Lubricant Analysis for Gas Turbine Condition Monitoring

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INTRODUCTION

Analysis of used lubricating oil is a fast evolving technique for predictive maintenance with any closed loop lubricating system such as those in gas and steam turbines, diesel and gasoline engines, transmissions, gearboxes, compressors, pumps, bearings and hydraulic systems.

To be effective in monitoring both machine condition and lubricant condition, a modern oil analysis program takes the form shown in Figure 1. Based on analysis of periodic oil samples, a laboratory diagnostic report is sent to the personnel responsible for the equipment to warn of any possible problem or to make a specific maintenance recommendation. The entire process, from sample taking to the diagnostic report, should take less than 48 hours to be effective. These reports, when combined with statistical analysis and trending, can provide an insight to management personnel on the effectiveness of the program, efficiency of the maintenance department, repair status of equipment, recurring problems, and even information on the performance of different lubricants.

Condition monitoring by oil analysis can be broken down into two categories, debris monitoring to measure the trace quantities of wear particles carried by the lubricant away from the wearing surfaces and lubricant condition monitoring to determine if the lubricant itself is fit for service based on physical and chemical tests.

DEBRIS MONITORING

Debris monitoring pertains primarily to the detection, and sometimes also the analysis, of metallic wear particles. The most common techniques and devices applied to this category

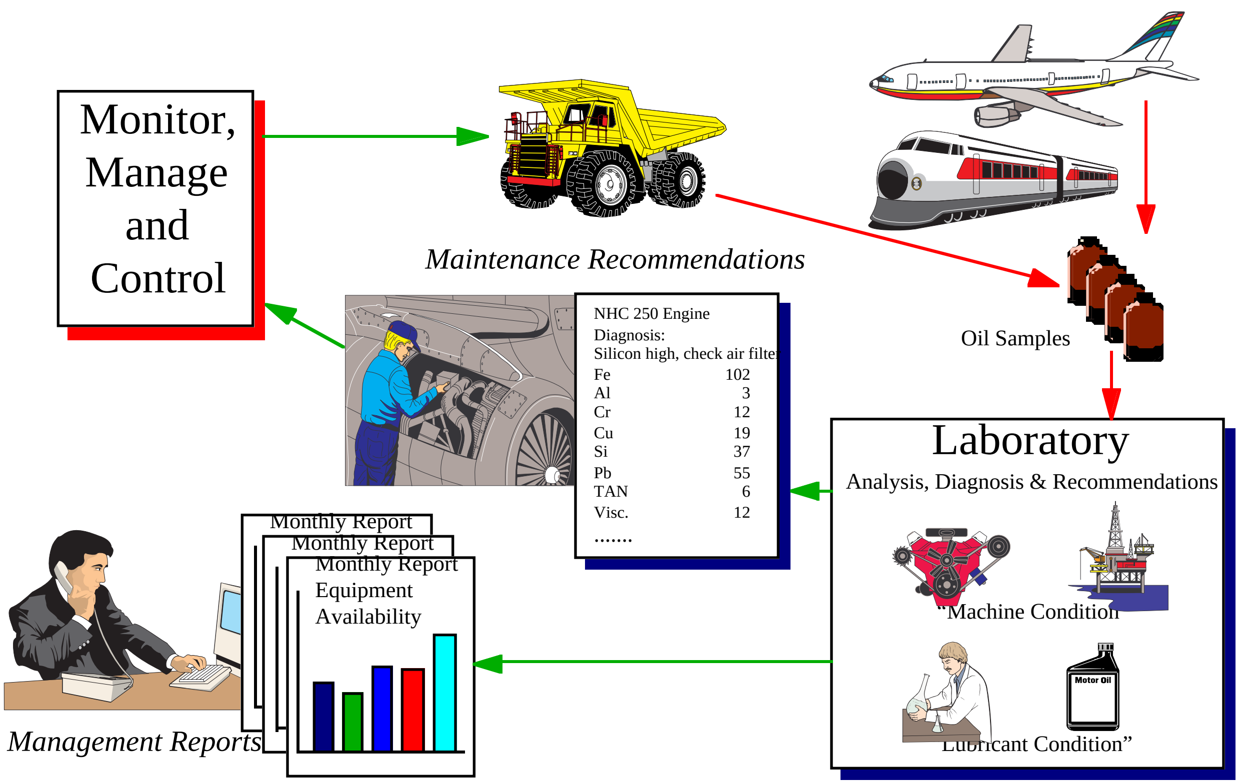

Figure 1, Oil Analysis Program, Flow Diagram of condition monitoring include atomic emission spectroscopy (AES), atomic absorption spectroscopy (AAS), X-ray fluorescence spectroscopy (XRF), ferrography, magnetic plugs, magnetic chip detectors, and microscopic examination of filter debris.

Debris monitoring is the backbone of oil analysis condition monitoring programs. It is effective in the sense that tests can be applied to determine that a system is nearing, or has reached, a failure mode. Further damage can thus be contained or avoided through immediate shutdown and repair.

