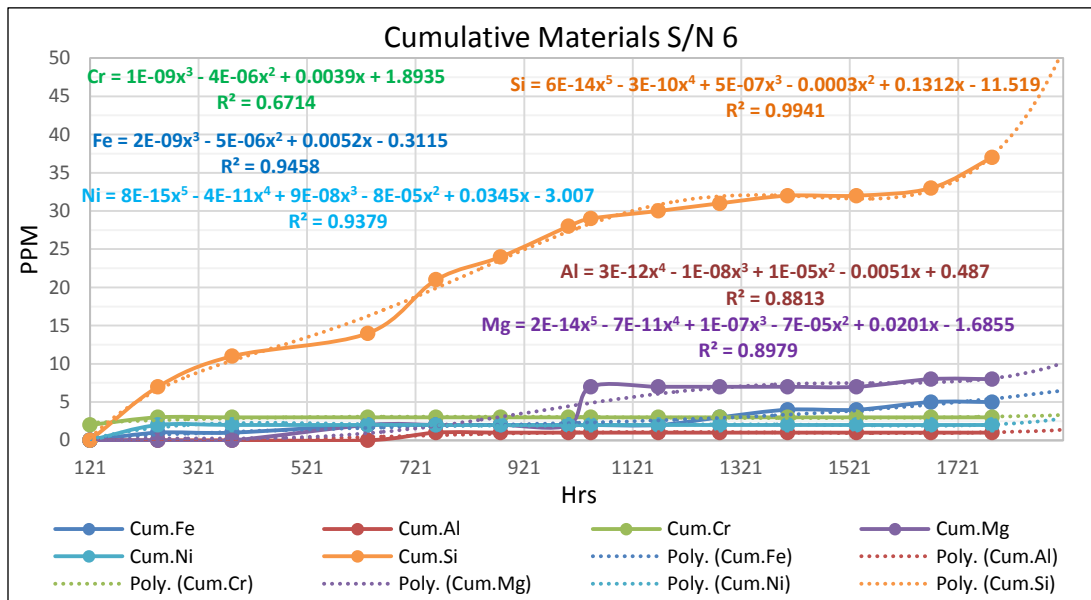


Figure 102 – Regression of Cumulative Fe, Al, Cr, Mg, Ni, and Si - S/N 6

In the graphs below (Figure 103), the cumulative values of wear material in engine S/N 7 are presented.

This engine completed the total time between overhaul, and as a result, the engine needs to be checked and expired parts to be changed. In the same way, the regression was applied, and the prediction after 125 hours shows a change in Si of about 15 PPM and in Mg of 3 PPM, but the others do not exhibit large changes.

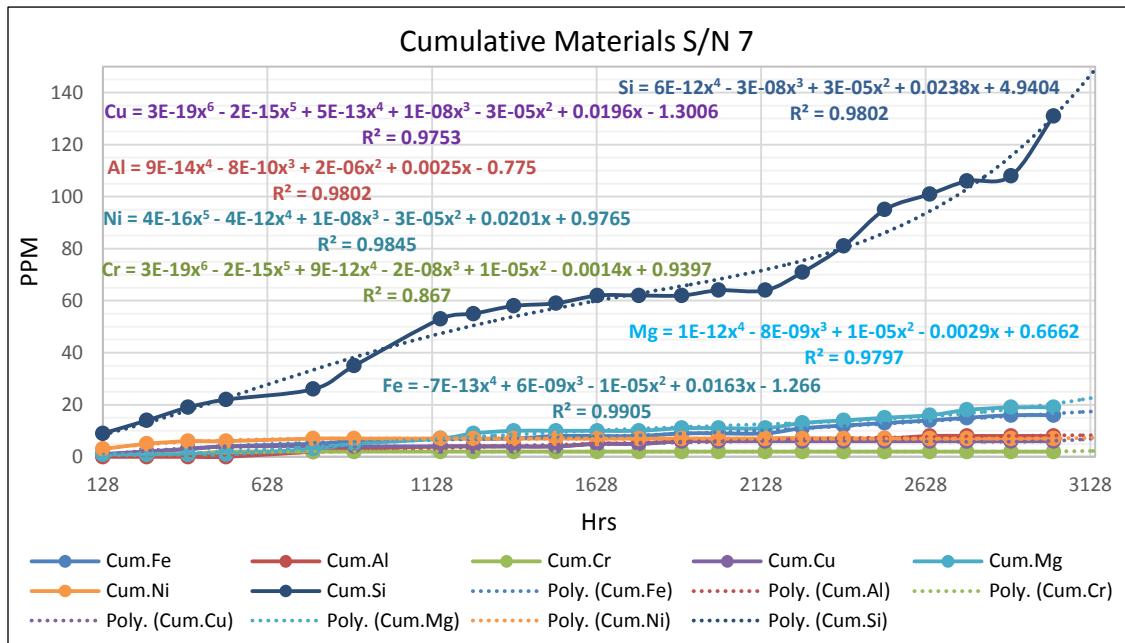


Figure 103 – Regression of Cumulative Fe, Al, Cr, Cu, Mg, Ni, and Si - S/N 7

Cumulative Materials for S/N 8 are exhibited in Figure 104 and the material with a significant change is Si, about 18 PPM in the prediction. Mg and Al show an increase of about 2 PPM, values within parameters.

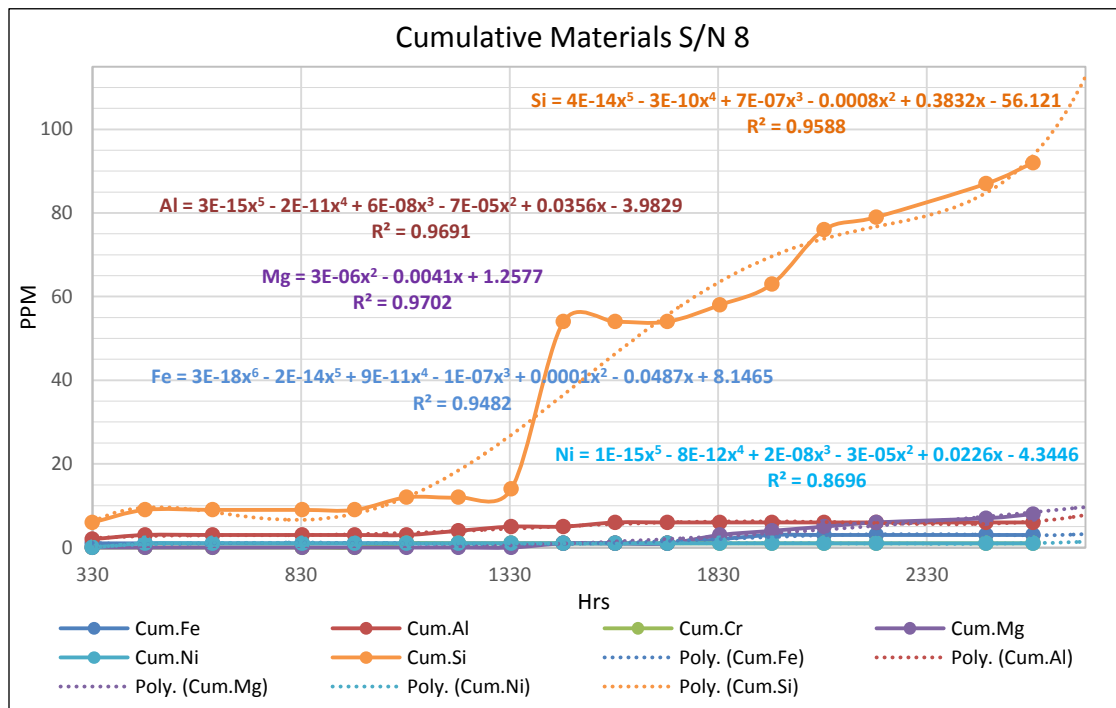


Figure 104 – Regression of Cumulative Fe, Al, Cr, Mg, Ni, and Si - S/N 8

In accordance with Figure 105 (Regression of Cumulative Fe, Al, Mg, Ni, and Si - S/N 9) the predictions for the different materials for this engine show Si 8 PPM, Mg 6 PPM, Fe and Al 2 PPM, and Ni 1 PPM for the next 125 hours of operation, since the R Squares are all between 0.99 and 0.9034.

