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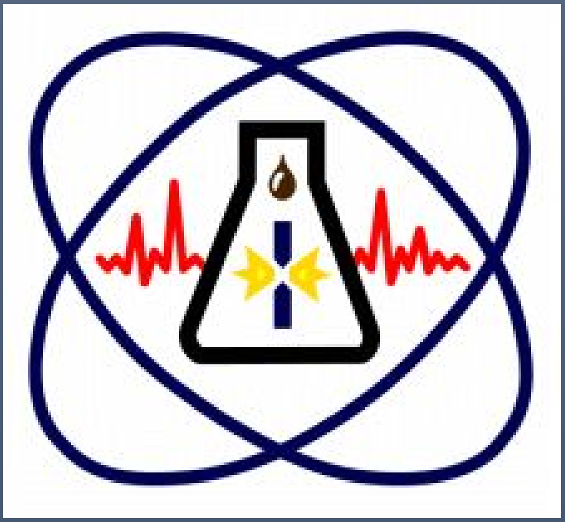

Lubrication Guide

AN IN-DEPTH LOOK INTO LUBE OIL ANALYSIS

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Introduction

Lube oil analysis has become an increasingly important tool for the preventive/predictive maintenance of oil-lubricated machinery. It is relatively inexpensive, results are returned in a short period of time (usually two days), and the results can be used in conjunction with other useful analytical tools such as vibration, thermography, and beta monitoring to diagnosis small problems before they become large, catastrophic problems. Successful preventive/predictive maintenance programs will produce less downtime, lower repair costs, and will prolong the life of equipment.

An Ounce of Prevention

The need for lube oil analysis can best be illustrated by the need for preventive maintenance to one's own body. Simple preventive measures such as routine check-ups help lengthen our life span. If a problem is detected, the doctor can make a correct diagnosis through further testing to help decide upon the proper corrective treatment. Lube oil analysis in its simplest form can be likened to a routine check-up. If a problem is suspected or indicated, more thorough analysis can be performed using all the tools at hand.

Value Analysis

The value of performing lube oil analysis as a regular part of your predictive/preventive maintenance program can be converted into real dollars saved by simple mathematics. If the cost of analysis is $25.00, and the unit is sampled each month for ten years, the total spent on lube oil analysis is $3,000. Now consider the replacement cost of that equipment, which is likely many times the cost of analysis. Then add the cost incurred by down-time, man-power, and parts needed to repair major damage caused by a lubrication related failure of a major component. Again, it is most likely significantly more than $3000. Generally, one or two minor 'saves' in ten years will pay for the cost of analysis many times over.

The value of lube oil analysis can even be measured in the cost of lives and injuries saved, as in the case of numerous product compressor and pump 'saves' in refineries and petrochemical plants.

Equipment Condition

Lube oil analysis usually serves as the first line of defense for checking the condition of the equipment in question. In most cases, bearing, gear, or piston wear will first be noticed by trend changes in the metals analysis. Depending on many factors, vibration may still be weeks or months away from picking up a slowly evolving wear situation. Lube oil analysis is often the warning flag that calls for closer vibration monitoring, thermography, etc. In situations where the first hint of trouble is noted by vibration monitoring, analytical ferrography may be called for to aid in the diagnosis. Lube oil analysis and vibration monitoring together can provide an effective program to indicate and diagnose wear situations in rotating equipment. Checking on equipment via lube oil analysis **will not** prevent wear from occurring; however, it may prevent further wear in many cases if the information received is acted upon. Using lube oil analysis to check on the condition of the lubricant **will** most often prevent wear.

Lubricant Condition

In addition to looking for wear metals, a complete lube oil analysis will also check for contaminants, some additives, and other physical properties to ensure the lubricant is performing its task adequately. Dilution with fuel, product, or water often is the root cause of wear situations and detecting this condition in time can prevent many wear situations from occurring in the first place. In some instances, changing an entire reservoir may be very costly, and reclamation may be needed. In others, simply replacing the oil may be sufficient. In either case, it is almost always less expensive to correct a bad or contaminated lubricant problem than to repair a piece of equipment.