Spectroscopy is the most widely applied technique for debris monitoring. It provides a quantitative, multi-elemental analysis of wear debris in lubricating oil. The elemental concentration of as many as 20 elements are reported in parts per million (ppm). Wear metals such as iron, aluminum, chromium, copper, tin, lead, silver, titanium and nickel are detectable, as well as lubricant additives such as calcium, barium, zinc, phosphorus, magnesium, boron and molybdenum. Certain contaminants such as silicon, sodium and potassium are also routinely detected. Trends are used to determine the mechanical health of a system. Concentration trends are established through routine monitoring to indicate if a continuing wear condition exists, the rate of wear, and as a consequence, the immediacy of the wear problem.

There are several types of spectrometers used for debris monitoring. These include, rotating disk arc emission (RDE), atomic absorption (AAS), X-ray fluorescence (XRF) and inductively coupled plasma (ICP) emission spectrometers. Each has its own advantages and disadvantages, however, the RDE technique is preferred for applications with large numbers of oil samples and is the most popular due to its ease of use in all types of environments.

An effective spectrometric oil analysis program is dependent upon interpretation of the analytical data. The interpretation is an evaluation of the maintenance status of an oil wetted system and consists of the laboratory's recommended maintenance action.

The evaluation process can be manual or computer assisted. It is based on wear metal guidelines for a particular piece of equipment, but must also take into account a combination of variables. Equipment operating conditions are a prime factor. The environment is also important; for example, an arid location will cause an increase in silicon readings accompanied by a corresponding increase of wear. Time since last oil change and oil consumption will affect readings and possibly disguise a wear trend. The length of time the equipment is in service is extremely important. During the engine break-in period, either when new or after overhaul, wear metal concentrations are abnormally high and are no cause for alarm. If equipment is left to stand idle for long periods of time, rust can form and iron readings will increase. Older systems will also generate more wear metals than fairly new ones of the same model. Load on the engine is also a factor, particularly changes in load; increases in wear may be due to an additional load placed on the engine. The chemical composition of the oil and coolant are also important. Metals present may not be due to wear at all, but rather due to an oil additive or coolant leak.

Since the spectrometer is able to differentiate between metals, it is able to determine which metals make up the total wear-metal content of the oil. For example, if only iron and aluminum are present in abnormal amounts, the analyst's job is much simpler. The entire system does not have to be torn down and inspected; the inspection can be restricted to those components made up of iron and aluminum. Knowing the relative concentrations of the elements will further narrow down their possible source. For example:

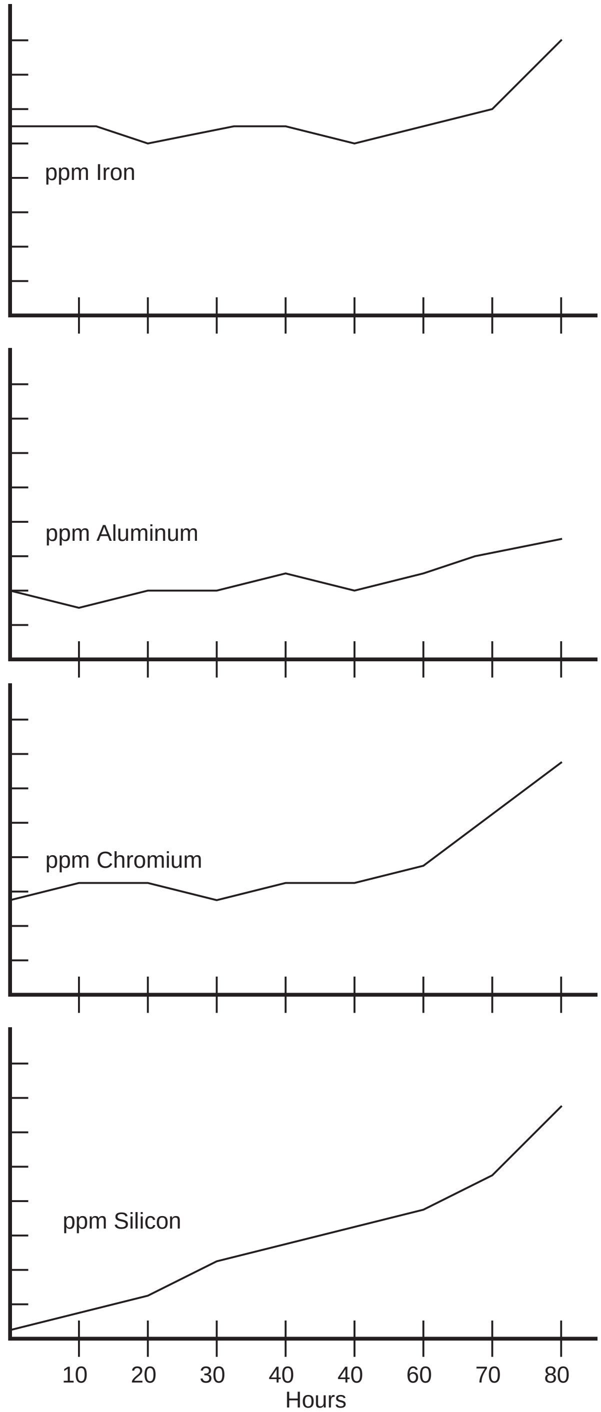

Figure 2, Spectrometric trend showing dirt ingestion

1. An increase in silver and nickel in a certain type of railroad diesel is indicative of bearing wear. If detected early enough, a relatively simple bearing replacement can be made, rather than a $30,000-$50,000 overhaul and crankshaft replacement.