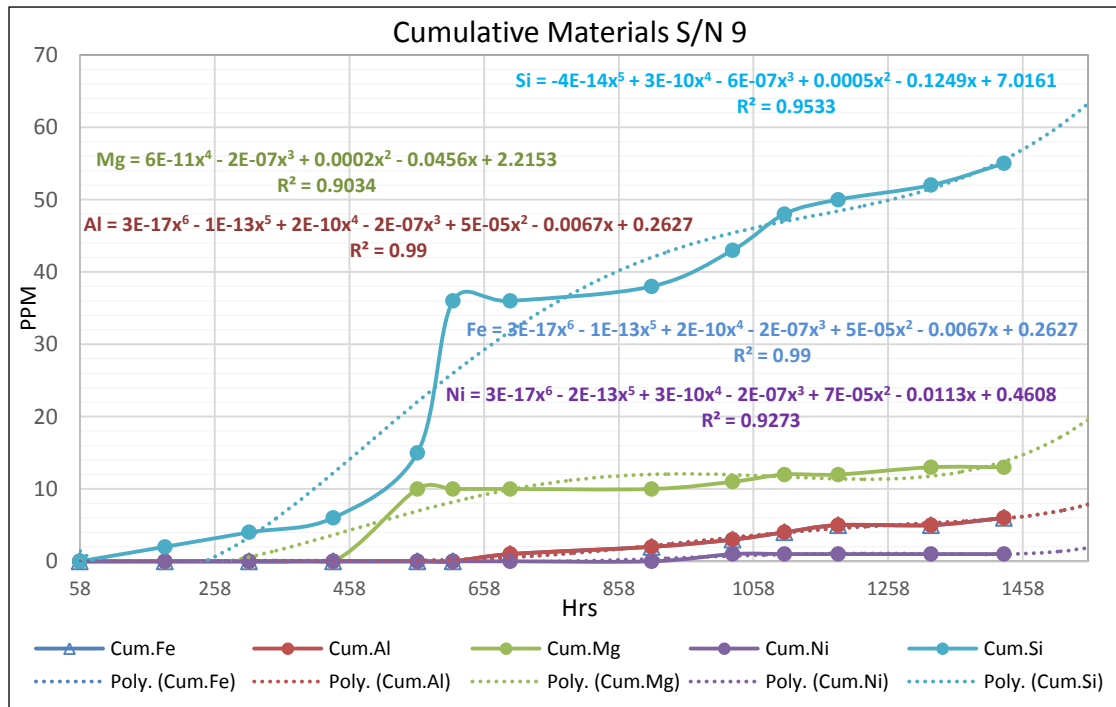


Figure 105 – Regression of Cumulative Fe, Al, Mg, Ni, and Si - S/N 9

The predictions for engine S/N 10 are presented in Figure 106. The forecast of different material is 6 PPM of Si, 1 PPM in Mg, 3 PPM in Cr, and 6 PPM in Al.

Since the normal range for silicon is between 0 and 27 PPM, 6 PPM poses no risk. For the case of chromium, the normal range is 0-4, and the prediction for the next test is determined to be 3 PPM, therefore within parameters. In the case of aluminum the normal range is between 0 and 11 PPM, so 6 PPM does not pose any risk until the next inspection, if the operating conditions are maintained in the same way.

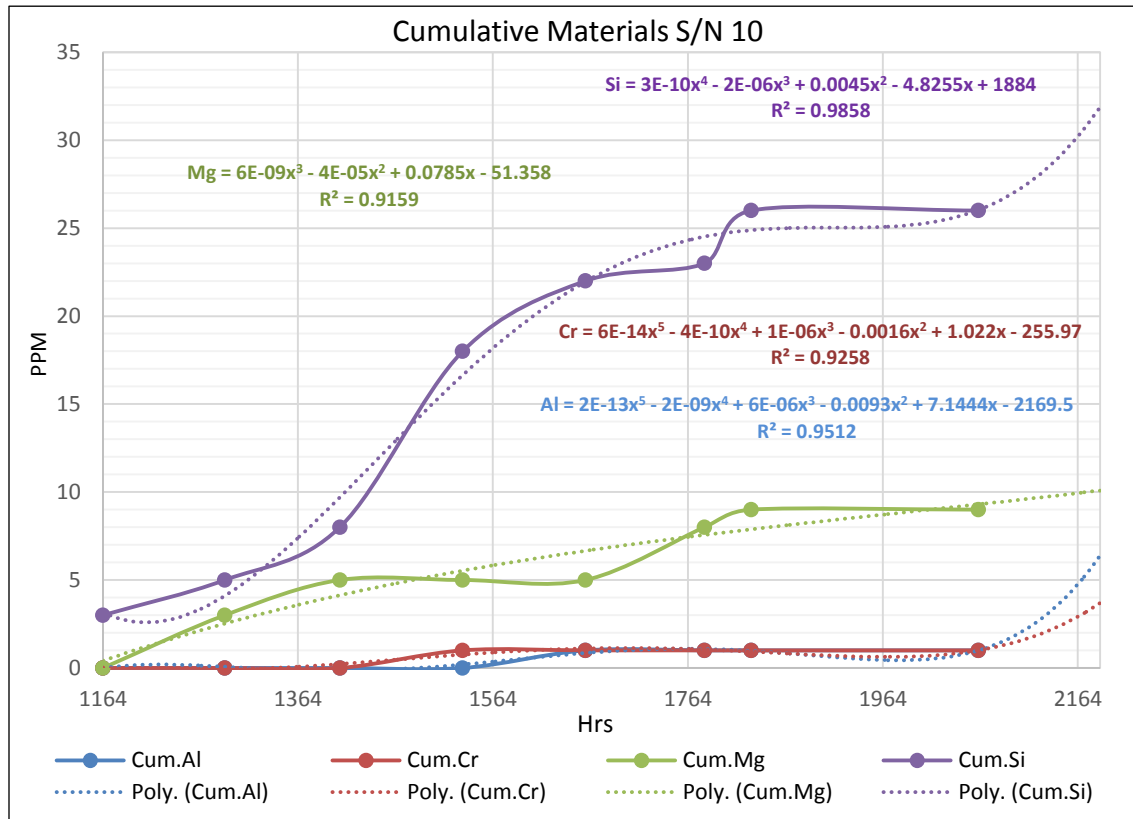


Figure 106 – Regression of Cumulative Al, Cr, Mg, and Si - S/N 10

Figure 107 displays the predictions for engine S/N 11. The biggest change is in Si, and it is about 15 PPM, but this does not present a problem. The others do not show more than 2 PPM in concentration.

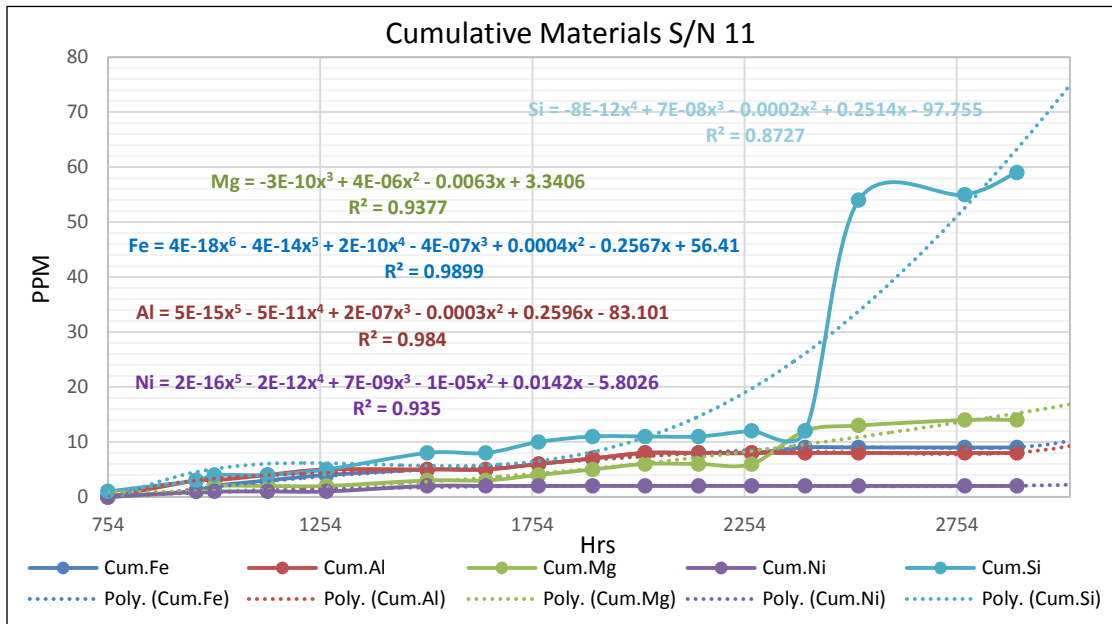


Figure 107 – Regression of Cumulative Fe, Al, Mg, Ni, and Si - S/N 11

Cumulative materials and predictions for engine S/N 12 are displayed in Figure 108, where Si presents 19 PPM for the next test, Ni about 6 PPM, Mg 2 PPM, Fe 3 PPM, and Al 2 PPM.