Lubrication Fundamentals

Base Stocks

Paraffinic

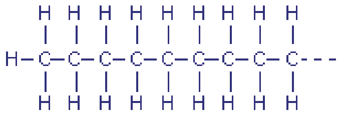


Figure 1. Paraffin Structure

- Predominantly straight chained hydrocarbons
- Relatively high wax content (1-10%)
- Contains some naphthanes and aromatics
- Most widely used for standard lubricants

Naphthenic

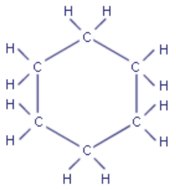


Figure 2. Napthene Structure

- Predominantly ring-shaped hydrocarbons
- Relatively wax free (trace)
- Contains some paraffins and aromatics
- Widely used for electrical insulating oils

Synthetic

- Manufactured hydrocarbons and compounds with predictable and repeatable structures
- 7-10 % of current lubricant market and growing
- High oxygen stability
- Low internal friction
- Good high and low temperature properties
- Different synthetics are manufactured for different applications
    - pao (poly-alpha-olefin) - most common
    - esters: diesters (dibasic acid esters), polyol esters, phosphate esters
    - pag (polyalkyeneglycols)
    - silicones, silicates, siloxanes
    - fluorocarbons
    - other, specialty lubricants

Intermediates/blends

- Combinations of the above types
- Provides some of the advantages of both blended products
- Can lower the cost of some synthetics, yet still provide adequate protection

Functions

Lubricating oils are called upon to perform many different functions necessary to ensure the long life of the equipment, such as removing heat and protecting the lubricated surfaces. Given the wide variety of loads, temperatures, and operating environments, it is clear why there are so many different lubricants available. A manufacturer may blend hundreds of different lubricating oils, each engineered to perform particular functions under particular operating conditions. For this reason, to specify a lubricant for any application, consult with your lubricant supplier to select the proper oil for the proper application.

Reduce Friction and Wear

Lubricating oil provides a fluid film between two metal wear surfaces to prevent them from touching. Metal surfaces moving in opposite directions and touching each other produce a tremendous amount of friction and heat. The energy produced can easily heat the surfaces to over 1000°F. Although it is localized, it is enough to melt bearings, gear, and other surfaces.

Remove Heat

As lubricant moves away from the metal contact point, the heat generated due to locally pressurizing that point stays with the lubricant. While oil does not conduct heat well, in normal operating conditions it provides sufficient heat transfer to prevent thermal runaway. In many cases, the lubricant must be cooled with an exchanger before being used to lubricate again.

Inhibit Corrosion or Rust

Oxygen is the main corrosive element found in lubrication systems. Oxygen will combine with certain metals and organics to create corrosive acids, oxidize the lubricant, and react with iron to form rust (FeO, Fe_2O_3, and Fe_3O_4). Hydrogen, when combined with chlorine (common additive in some lubricants) and water, forms hydrochloric acid which will attack metal surfaces if unabated. Some lubricants are called vapor-phase lubricants, because they contain alkaline amines that will vaporize at certain temperatures and coat metal surfaces with a rust-preventing layer of organics.

Remove Wear Particulates

Some lubricant additives will coagulate particulate matter so it will drop out in the sump or be removed through filtration. Other additive packages will attach themselves to particulates so their combined specific gravity is at or near the specific gravity of the lubricant. This will prevent the particulate from falling out of suspension and depositing in unwanted places. Some are heat-dependent so that when the oil is hot it will disperse the particulates, but when the oil cools a few degrees it will coagulate them and allow them to fall out of suspension or be filtered out. Others are time-dependent, i.e., at first they will suspend the particulates but gradually they will coagulate them to allow the coagulated masses to drop out in the sump or be removed by filtration.

Minimize Contaminants

Lubricants can provide an intermediate fluid to absorb and/or reject contaminants, depending upon the application. A good seal lubricant will readily absorb gases as well as readily release them when heated or scrubbed with air or glycol. Many lubricants are designed to release water easily, usually in the sump or the filter. Other lubricants have additives that will coagulate particles so they can be filtered out. Some lubricants have a combination of these characteristics. When selecting a specific lubricant for a specific application, it is best to discuss the application with your lubricant supplier.

Transfer Energy

Because liquids are virtually uncompressible, you can exert a pressure on one liquid surface and apply it to all the other corresponding surfaces in the volume containing that liquid. If a tube is filled with a liquid and has identical movable plates on the ends, applying a force to one plate (the "input") will apply the same force to the other ("output") plate. If the input plate is twice as large as the output plate, the output plate will receive a force twice as large as the force on the input plate. This ability to "amplify" input forces is why many forklifts use a hydraulic mechanism.