2. An increase in the amount of silicon in conjunction with a corresponding increase in iron, aluminum, and chromium is probably caused by dirt ingestion, Figure 2. Air filter replacement and oil change may be the only maintenance action required. An increase of silicon alone may mean the oil type was changed to one containing a silicon-based antifoaming agent and no maintenance action is required. The trend without an increase of silicon could mean piston wear.

3. Sometimes even the slightest increase or presence of an element can be cause for alarm. The bearing shown in Figure 3 was removed from the gearbox of an aircraft. The presence of only 2 ppm (parts-per-million) of copper was sufficient to warrant maintenance action. The source of the copper was the bronze bearing cage.

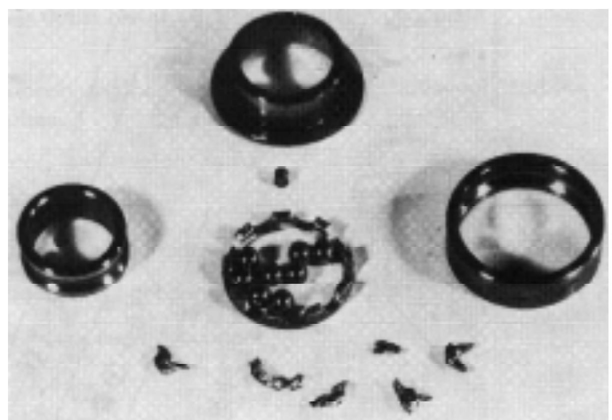

Figure 3, Example of a bearing failure

4. A trend showing the presence of boron in most water-cooled systems would indicate a coolant leak. If left unchecked, the coolant combines with combustion products and forms harmful acids which attack metal.

Oil analysis by itself or in conjunction with additional simple tests can be used to extend oil change intervals. This is accomplished by monitoring the oil's additives package and contamination, an added capability that makes oil analysis even more cost effective and popular in today's unpredictable oil market.

LUBRICANT CONDITION MONITORING

The second part of an effective oil analysis program is lubricant condition monitoring to determine the effectiveness and remaining life of the lubricant based on degradation and contamination analysis. The number and type of tests performed on a used oil sample vary with the type of oil and the type of machine being monitored. Physical property tests performed by the typical used oil analysis laboratory, often using modifications of ASTM procedures to reduce analysis time, include the following: viscosity, TBN (Total Base Number), TAN (Total Acid Number), water content (Karl Fischer), fuel dilution, and insolubles.

Physical property analysis has been a "must" product of the commercial laboratories and is becoming a serious consideration of the military programs. It consists of a series of related tests which determine the contamination and degradation of a lubricant. Physical property analysis is synonymous to extended oil change interval which is, of course, at today's prices, the same as money in the bank to users of larger quantities of lubricants. Oil change intervals are generally based on mileage or time on a system. Physical property analysis, on the other hand, allows retention of the oil in a system as long as it holds its beneficial properties.

The extended oil change program is what makes oil analysis appealing and sellable to the owner of large fleets of vehicles. The typical program consists of wear metal analysis and the six tests shown in 1. The first four tests monitor oil degradation and the remainder, contamination.

Table 1, Lubricant Physical Properties

Oxidation
Nitration
Viscosity
Additive Depletion
Water Dilution
Fuel Dilution
Solids

Oxidation is a term used to describe degradation of a lubricant caused by chemical reaction between the oil and oxygen at the elevated temperatures of operation. The result is an acidic condition and sludge which cause component wear and oil thickening. Oxidation reduces a system's service life and impairs oil circulation.

Nitration in some aspects is similar to oxidation, but in this instance, nitrogen-containing compounds combine with used oil to form oxides, mostly at the top of the cylinders. Nitration is an indication of blow-by and is characterized by oil thickening and an offensive odor.

The flow rate of a lubricant in relation to time is referred to as viscosity and it is one of the most important properties of a lubricant. An abnormally low viscosity reduces oil film strength which is its ability to prevent metal to metal contact. Its ability to carry contaminants away from moving parts and sealing ability will also be degraded. An abnormally high viscosity reduces the effectiveness of the lubricant and the contaminants which are the cause of it will increase wear of components and could create harmful deposits.