Nickel could represent a risk, because the predicted value is in the marginal range in accordance with the NAVAIR table. To reduce risk in this case the time to the next test could be reduced, for example in the middle of the period (67 hours).

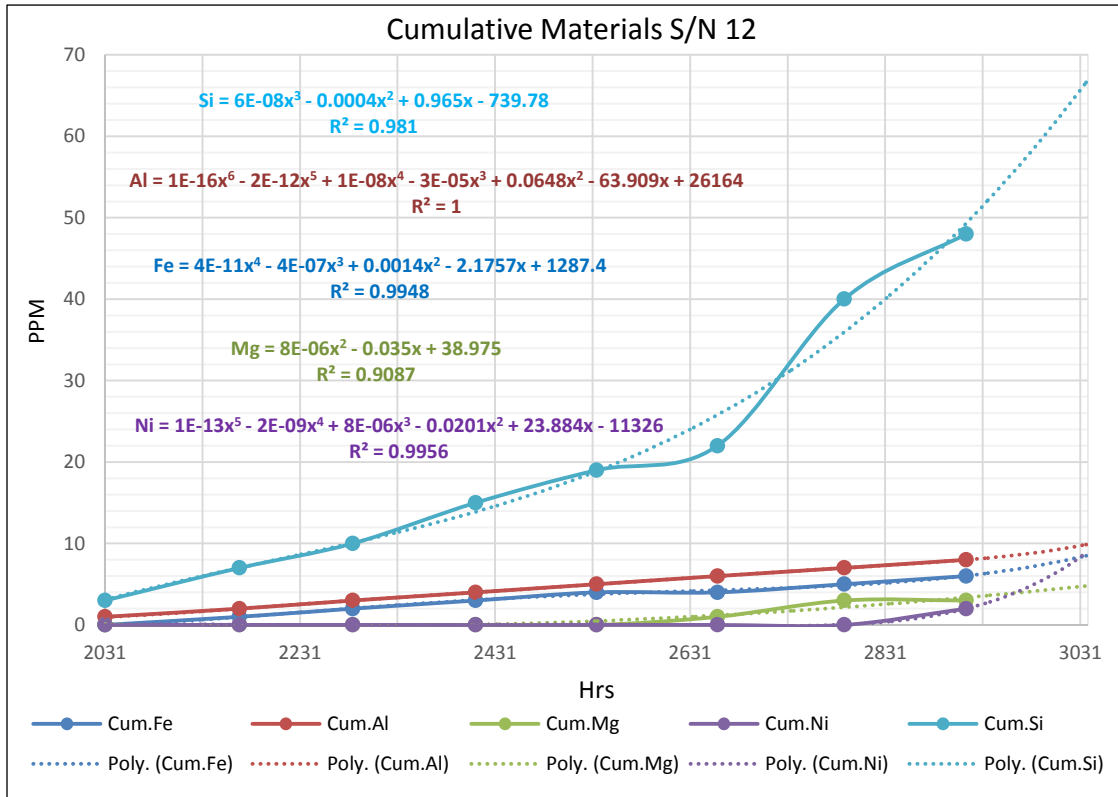


Figure 108 – Regression of Cumulative Fe, Al, Mg, Ni, and Si - S/N 12

For engine S/N 13 Figure 109 (Regression of Cumulative Si) and Figure 110 (Regression of Cumulative Fe, Al, and Mg) were used. The value for Si in accordance with the prediction could be 18 PPM, and this does not present a risk until the next test.

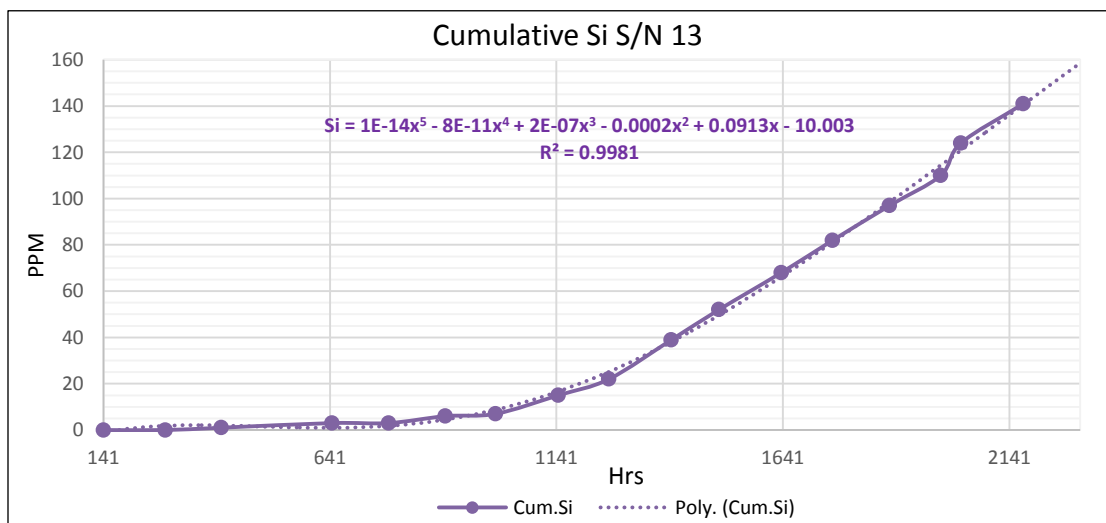


Figure 109 – Regression of Cumulative Si - S/N 13

For the rest of the materials (Figure 110) that have cumulative values, Mg shows 8 PPM of prediction, Fe and Al 2 PPM.

8 PPM of magnesium can pose a significant risk as this means at the high range in the concentration of this material. Again it would be convenient to repeat the sampling in half the time programmed.

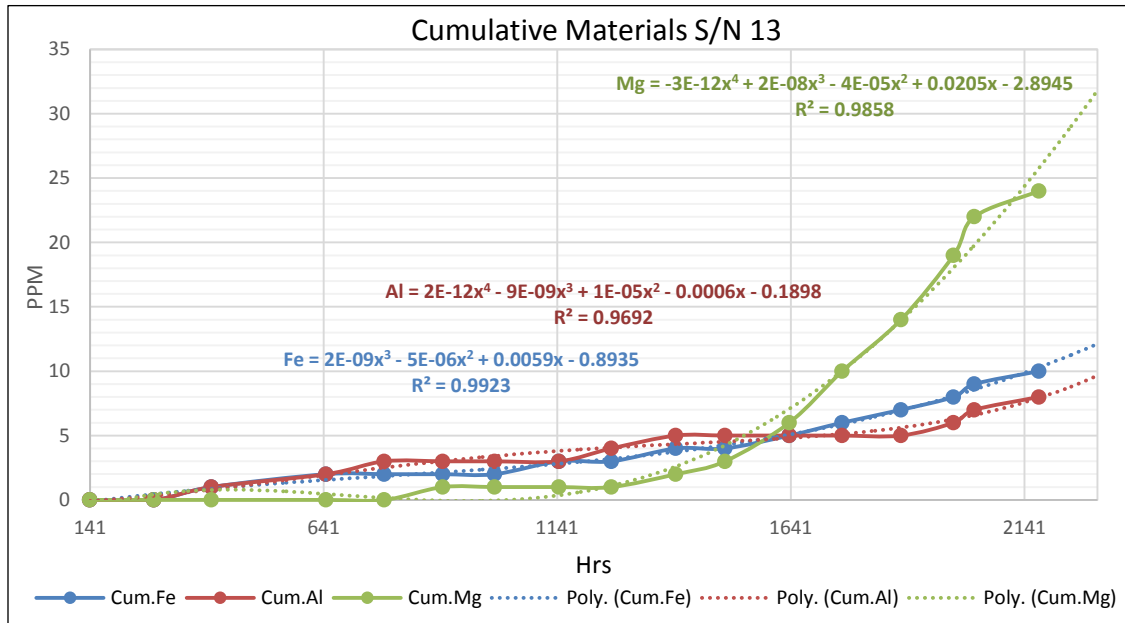


Figure 110 – Regression of Cumulative Fe, Al, Mg, Ni, and Si - S/N 13

Figure 111 displays the cumulative concentrations and predictions for the next result for engine S/N 14.