However, in order to do this consistently and concisely, the fluid used to do the work must be clean enough not to leave a deposit anywhere in the system, which would change the dynamics of the hydraulic calculations. The cleanliness level of the lubricant in question can be established by *particle count analysis*, which is reported in ISO (International Standards Organization) standards. Cleanliness levels are very important in numerical control systems, high speed turbines, and hyper-compressors.

Types

Hydrodynamic Lubrication

> The adhesive properties of the oil on a turning shaft draw the oil under the shaft and create a hydrodynamic wedge or film due to the oil's resistance to being pressed out.

Elastohydrodynamic Lubrication

> Typical of roller bearings. Deformation occurs in the contact zone increasing the surface area. Film becomes very thin and lubricant changes instantaneously to solid or semi-solid.

Boundary Lubrication

> Sliding surface lubrication such as reciprocating cylinders during starts, stops, shock loads, and directional changes. Uses extreme pressure and anti-wear additives to combine with metal surface to form a sacrificial layer of protection.

Hydraulics

In addition to lubrication, oils can be used for *hydraulics*: the transmission of force or motion using confined fluids to perform work. Hydraulic fluids are formulated with combination of additives and characteristics to meet various application requirements and price constraints.

An oil needs several qualities to be suitable for hydraulic applications:

- Chemical stability and oxidation resistance
- Corrosion protection (most hydraulic systems contains a variety of metals)
- Compatible with elastomer seal material
- Light enough to prevent sluggish response, yet heavy enough to provide required lubrication.
- Good anti-foam characteristics to prevent sluggish response
- Inhibited to prevent rust

In addition to the general qualities above, certain applications may call for fire-resistance, high temperature stability, or good low temperature characteristics.

Pressurized Lubrication Systems

In a *pressurized lubrication system*, oil is pumped from a sump or reservoir through coolers and filters and finally to the lubricated components. The oil is then collected by a manifold and returned to the sump. Other auxiliary equipment may be added to the system, such as bypass filtration systems, centrifuges, degassifiers, etc. A pressurized system is applicable for use in most gear and bearing systems because it allows for cooling and filtration.

A typical pressurized system contains some of the following components:

- Sump, reservoir, or day tank
- Pump or multiple pumps
- Cooler, usually water cooled
- Filter or screen
- Collection manifold

Splash Lubrication Systems

In a *splash lubrication system*, lubricated components are partially immersed in an oil bath, and the rotational movement of the component splashes oil to other parts and areas of the equipment. This is sometimes aided by a slinger ring, which rotates freely with the shaft rotation, picks up oil from the bath, and 'slings' it to the top of the bearing and other locations in the system. This kind of system is appropriate for gear, chain, and roller bearing systems which do not require cooling.

Stream/Spray Lubrication Systems

With a *stream/spray lubrication system*, a stream of pressurized lubricant is aimed directly at the component to be lubricated. (The stream may be nebulized into a spray for better coverage.) Used lubricant is usually collected and returned to the sump by gravity. It is used primarily in gear and roller bearing systems.

Mist Lubrication Systems

A *mist lubrication system* works by atomizing oil into sub-micron droplets with clean, dry compressed air. The mist, which looks like smoke, is piped to the oil-lubricated compartment at a slight positive pressure. The mist coalesces on the component surface to provide lubrication. Mist systems provide a slight positive pressure in the compartment providing a purge. Older mist systems were vented to the atmosphere, but newer systems are closed systems, allowing the coalesced lubricant to be reused. They work well with gear and roller bearing systems.

Drip Lubrication Systems

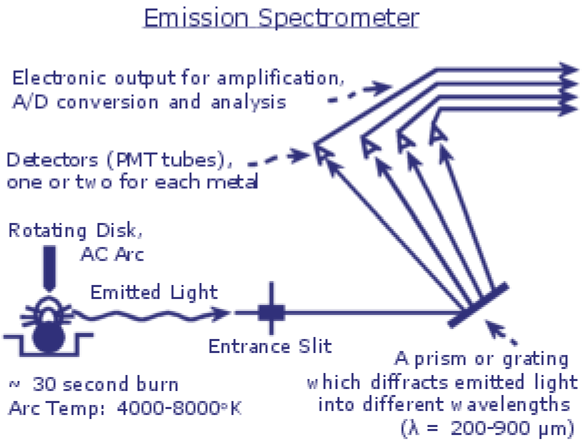
Drip lubrication system release continuous metered drops of oil onto the lubricated assembly. They are most often once-through systems: collection cups are emptied periodically or dumped into a water/oil sewer system. Drip systems are suited for small, lightly loaded roller bearing systems.