The use of chemical additives in lubricants has become extremely important in modern machinery. As mentioned earlier, an additive may be in the lubricant to combat an adverse condition or enhance lubricating properties. Some additives are required for efficient operation. In some cases, the presence of an incorrect additive can be detrimental to the equipment. For these reasons, the quantity and type must be continuously monitored. Additive depletion testing has, therefore, become very important in oil analysis programs.

Water in the oil is a result of coolant or anti-freeze leaks, or, in the case of marine applications, can be caused by sea water. Excessive amounts of water will cause wear, attack bearing metal, and affect the lubricating qualities of the oil. Excessive water could be an indication of inadequate head torquing, a cracked head, or broken lining.

Small amounts of fuel in the lubricant do not present a problem. At engine operating temperatures, small amounts evaporate and an equilibrium is reached. Large amounts of fuel dilution result in the same detrimental effects as experienced with water dilution.

Solids in a lubricant may be due to ingested dirt, wear metals, or byproducts of an incomplete combustion process. It is indicative of carburetor problems, oil filter saturation, and an indication of the efficiency of the air intake system. Excessive solids will cause wear.

TURNKEY USED OIL ANALYSIS LABORATORIES

The configuration and required instrumentation of a laboratory will vary based on the machines being monitored and the sample work load. A full-service laboratory is shown in Figure 4. In a modern oil analysis program, the basic minimum components consist of an emission spectrometer, a Fourier Transform-Infrared spectrometer (FT-IR) and a viscometer. Each instrument sends its results to a data based laboratory information management system for data storage, evaluation and reporting.

A rotating disc emission (RDE) spectrometer is the basic instrument recommended for routine measurement of the elemental concentration of wear metals, contaminants and additives. It provides simplicity of operation, sensitivity to larger particles, freedom from diluting samples, and requires no gas or cooling water while completing analysis of approximately 20 elements in less than a minute. An atomic absorption spectrometer (AAS) is seldom used unless the sample volume is extremely low and cost per sample is not a consideration. An inductively coupled plasma (ICP) spectrometer is recommended only where absolute accuracy of results is important, such as quantification of additive elements in a lubricating-blending plant.

FT-IR spectrometers for used oil analysis have dedicated programs which extract lubricant degradation and contamination parameters from the measured spectrum of the used oil sample. The technique is fast, less than a minute per sample, and provides data on oxidation, nitration, sulfation, soot, fuel dilution, water and glycol contamination and in some cases, additive depletion. As a fast trending technique, it has become a standard instrument in many high sample volume used oil analysis laboratories.

A viscometer is the third required instrument in the basic turnkey used oil analysis system. Viscosity is the single most important physical characteristic of a lubricant since it determines load carrying ability as well as flow and heat flow characteristics. Manual viscometers are inexpensive and work well in low sample volume requirements. Automatic viscometers are readily available for various degrees of automation and unattended operation.

In the basic system, measurements from each analytical instrument are sent to a central computer file where the results are incorporated into a history file for each unit (specific machine or sampling point on a machine). When tests are complete, the computer calls up the file of each unit and compares the results to a criteria matrix with allowable limits and to past analyses. In an automatic evaluation mode, records for samples with all data within limits are passed directly to the history file and a report with no recommended action is sent to the maintenance personnel. Samples with "out of limit readings" are flagged for review by the laboratory expert, who can then send a report with a maintenance recommendation to the maintenance personnel via telephone, telefax or printed copy.

This basic used oil analysis laboratory can be expanded as the analytical requirements of the laboratory or the sample work load increase. Ferrography, which magnetically separates the wear particles in an oil sample and arranges them according to size on a microscope substrate, gives important supplemental information on ferrous particles too large to be measured by routine spectrometric methods.

Total Acid Number (TAN), Total Base Number (TBN), and Karl Fischer water determination are three frequently performed ASTM tests for oil degradation and contamination. An automatic titrator is sometimes supplied with a turnkey system if more definitive information than that supplied