The forecast shows in Si an increase of 11 PPM, in Fe 2 PPM, 1 PPM in Al, Mg 6 PPM, and Cr 2 PPM. In this engine, the same situation exists as in the previous engine. The preoccupation is with Mg, and it will be in Marginal Range (NAVAIR Table).

Adopting a conservative decision would be to do a sample in the middle of the period.

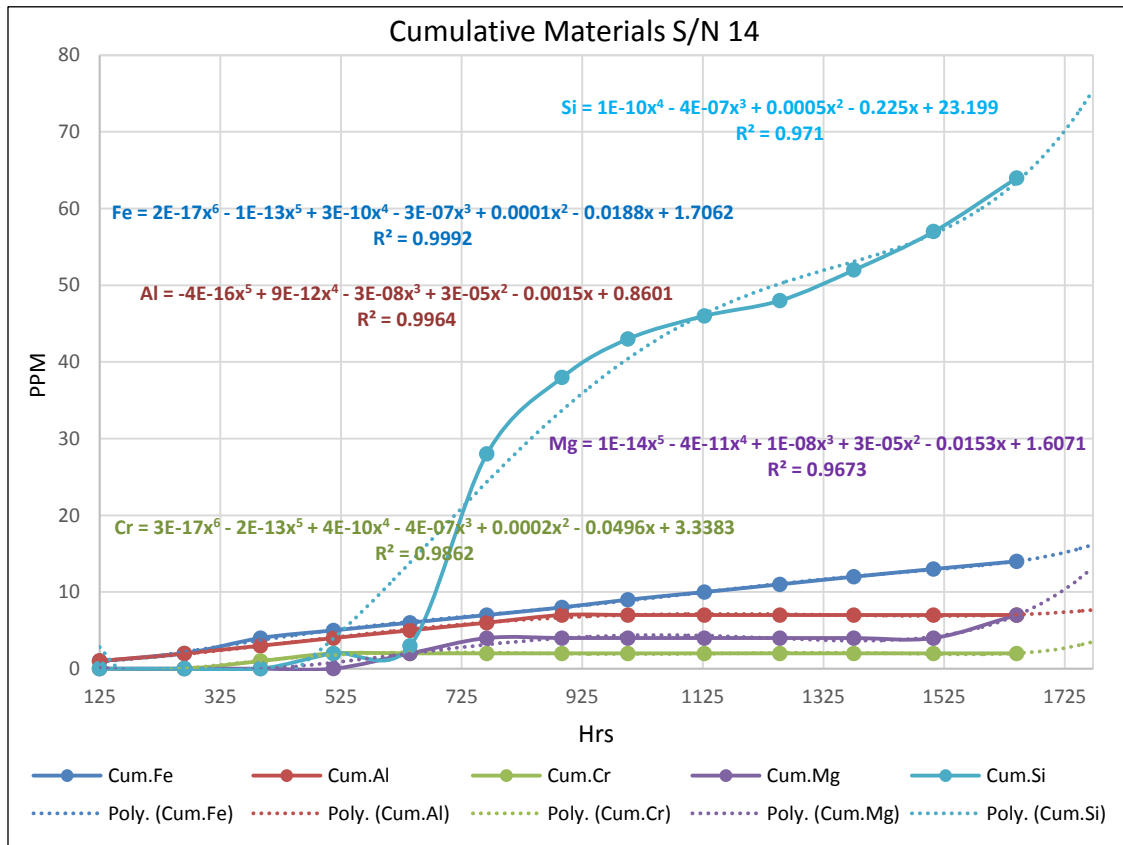


Figure 111 – Regression of Cumulative Fe, Al, Cr, Mg, and Si - S/N 14

In engine S/N 15, Figure 112 shows the wear behavior of the engine, and it has a clear difference in the first part of the graph (test 1 to 5) and other behavior in the second part (test 6 to 9). There are more than 4 years without working and an increase of 43 PPM between test number 5 and 6.

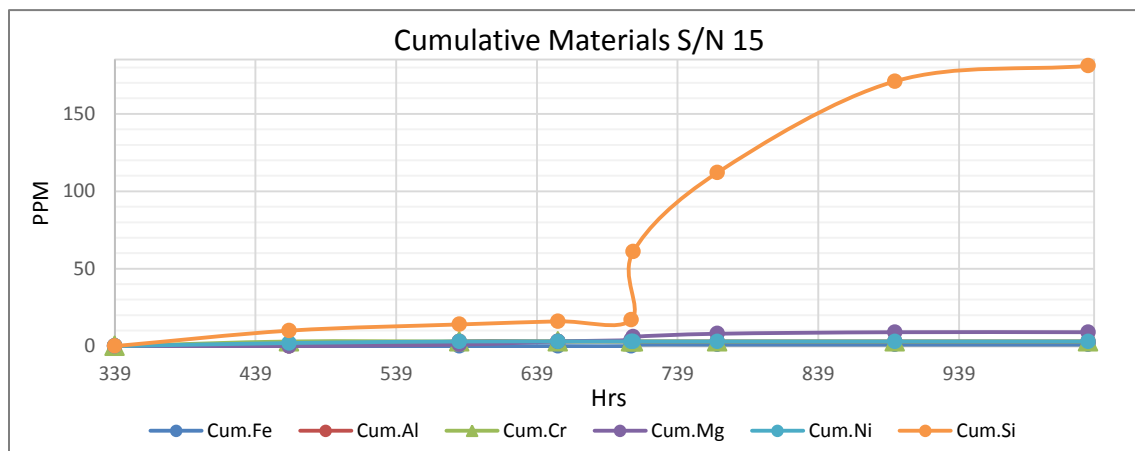


Figure 112 – Wear Behavior S/N 15

For predictions, Figure 113 presents Si for the next 125 hours in the engine and Figure 114 (Cumulative Fe, Al, Cr, Mg and Ni).

The first figure of cumulative Si (Figure 113) was made, and the prediction was about 27 PPM with a linear regression and 77% of R Square. The last value of concentration of Si was 8 PPM (test number 9), a value that is not enough for changing the oil. As a consequence of this prediction, the sample would be convenient for making in half the time.