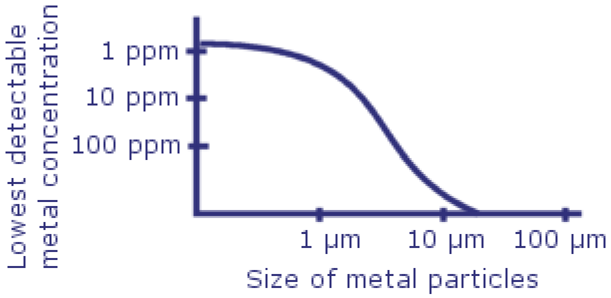
Lube Oil Analysis Tests

Rotating Disc Electrode-Atomic Emission Spectrometer (RDE-AES)

The heart of most lube oil analysis programs is a check for metals. With today's technology, this is usually a quick, simple, and cost-effective test. The two most common instruments used for this are the ICP (inductively coupled plasma) spectrometer and the rotating disk atomic emission spectrometer. Either of these two instruments can be set up to analyze twenty-five or more single metal elements simultaneously. This section is focused on the atomic emission spectrometer.

When this test is conducted, a carbon disk rotates in a small representative portion of the sample. The disk's rotation throws some of the oil into a high voltage AC arc between the rotating disk and another carbon electrode. The temperature of this arc is from 4000° to 8000° Kelvin, depending on a number of factors including the oil type and major constituents. This 'burn' lasts for about 30 seconds. As the metal atoms or small particles are vaporized in the arc, each metal gives off light at a particular wavelength, and is part of the total emitted light. Detection efficiency for the rotating disk atomic emission spectrometer when 20 or more metals are measured simultaneously A prism or grating then diffracts the emitted light into different wavelengths, and the intensity of each of the metal wavelengths is measured by its own photo-multiplier tube, or PMT. A computer plots the output from the PMT on a curve which was developed from NITS traceable standards. The curve position is then converted back to parts per million, or *ppm*. This is the value you receive on your reports.





The spectrographic metals reported fall into three categories:

Wear	**Additive**	**Contaminant**
Iron	Silicon	Silicon
Lead	Boron	Boron
Copper	Copper	Sodium
Tin	Sodium	Phosphorous
Aluminum	Phosphorous	Potassium
Chromium	Zinc	Calcium
Nickel	Calcium	Magnesium
Silver	Magnesium	
Titanium	Molybdenum	
Zinc	Antimony	

Advantages

- A properly operated and programmed emission spectrometer can average one sample per minute. This speed, along with the amount of data generated (twenty or more elements), makes this perhaps the most cost-effective test of all.
- NIST standards are readily available for calibration curve generation.
- Accuracy is usually within acceptable limits.
- Results are easily used for trend analysis.
- Results include some contaminant and additive metals as well as wear metals.

Disadvantages

The major disadvantage of the atomic emission spectrometer is the particle size limitation. Usable detection efficiency is limited to an average of 10 microns, thus large 50 and 100 micron particles will not be seen as easily by the detection system. The limitation on the detection efficiency size will vary with each metal, along with such things as the thickness of the metal oxide layer on the particle's surface and the melting point of each metal. Usually, however, when the number of large particles increases in a sample, so does the number of smaller particles (1-10 microns in size). This is one of the reasons that trending becomes so important when looking at emission spectrometer data. Also, this size limitation can be overcome by acid digestion of the sample which reduces the metals particles to an ionic state so they can be easily seen by the spectrometer. This is done at the sacrifice of speed and efficiency, however.

Karl Fischer

This is a quantitative test which determines the amount of water present in the oil. Water can be present in three forms: dissolved, emulsified, or free. The Karl Fischer Water Titration measures all three. The test is accurate down to the 10 ppm level and is the only acceptable test for measuring quantities below 500 ppm. This is important when looking at turbine, pump, and compressor oils, which most often have a tolerance level of about 100 ppm. Today this test is most often done on automatic titrators which are extremely sensitive.

A small measured amount of representative sample is introduced in the reaction vessel. This amount is usually 1 cc; however, the analyst will vary this according to how much water is expected. In the reaction vessel, water molecules will react with an iodine solution to form iodate. This iodate will increase the potential at a platinum electrode. The current increase as a result of the potential increase is directly related to the amount of water present. When all the water molecules have been titrated, the potential will return to its normal state. The instrument will analyze the curve created by the current increase vs. time and calculate the amount of water present. Results are reported in parts per million (ppm).