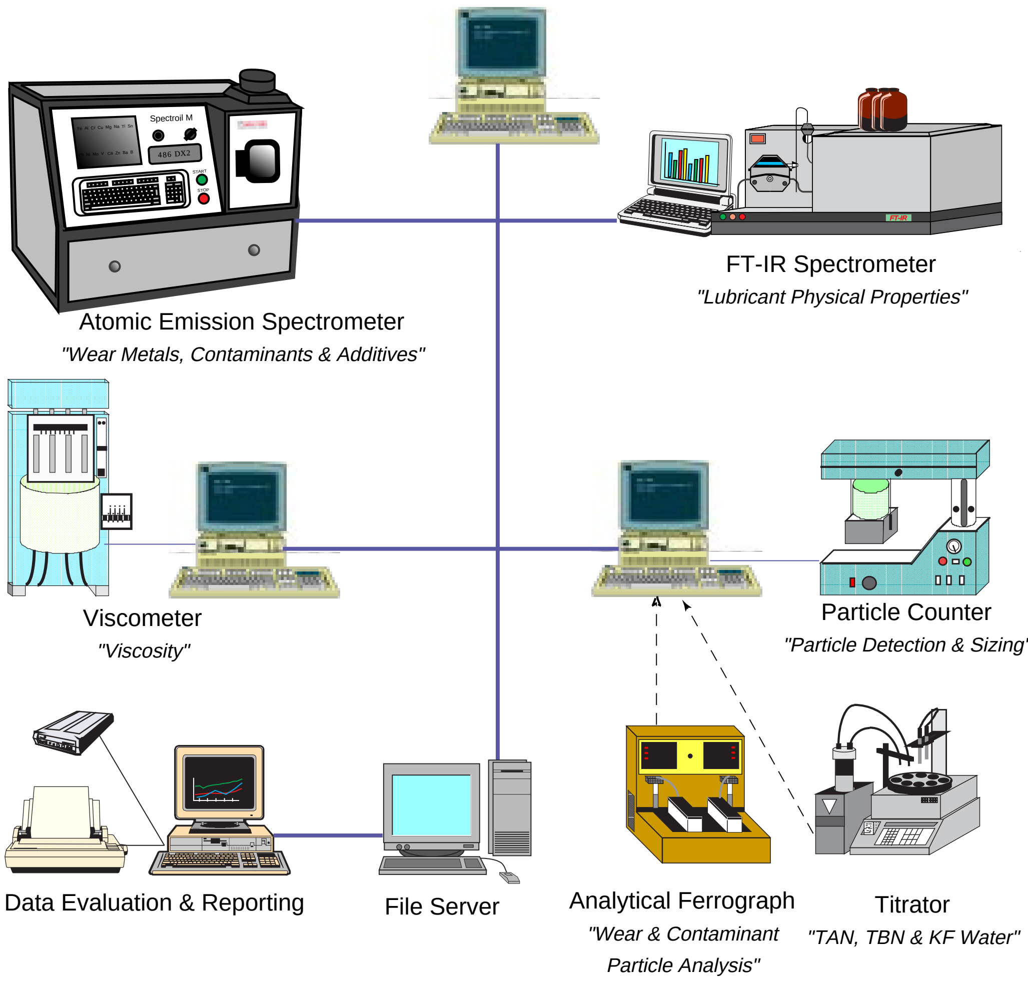

Figure 4, Full-service turnkey used oil analysis laboratory by the FT-IR spectrometer is required.

Particle count measurement is sometimes recommended, primarily for use with hydraulic systems or other clean lubricating oil systems such as those for turbines and compressors.

With this added equipment, the used oil analysis laboratory combines the analytical speed required for large sample volumes with the additional capabilities of providing specialized ASTM based tests. It contains instruments and operating software designed specifically for used oil analysis with turnaround times of 24 to 48 hours to provide data trends used for effective machine condition monitoring. With expanding needs, a local area network (LAN) can be used to share information and additional tests can be added to match specific machinery monitoring needs.

CASE HISTORIES

The following are a selection of predictive maintenance examples. They show the effectiveness and versatility of well managed and properly applied condition monitoring programs based on oil analysis.

Aircraft Turbines

Several case histories documented at Nellis Air Force Base, Nevada, are good examples of oil analysis as applied to aircraft components.

Case 1

Table 2 shows the last seven spectrometric oil analysis results of the lubricant taken from an F100-100 engine out of an F15 aircraft. Note from the spectrometric readings that initially there was no trend; however, after 430 hours of operation, the iron content jumped from 4 to 11 parts-per-million from one flight to the next. A check sample and ground run gave the laboratory sufficient cause to request a teardown. The cause for the increase in iron is shown in Figure 5. The number 4 bearing case was found to be broken and pieces were found in the sump. This is an ideal example of the SOAP program's capability of predicting an imminent malfunction and preventing catastrophic failure.

Table 2, SOAP Trend on F100-100 Aircraft Engine, End Item F15

	Reason for			**Elements**				**Lab**
OVHL	**Sample**	**F e**	**Ag**	**Al**	**Cr**	**Ni**	**Ti**	**Recommendation**
424	**R**	4	0	0	0	1	1	**A**
426	**R**	4	0	0	1	1	1	**A**
427	**R**	4	0	2	1	1	1	**A**
428	**R**	4	0	2	1	1	1	**A**
430	**R**	3	0	2	1	1	1	**B**
430	**R**	12	0	2	1	1	1	**G**
430	**L**	12	0	2	1	1	1	**T**

R = Routine; **L** = Lab Requested; **B** = Submit Special Sample ASAP;
A = No Recommendation, Continue Routine Sampling
G = Sample After Each Flight - DO NOT FLY UNTIL RESULTS ARE KNOWN;
T = GROUND UNIT, Examine for Discrepancy, Advise Lab