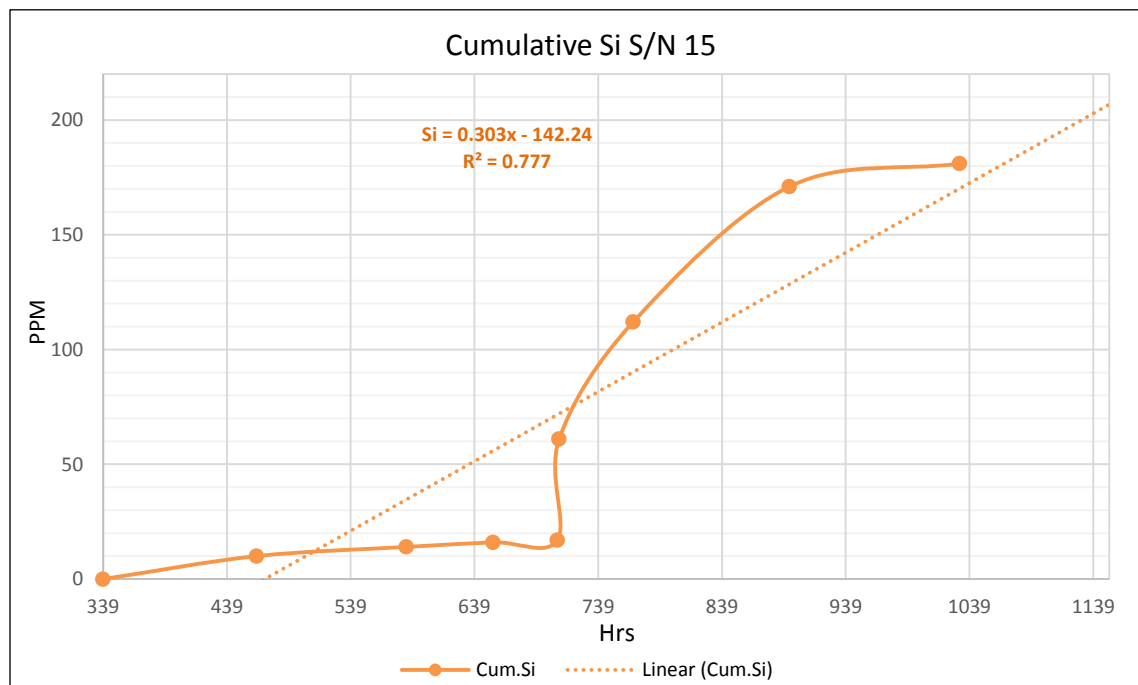


Figure 113 – Regression of Cumulative Si - S/N 15

Figure 114 displays predictions for Fe, Al, Cr, Mg, and Ni. Mg is the material with more increase present, about 3 PPM; 2 PPM in Al; 1 PPM in Ni; 2 PPM in Cr; and 1 PPM in Fe. Linear regression and Polynomial order 2 have low values of R Square, but they are the unique options with predictions equal to or more than the previous results, a requirement for cumulative values.

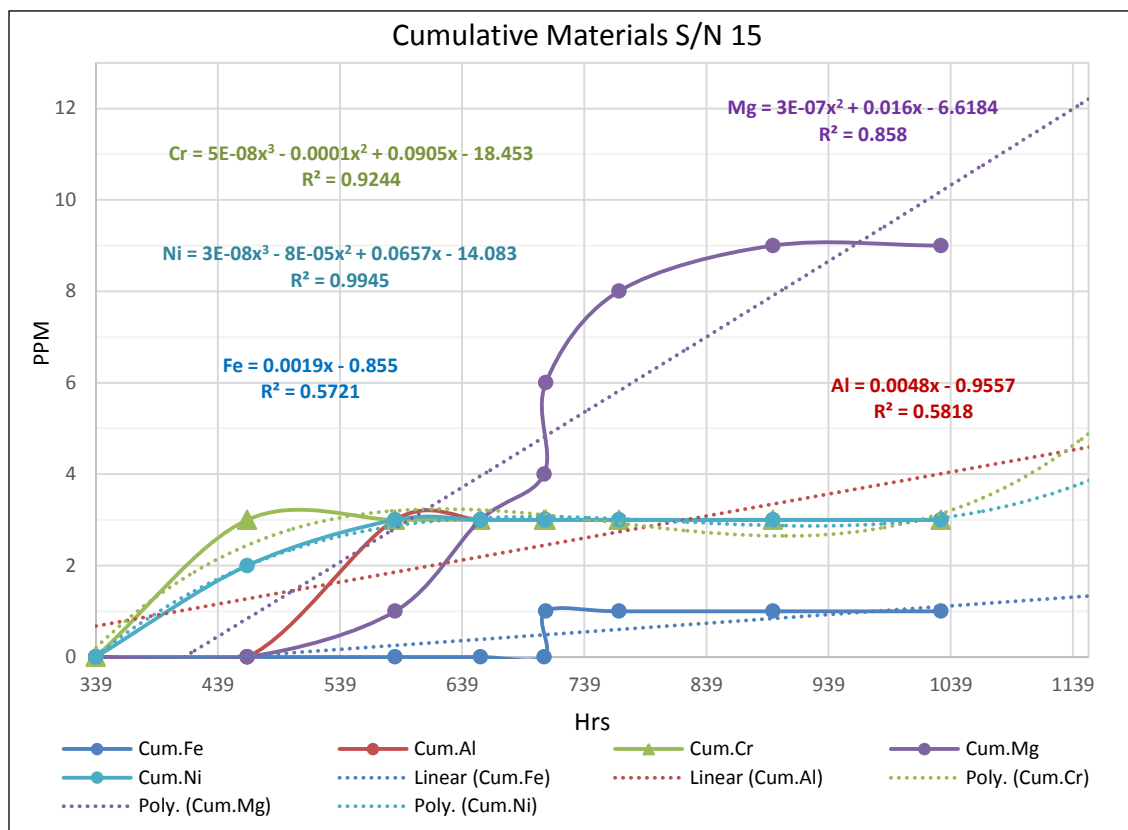


Figure 114 – Regression of Cumulative Fe, Al, Cr, Mg, and Ni - S/N 15

Continuing with the predictions, Figure 115 displays the cumulative wear materials and predictions in engine S/N 16.

This shows Si with 9 PPM, Fe about 2 PPM, Al 1 PPM, Cr 1 PPM, and Mg in approximately 4 PPM, all within parameters in accordance with the NAVAIR table.

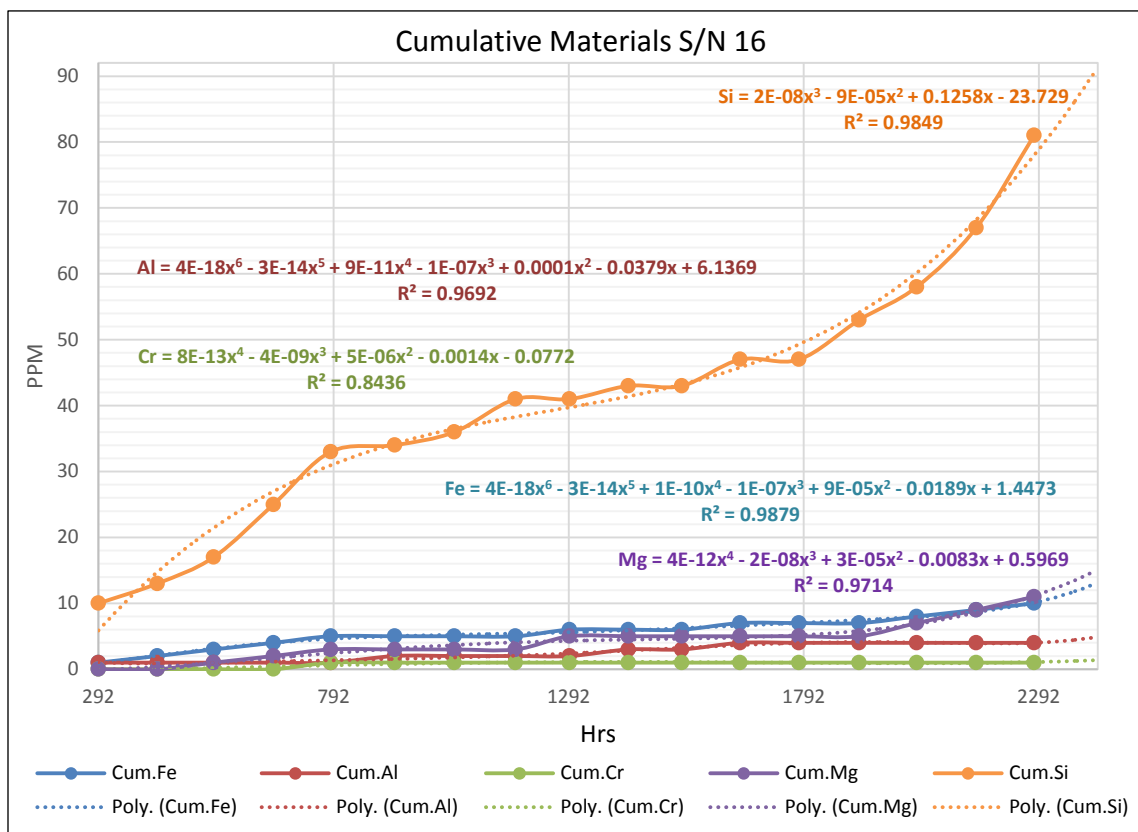


Figure 115 – Regression of Cumulative Fe, Al, Cr, Mg, and Si - S/N 16

The predictions for engine S/N 17 are graphed (Figure 116) and where the next results after 125 hours of operation as Si: 3 PPM, Mg: 2 PPM, Al: 2 PPM, Fe: 2 PPM, Cr: 1 PPM, and Cu: 1 PPM. The rest are zero.