Advantages

- Even trace amounts of water can be determined.
- The test is relatively quick and easy to run on an automatic titrator.
- The results are generally repeatable to within 5%.

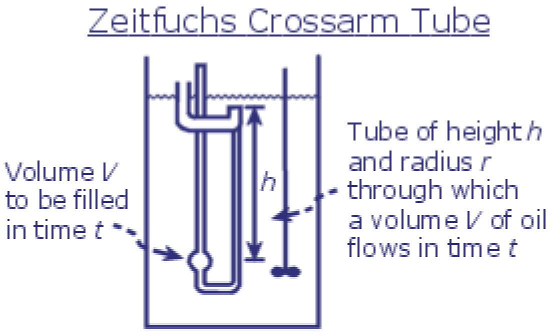
Disadvantages

- The required reagents are costly.
- Certain sulfur compounds have a positive interference on the results.

Viscosity

Viscosity is one of the key properties of a lubricant. Oils are generally referred to by their viscosity grade. (For example, ISO 32 and 10w30 refer to viscosity ranges.) With the exception of engine oils, most viscosities are measured at 40°C, with results expressed as Centistokes (cSt), or at 100°F, with results expressed as Saybolt Universal Seconds (SUS). Engine oils are generally run at 100°C or 210°F. A change in the viscosity of an oil usually indicates contamination and/or degradation of the oil. Viscosity is also a good test to see if the correct oil is in a given piece of equipment.

Viscosity tests are run in a number of different types of measuring tubes in a constant temperature bath. We use a Zeitfuchs Crossarm Tube. A small amount of sample is introduced into the crossarm and the temperature is allowed to reach equilibrium with the bath. The crossarm gives the oil a constant head pressure when it is being measured. After the oil reaches the equilibrium temperature (about 5 minutes), the oil is pushed over the crossarm and flows down the tube to fill a measured volume chamber. The time it takes to fill the volume chamber is measured down to a tenth of a second. This time is then multiplied by the tube factor, and the results are in units of cSt. Centistokes can be converted to SUS when the viscosities are being run at 100°F or 210°F.



Advantages

- Viscosity tests are accurate, easy to run, and relatively inexpensive (no reagent costs).
- The results are easily trended and is often the first indication of oil degradation and/or contamination.

TAN

As lube oil breaks down, a variety of acids are formed. These acids cause corrosion to any metal component that is subject to corrosion, especially babbitt bearings. Acids are often introduced into lube oils as contaminants. The Total Acid Number titration accounts for all the acids present, either introduced or formed. Some lube oils, especially synthetics, have a base line TAN of as much as 0.7 or greater mg KOH/gram of oil. Most mineral oil lubricants will have 0.0 or 0.1 as a base line.

Two to five grams of oil are mixed with 100 mls of solvent. The solvent consists of 50% toluene, 49.5% isopropanol, and 0.5% water. This mixture is then titrated with 0.1N potassium hydroxide to an end point of 11. A color indicator, p-Naphtholbenzein, changes from orange to green at pH 11. The amount of titrant needed to reach this end point is measured and reported as milligrams KOH/gram of oil.

Advantages

- The test is quick, accurate, and sensitive to even slight acid content.
- The results are easily trended.
- Reagent costs are relatively low.

Disadvantages

- Some lube oil additives will be included in the results.

TBN

Engine oils contain additives to neutralize acids as they build up. This ability to neutralize acid is measured by the Total Base Number, or TBN test.

The test is similar to the TAN test, except the titrant used is 0.1N Hydrochloric acid, and the solution is titrated to an end point of pH 3. Either a color indicator or pH meter can be used to measure the end point.

Advantages

- The results are a good indication of additive depletion in engine oils.

Disadvantages

- Results are not always consistent when using a pH meter to measure the end point.

Infrared

As oil degrades, especially in internal combustion engines, oxidation biproducts are formed. Also, nitration of the oil can occur which is indicative of oil degradation. The level of oxidation and nitration of the lube oil can be measured by infrared analysis. Different atom-to-atom bonds absorb light in different points in the infrared region. This fact can be used to detect oxidation (carbon oxygen double bonds) and nitration (carbon nitrous-oxide bonds). The amount of light absorbed is measured to give a number usually ranging from 1 to 4. This number represents the % transmittance decrease divided by 10. Typically, new engine oil may have a base line oxidation/nitration of 1/0 or 1/1. These are caused by additives.