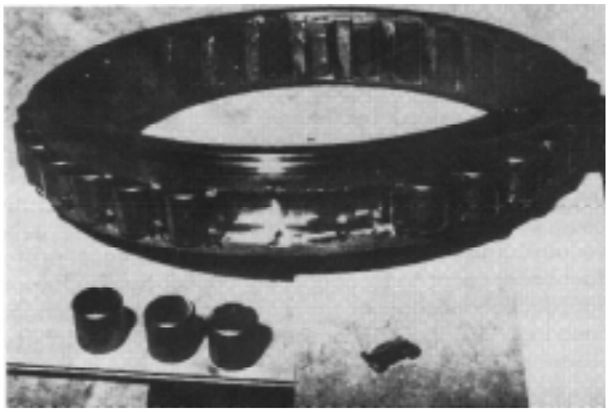

Figure 5, No.4 Bearing from F100-100 engine

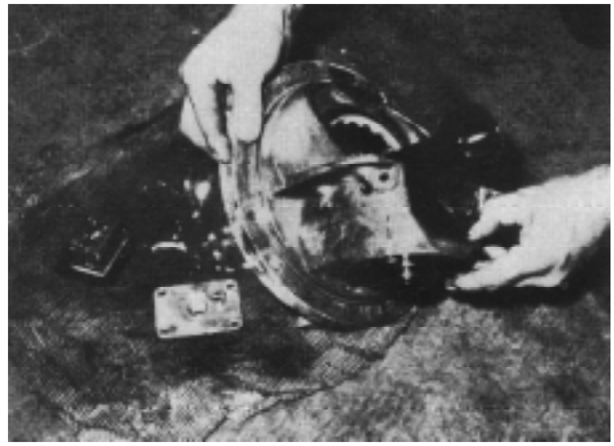

Figure 6, Gearbox from J79-GE-15 Engine

Case 2

The spectrometric analysis results for a J79 engine out of an F4C Phantom aircraft are shown in Table 3. The laboratory requested a resample when an increase in the sample aluminum content from 3 to 10 parts-per-million was noted. A teardown revealed that the inlet gearbox vertical drive shaft shims had torn loose and metal particles were found in the screen. Note the particles and cracked housing in Figure 6. Obviously, JOAP did not detect the large particles shown, but enough smaller ones were present to indicate the increasing aluminum trend.

Case 3

A TF30P3 engine out of a F111 Aircraft did not show a drastic increase in the wear metal trend. The iron content increased very gradually with operation and oscillated back and forth near the upper allowable iron threshold. When the iron level reached the threshold for the second time over several hours of operation, the engine was recommended for teardown. Upon disassembly for overhaul, the discrepancy found by the depot facility was a loose outer case in the tower shaft bearing (Figure 7), causing it to turn in its housing.

Table 3, JOAP Trend on a J79 Aircraft Engine, End Item F4C

	Reason for	Elements						Lab
OVHL	**Sample**	**Fe**	**Ag**	**Al**	**Cr**	**Mg**	**Ni**	**Recommendation**
181	**R**	23	0	0	0	11	1	**A**
196	**R**	26	0	4	1	10	1	**B**
196	**L**	24	0	4	1	10	1	**G**
196	**R**	26	0	3	1	11	1	**A**
197	**R**	26	0	5	1	12	1	**A**
198	**R**	28	0	7	1	13	1	**A**
202	**R**	31	0	10		14	1	**F**
202	**L**	34	0	11	1	18	1	**T**

R = Routine; **L** = Lab Requested; **B** = Submit Special Sample ASAP;
A = No Recommendation, Continue Routine Sampling
F = Submit Special Sample After Each Flying Day
G = Sample After Each Flight - DO NOT FLY UNTIL RESULTS ARE KNOWN;
T = GROUND UNIT, Examine for Discrepancy, Advise Lab

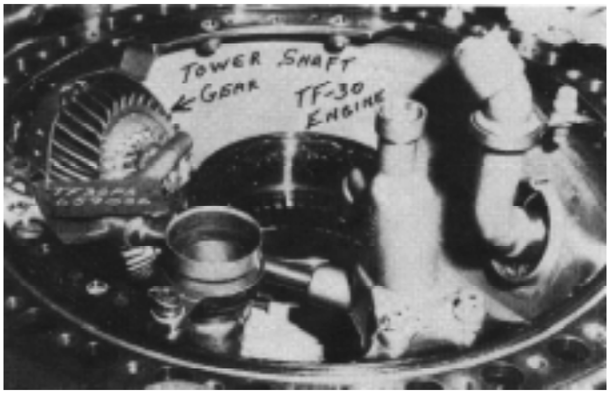

Figure 7, Tower shaft bearing TF30P3 engine

Lubricant Mix-Up

A serious recurring problem in maintenance procedures is the use of an incorrect lubricant. A condition monitoring program can readily identify such problems through the analysis of the lubricant additive package and lubricant physical property analysis.

The most common occurrence of lubricant mix-ups occur when an oil system is "topped off" to replace the oil that has been lost due to use or leakage. Usually a small amount of incorrect oil in a large closed loop system presents few immediate problems. This is, however, not the case in certain diesel engines as illustrated by this example.

Table 4 below is a summary of the last four oil analyses for a medium speed diesel engine from a locomotive. Only the most significant analytical data is shown.