This forecast does not present alarms for the next period if the operation is done in the same manner.

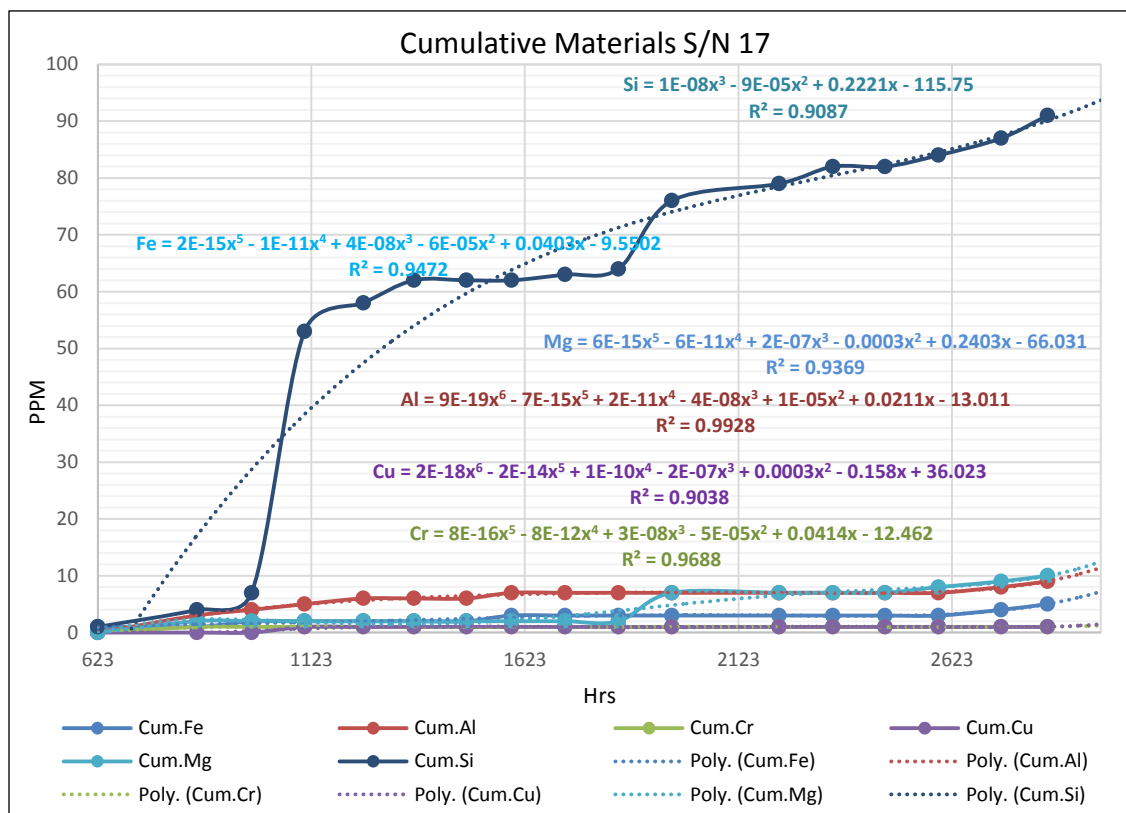


Figure 116 – Regression of Cumulative Fe, Al, Cr, Cu, Mg and Si - S/N 17

Engine S/N 18 has a prediction for each material that is shown in Figure 117. The estimated values are Si: 10 PPM, Mg: 4 PPM, Ni: 3, Fe: 2 PPM, Cu: 3 PPM, and Cr: 1 PPM. All values are within parameters.

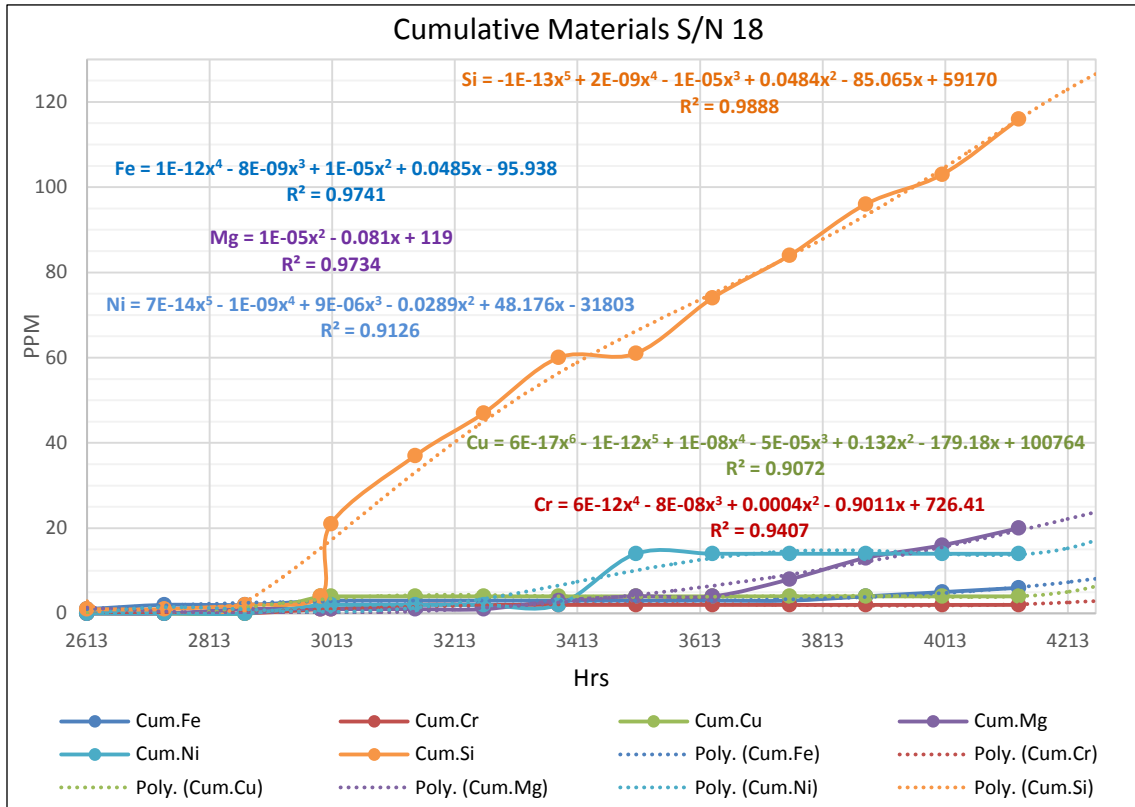


Figure 117 – Regression of Cumulative Fe, Cr, Cu, Mg, Ni, and Si - S/N 18

Figure 118 demonstrates the predictions for engine S/N 19 in wear materials and the values are Si: 17 PPM; Fe: 2 PPM; Mg: 3 PPM; Al: 2 PPM, Ni: 2 PPM; Cu: 1 PPM; and Cr: 1 PPM.

None of the materials has a value that triggers a risk alarm during operation in the next 125 hours. But it is interesting to see that the next sample could present issues of Fe-Cu-Mg and Fe-Cu-Al, where both are about “Accessory bushing bearing turning in magnesium housing” (NAVAIR 17-15-50.3 / TM 38-301-3 / T.O. 33-1-37-3 / CGTO 33-1-37-3, 2013, p. 1-2).