The data clearly shows that after the first two samples, an incorrect oil was used to top-off the reservoir. The three additive metals magnesium (Mg), Phosphorus (P), and zinc (Zn) appear in the third analysis and increase in the fourth, a clear indication that the oil formulation has changed. In this type of engine, an incorrect oil which contains a zinc based additive package can result in severe wear problems. Several components such as bearings and wrist pins have silver coatings which corrode and wear in the presence of zinc. The early stages of the corrosive action cause by the zinc additive is indicated by the increase in the iron, copper and silver wear metals. A recommendation based on the analysis was made to drain and flush the system and to observe correct top-off oil requirements. Without oil analysis, the wear problem could have resulted in a bearing failure and a major overhaul costing over $150,000.

Contamination Example on a Pump Turbine

Pump turbines are used in many parts of the world to generate electrical power. Water is pumped to an elevated reservoir at night when power is relatively inexpensive. During peak power requirement periods, the water is allowed to flow downhill to turn a turbine which is coupled to a generator. These are reliable systems. However, condition monitoring based on oil analysis can be very effective at predicting a possible failure in the very early stages of the problem and prior to secondary damage or catastrophic failure.

A pump storage system of an electric utility was part of a condition monitoring program when the laboratory detected an increase in “coarse” wear particles in the upper guide bearing assembly of the turbine. Although the normal analysis using an emission spectrometer was acceptable, the laboratory requested more frequent sampling based on the data for iron and babbit metals obtained with a large particle detection system option to the emission spectrometer. The original and the next three analyses using the standard emission spectrometer and the large

Table 4, Spectrometric Results for an EMD Medium Speed Diesel Locomotive

Date	Fe	Cu	Ag	Mg	P	Zn
9/30	19	10	0	0	0	3
12/23	21	10	0	0	9	3
3/23	27	13	2	107	75	90
6/11	25	30	10	220	110	123

particle detection (Rotrode Filter Spectroscopy, RFS) technique are shown in Figure 8. Although the normal emission spectrometric analysis does not show a trend, the RFS analysis definitely does.

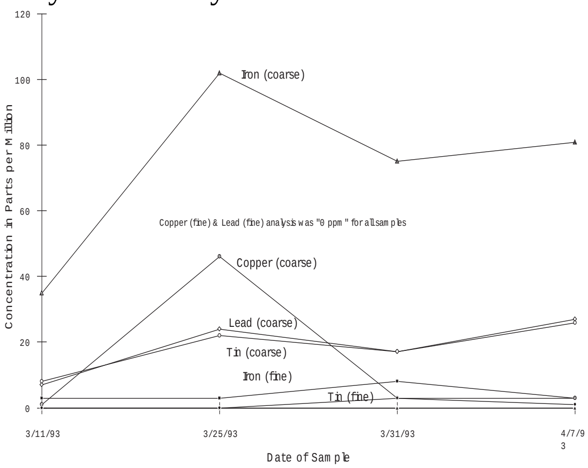

Figure 8, Pump Turbine Guide Bearing Wear Trend

Ferrographic analysis on the last two samples verified the presence of large cutting wear particles, Figure 9, causing the laboratory to issue an ALERT.

However, the presence of spheres on the ferrogram was the eventual indicator which lead to the source of the wear problem. Tilting pad bearings such as those used on the turbine do not generate spheres in a wear mode. Weld beads were suspect and it was eventually verified that the turbine had not been protected during overhead construction work. Weld debris including weld beads, and not a defective component, were the cause of the wear trend.

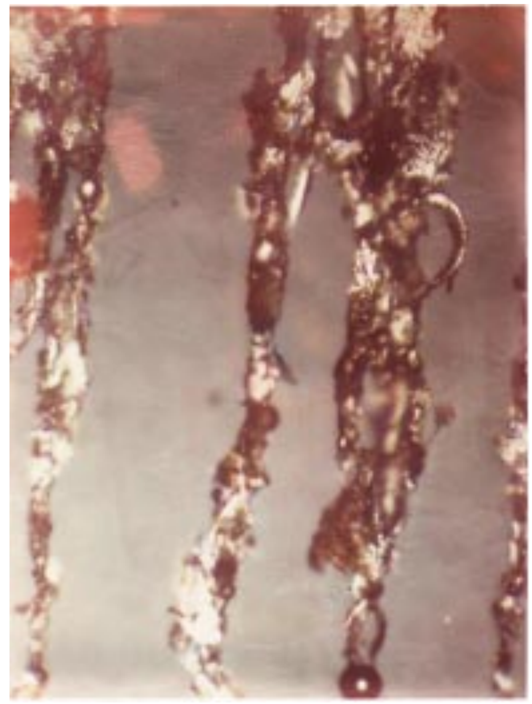

Figure 9, Ferrogram Showing Cutting Wear and Weld Beads

Although the wear was not critical, the oil was cleaned as a precaution and more frequent oil analysis monitoring was recommended. The wear trend if undetected by oil analysis may or may not have lead to a catastrophic failure. The thought of failure is not a pleasant one, especially in view that such a failure can require a multi-millon dollar overhaul.