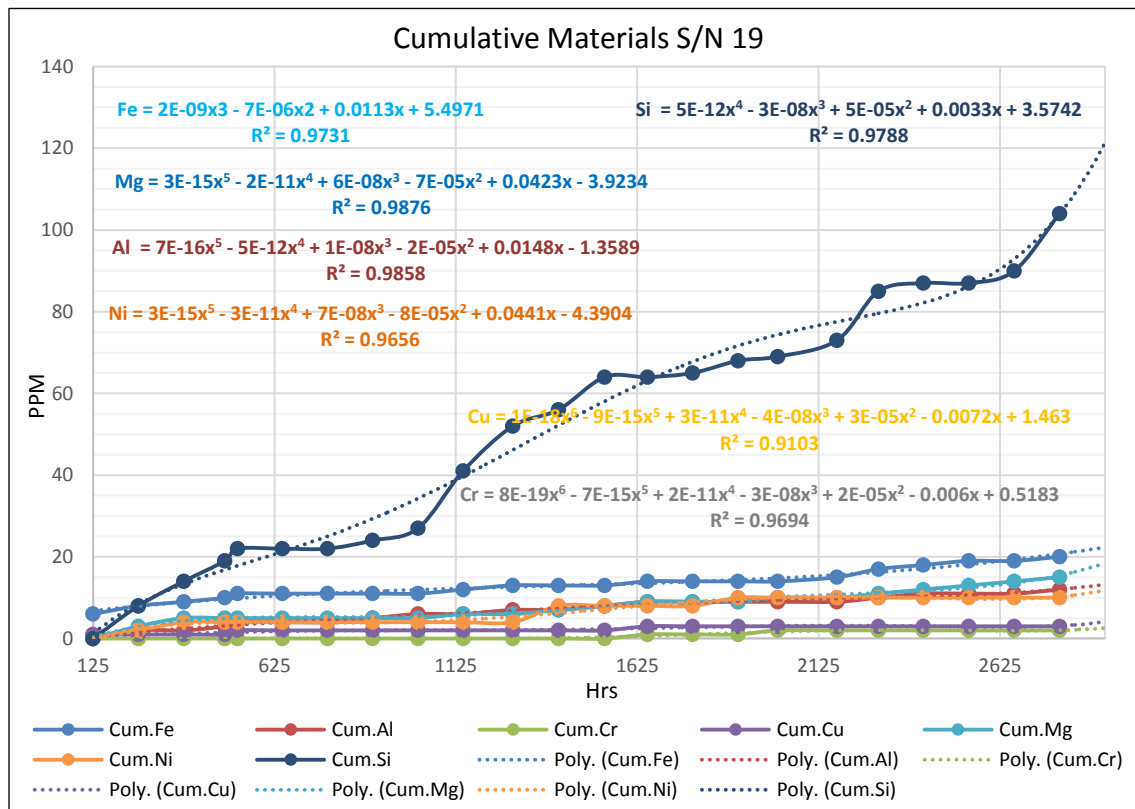


Figure 118 – Regression of Cumulative Fe, Al, Cr, Cu, Mg, Ni, and Si - S/N 19

SPECTROMETRIC OIL ANALYSIS PROGRAM ENHANCEMENTS FOR THE ARGENTINE AIR FORCE

Introduction

The Argentine Air Force continues to make a great effort to keep up to date and improve their logistics processes related to materials management. It is a permanent intention to reduce not only risks in the operation of various aerial systems, but also the direct and indirect costs associated with maintenance, in order to achieve maximum utilization of scarce resources.

This thesis is sponsored by the Direction General of Material with the aim of reinforcing the importance of predictive maintenance, motivated by the daily urgencies of shortages of materials, and lack of awareness of data recorded to achieve and predict events and unfavorable conditions for the organization. With information provided by the engine user of PTA6-25, the School Technical Group of Maintenance, and the Materials Testing Laboratory, an analysis of oil sample results and testing procedures was performed to predict and/or improve the predictive maintenance system used in the Air Force.

Literature Review

References

NAVARO "P-630-3" 2013, 90-215-2-12

NAVARO "P-630-3" 2013, 90-215-2-12

NAVARO "P-630-3" 2013, 90-215-2-12

Research Questions

Question 1: Are the data extracted enough to fulfill the requirement of predicting the next result for the sample of oil, avoiding unnecessary risk management and operational risk?

Question 2: Do the data extracted meet the quality to fulfill the requirement for predicting the next result for the oil sample?

Question 3: Is it possible to change or optimize the system of spectrometric analysis of oil applied in the FAA?

Question 4: Does the technical report require some type of upgrade?

Conclusions of this research

The technical report needs to be updated and the formulas used in it corrected. The lack of written procedures about how the sample needs to be extracted is another problem that needs to be addressed to ensure proper oil sampling. Once the procedures have been established, it is necessary to ensure that it is performed correctly. Solving this problem will require the adequate training of the personnel that extract samples.

The analysis of the data is very important for knowing the reasons why the sample has variation, and then corrections made in a timely manner. The correct recording of oil consumption and changed and the number of times it is refilled. All other variables that are related to the oil sample must be recorded. The analysis of the data will allow the comparison of wear is a useful tool to apply because it can reveal irregularities among engines. The correlations combined with graphs are necessary for making conclusions about the advancement of the program of spectrometry and the relations among variables. The automation of the reference is important as a way to develop an alarm system in the case of exceeding the maximum values for each material, and for recording the results of the test. Finally, an important procedure is the regression for predicting the next result of the sample.

Every analysis proposed is complementary and contributed to reduced risks in operation and management. As a consequence, all together form a package that is necessary to apply with the only intention to reach the goal. No less important is to work together, the laboratory and the user, with the same goal, applying improvement processes to reduce risk.

Macro Analysis

Eight samples were found

Twelve materials used to be checked, and only eight are analyzed

2) The weapon system (Taurus) presented to the AA in 1987, and the requirement for making oil analysis was not applied. The report from 1987 until 2000, or 21 years of oil maintenance the regularity and improving processes.

3) The forms used for the laboratory have the data in English format (intermediate), while the forms and can include mistakes in the analysis of the data. The root cause is the lack of training in the Air Force and the lack of communication with the laboratory.

4) Technical Report C.T. (FA202-12-22A000) is a common regulation for every aeromedical sample in the Air Force, but it does not have the necessary information to be able to make a comparison between samples could be high, and the results were reliable.

5) The analysis of the data showed that the oil sample had some irregularities, such as: variation in brown, change of oil, exchange of particles, found in magnetic plate, other type of contamination, an oxidation analysis, after more analysis, change of filter, comparison testing and so on.

6) In accordance with the Technical Report C.T. (FA202-12-22A000), the user needs to apply the automation of the reference is important as a way to develop an alarm system in the case of exceeding the maximum values for each material, and for recording the results of the test.

7) The analysis of the data showed that the oil sample had some irregularities, such as: variation in brown, change of oil, exchange of particles, found in magnetic plate, other type of contamination, an oxidation analysis, after more analysis, change of filter, comparison testing and so on.

Micro Analysis

"Evaluation for comparison of wear material"

Analysis of Metals: Micro-objects were observed under a microscope. Different times the object was analyzed at 100x, 200x, 400x, 800x, 1600x, 3200x, 6400x, 12800x, 25600x, 51200x, 102400x, 204800x, 409600x, 819200x, 1638400x, 3276800x, 6553600x, 13107200x, 26214400x, 52428800x, 104857600x, 209715200x, 419430400x, 838860800x, 1677721600x, 3355443200x, 6710886400x, 13421772800x, 26843545600x, 53687091200x, 107374182400x, 214748364800x, 429496729600x, 858993459200x, 1717986918400x, 3435973836800x, 6871947673600x, 13743895347200x, 27487790694400x, 54975581388800x, 109951162777600x, 219902325555200x, 439804651110400x, 879609302220800x, 1759218604441600x, 3518437208883200x, 7036874417766400x, 14073748835532800x, 28147497671065600x, 56294995342131200x, 112589990684262400x, 225179981368524800x, 450359962737049600x, 900719925474099200x, 1801439850948198400x, 3602879701896396800x, 7205759403792793600x, 14411518807585587200x, 28823037615171174400x, 57646075230342348800x, 115292150460684697600x, 230584300921369395200x, 461168601842738790400x, 922337203685477580800x, 1844674407370955161600x, 3689348814741910323200x, 7378697629483820646400x, 14757395258967641292800x, 29514790517935282585600x, 59029581035870565171200x, 118059162071741130342400x, 236118324143482260684800x, 472236648286964521369600x, 944473296573929042739200x, 1888946593147858085478400x, 3777893186295716170956800x, 7555786372591432341913600x, 15111572745182864683827200x, 30223145490365729367654400x, 60446290980731458735308800x, 120892581961462917470617600x, 241785163922925834941235200x, 483570327845851669882470400x, 967140655691703339764940800x, 1934281311383406679529881600x, 3868562622766813359059763200x, 7737125245533626718119526400x, 15474250491067253436239052800x, 30948500982134506872478105600x, 61897001964269013744956211200x, 123794003928538027489912422400x, 247588007857076054979824844800x, 495176015714152109959649689600x, 990352031428304219919299379200x, 1980704062856608439838598758400x, 3961408125713216879677197516800x, 7922816251426433759354395033600x, 15845632502852867518708790067200x, 31691265005705735037417580134400x, 63382530011411470074835160268800x, 126765060022822940149670320537600x, 253530120045645880299340641075200x, 507060240091291760598681282150400x, 1014120480182583521197362564300800x, 2028240960365167042394725128601600x, 4056481920730334084789450257203200x, 8112963841460668169578900514406400x, 16225927682921336339157801028812800x, 32451855365842672678315602057625600x, 64903710731685345356631204115251200x, 129807421463370690713262408230502400x, 259

Bibliography

- ASTM D 5185-02 (2002) "Standard Test Method for Determination of Additive Elements, wear metals, and contaminants in used lubricating oils and determination of selected elements in basic oils by inductively coupled plasma atomic emission spectrometry (ICP-AES)" - ASTM INTERNATIONAL.
- AVOTEK (2011) "Aircraft Powerplant Maintenance" Second Edition - AVOTEK INFORMATION RESOURCES.
- Boissel, Oliver (2016) "Basics of an oil analysis program" Available from <https://www.mobil.com/en/industrial/lubricant-expertise/resources/basics-oil-analysis-program> - ExxonMobil Fuels & Lubricants - Feb 22, 2016.
- Bowen, E. Roderic, and Wescott, Vernon C. (1980) "Free metal wear particles steel and steel based alloys" Wear particle atlas - Volume I - FOXBORO ANALYTICAL.
- Chase, Richard B., Shanker, Rave, and Jacobs, F. Robert (2014) "Operations and Supply Chain Management" 14th Edition - McGraw Hill Education.
- Deming, W. Edwards (1991) "Out of the Crisis" Massachusetts Institute of Technology - Sixteenth Printing.
- Evans, John S. & Hunt, Trevor M. (2008) "The Oil Analysis Handbook" First Edition - Coxmoor Publishing Co.
- Fitch, James C. (2000) "The Lubrication Field Test and Inspection Guide" Noria Corporation.
- Freelin, Julie Michelle (1990) "Inductively Coupled Plasma Atomic Emission Spectroscopy applied to the Analysis of Wear Metals in Lubricating Oil and Related Studies" The University of Arizona - UMI.
- Huff, Cheryl and Boswell, Charles (2005) "How to Read Your Oil Analysis Report" PoMA Corporation - Lubrication Excellence 2005 Conference Proceedings - Pages: 34-35 - Industrial Maintenance & Reliability Reference Guide.
- Intertek (2016) "Wear Metals Testing for Lubricants and Fluids" Available from <http://www.intertek.com/ocm/wear-metals/> - Nov 12, 2016.
- Jardine, A.K.S., Anderson, P.M., and Mann, D.S. (1987) "Application of the Weibull Proportional Hazards Model to Aircraft and Marine Engine Failure Data" Quality and Reliability Engineering International - Volume: 3, Issue: 2, Pages: 77-82.

- Kroes, Michael J., Watkins, William A., Delp, Frank, and Sterkenburg, Ronald (2013) "Aircraft Maintenance & Repair" Seventh Edition - McGraw Hill Education.
- Leugner, L. (2005) "Effective Data Collection for Thorough Failure Analysis" Maintenance Technology International Inc. - Reliability Word 2005 Conference Proceedings - Pages: 230-235 - Industrial Maintenance & Reliability Reference Guide.
- Lotan, D. (1972) "Spectrometric Oil Analysis - Use and Interpretation of Data" Société d' Etude et de Construction de Moteurs d' Aviation (France) - SAE - National Business Aircraft Meeting - Wichita, Kansas - March 15-17, 1972.
- Mack Trucks Inc. (2002) "MACK DIESEL AND NATURAL GAS - Engine Oil Analysis" Engine 3-301- Oct 2002.
- MAPO 44 (2016) - Manual Aeronáutico de Procedimientos Orgánicos de la Escuela de Aviación Militar - Fuerza Aérea Argentina.
- MAPO 52 (2016) - Manual Aeronáutico de Procedimientos Orgánicos de la Dirección de Mantenimiento del Material - Fuerza Aérea Argentina.
- MAPO 9 (2016) - Manual Aeronáutico de Procedimientos Orgánicos de la Dirección General de Material - Fuerza Aérea Argentina.
- NAVAIR 17-15-50.3 / TM 38-301-3 / T.O. 33-1-37-3 / CGTO 33-1-37-3 (2013) - Technical Manual - Joint Oil Analysis Program Manual - Volume III - Introduction and Aeronautical Equipment Wear Metal Analytical Methodology - 30 August 2013 - Change 0.
- Nicholas, Jack R., Jr. (P.E, CMRP), MQS LLC and Troyer, Drew D. (CRE, CMRP) (2005) "Procedure-Based Maintenance" Noria Corporation - Reliability Word 2005 Conference Proceedings - Pages: 257-264 - Industrial Maintenance & Reliability Reference Guide.
- Oil Analyzers Inc. (2016) - Fluid Analysis - Available from <http://www.oaitesting.com/about.aspx> - Nov 12, 2016.
- Pratt & Whitney Canada (2012) - Maintenance Manual - Manual Part NO. 3032142 - Standard Practices - Maintenance Practices 70-00-00 - May 18/2012.
- RAC 1 (2010) - Reglamento de Doctrina Básica - Fuerza Aérea Argentina.

- Reh, F. John (2016) "You Can't Manage What You Don't Measure" Business Management and Leadership - Updated April 25, 2016 - Available from <https://www.thebalance.com/you-can-t-manage-what-you-dont-measure-2275996>.
- Reilly, Steve (2006) "Asset Basic Care from a TPM/Six Sigma Perspective" Design Maintenance Systems Inc. - 2006 Conference Proceedings - Pages: 267-274 - Industrial Maintenance & Reliability Reference Guide.
- Spurlock, Matt (2005) "How to Set Alarms for Oil and Wear Debris Analysis" Noria Corporation - Lubrication Excellence 2005 Conference Proceedings - Pages: 64-67 - Industrial Maintenance & Reliability Reference Guide.
- Technical Report C.T. FA42B2-1-2 - 23ABR86 (1986) - Fuerza Aérea Argentina - Comando de Material.
- Toms, Larry A. and Toms, Allison M. (2008) "Machinery Oil Analysis, Methods, Automation & Benefits" Third Edition - Stle.
- Wang, W. and Zhang, W. (2005) "A model to predict the residual life of aircraft engines based upon oil analysis data" Naval Research Logistics - Volume: 52, Issue: 3, Pages:276-284.
- Zhao, Yuegang (2014) "Oil Analysis Handbook for Predictive Equipment Maintenance" Spectro Scientific - Available from http://www.spectrosci.com/default/assets/File/SpectroSci_OilAnalysisHandbook_FIN_AL_2014-08.pdf. Wang, W. and Zhang, W. (2005) "A model to predict the residual life of aircraft engines based upon oil analysis data" Naval Research Logistics - Volume: 52, Issue: 3, Pages:276-284.

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14. ABSTRACT The Argentine Air Force continues to make a great effort to keep up to date and improve their logistics processes related to materials management. It is a permanent intention to reduce not only risks in the operation of various aerial systems, but also the direct and indirect costs associated with maintenance, in order to achieve maximum utilization of scarce resources. This thesis is sponsored by the Direction General of Material with the aim of reinforcing the importance of predictive maintenance, motivated by the daily urgencies of shortages of materials, and lack of awareness of data recorded to achieve and predict events and unfavorable conditions for the organization. With information provided by the engine user of PTA6-25, the School Technical Group of Maintenance, and the Materials Testing Laboratory, an analysis of oil sample results and testing procedures was performed to predict and/or improve the predictive maintenance system used in the Air Force.					
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