CONCLUSION

It is never too late to implement a machine condition monitoring program. The benefits of the program can be realized in a very short period of time. Figure 10 is a typical summary of the types of problems that will be encountered in most instances. A number of serious or critical problems will be identified almost immediately. These will require immediate attention to avoid secondary damage, unexpected downtime or a major overhaul. A surprising number of imminent problems will also be identified. These are the future unplanned failures and should be scheduled for action and/or repair during the next scheduled maintenance shutdown.

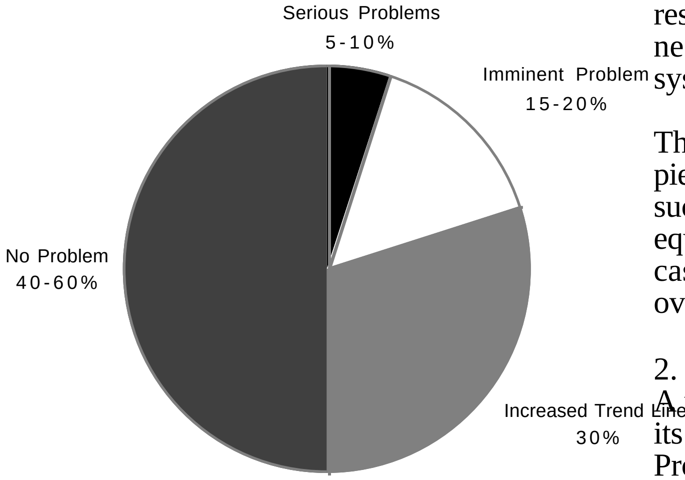

Figure 10, Summary of Problems in a Maintenance Program

The objectives of a predictive maintenance program based on condition monitoring through oil analysis is to identify potential failures in their early stages when repairs can still be initiated and costly secondary damage is avoided. A second objective is to monitor the quality of lubricants and to reduce lubricant usage through extended oil change intervals. The net benefits are reduce maintenance costs, increase equipment availability and life, reduce lubricant usage and improve safety. They can be summarized as follows:

1. *REDUCE MAINTENANCE COSTS*
This is the most apparent advantage, but sometimes the most difficult to document. Several problems can be avoided through an oil analysis program:

a. Total Equipment Loss. A serious mechanical failure can result in the total destruction of that piece of equipment. An obvious example could be the failure of the main bearing in a turbine.

b. Secondary Damage. The failure of a minor component can often result in much more extensive damage to the equipment. For example, if detected early enough, the replacement of a defective bearing can prevent the catastrophic damage and cost associated with a crankshaft replacement.

c. Over-Maintenance. A system of routine, scheduled maintenance will inevitably result in work that is performed before it is necessary. An on-condition maintenance system based on oil analysis can prevent this.

d. Maintenance-Generated Failures. The potential of human error exists whenever a piece of equipment is overhauled. A mistake such as the failure to tighten a bolt can result in equipment damage and failure when, in many cases, the equipment need not have been overhauled in the first place.

2. *INCREASE EQUIPMENT AVAILABILITY*
A mining company must make effective use of its equipment in order to fulfill its function. Profitability or effectiveness is lost every time a piece of equipment is in the shop due to secondary damage or unnecessary maintenance.

3. *REDUCE LUBRICANT USAGE*
The analysis of oil for degradation and contamination provides an indicator of its ability to lubricate. If the reserve alkalinity, detergent, and extreme pressure qualities have not degraded and the contamination is low, the oil change interval can be extended, conserving both money and natural resources.

4. *IMPROVE SAFETY*
When considering aviation, not much more need be said, especially in the case of single engine aircraft. Other equipment such as diesels, compressors, or generators, may also pose potential safety hazards in the event of a major destructive failure.

It is almost impossible in today's competitive environment to operate a mine without some kind of predictive maintenance program. Condition monitoring based on oil analysis is a proven technique which leads to more efficient use of equipment and maintenance savings. Some basic principles that must be followed in implementing such a program to fully realize its benefits are:

1. *Well Defined Purpose* - You must clearly state what is to be accomplished. In most cases it is to save maintenance costs and improve equipment availability.

2. *Appropriate Tests* - Testing takes time and costs money. Many tests are possible, but the proper mix provides the necessary data and a certain amount of double checking.

3. *Careful and Timely Sampling* - An oil analysis program creates reports based on the analysis of the oil taken to the laboratory. An improperly taken or contaminated sample results in poor and erroneous data. Samples taken too infrequently can miss a potential problem, and those taken too frequently add to operating cost.

4. *Commitment to Act on the Information* - Everyone from the individual who takes the sample, the laboratory personnel and maintenance and management personnel must be committed to act on the information produced by the laboratory. It does no one any good , for example, if a mechanic ignores the information provided by the laboratory

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