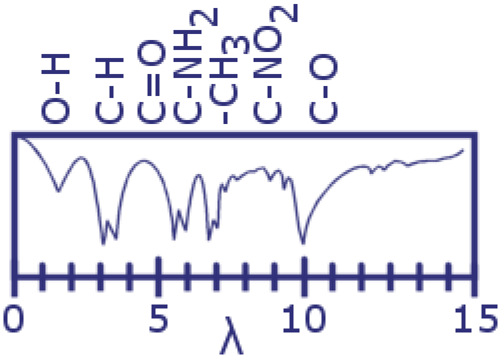


Figure 3. The downward peaks represent light absorption for those atom bonds listed.

A few drops of lube oil are placed in a cell with a path length of 0.005 centimeters. An infrared light beam is then passed through the cell window at wavelengths from 400 to 4500 cms. Oxidation and nitration product atom bonds will then become excited (vibrate, stretch, or bend) and absorb light at their own wavelength. The percentage transmittance decrease is measured and reported as *% transmittance decrease/10*.

Advantages

- The test is quick, accurate, and simple to run.
- Other contaminants such as fuel, glycol, and water can also been seen on the spectra.

Disadvantages

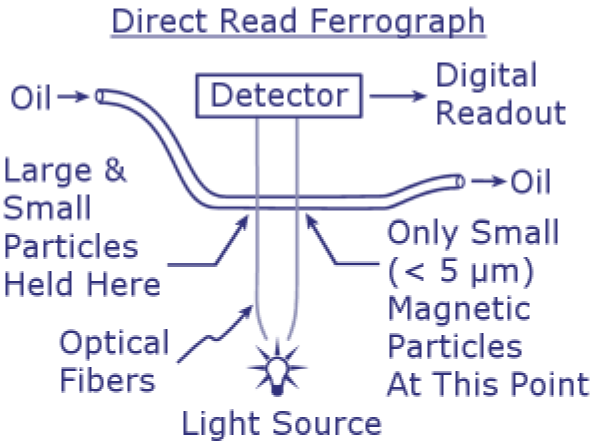
- Esters and di-esters mask the oxidation peak.
- Other additives also show up on the oxidation peak.

Flash Point

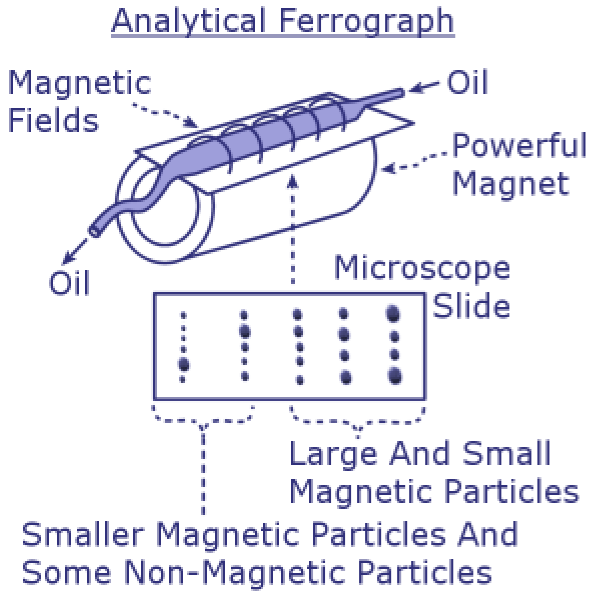
Checking the flash point of engine oils is a good way to check for excessive fuel dilution. No. 2 diesel fuel has a flash point of around 180°F, while gasoline has a flash point below 0°F. Most engine oils have a flash point around 425°F. A 2% diesel fuel dilution will lower the flash point of engine oil to about 400°F, while a 2% gasoline fuel dilution will even be lower. This test is also good for pumps and compressors where flammables are involved.

Approximately two ounces of oil are poured into an open cast iron cup. The flash cup is then placed on top of a heater which slowly raises the temperature of the oil. A calibrated thermometer is placed in the oil to monitor the temperature, and a small flame is placed approximately 1/2" above the cup. When the oil gets hot enough to give off flammable gases, the flame will flash the gases. The temperature of the oil at this point is the flash point. The temperature at which the lube oil is capable of sustaining a flame, is the fire point.

Ferrography



Ferrography actually consists of two different procedures. The first is called a **Direct Read Ferrograph**. A small representative portion of the lubricant, usually 1.0 ml, is diluted with a solvent and flowed through a glass tube at a slight incline over a permanent magnet. Two light detectors placed in series along the glass tube will measure the difference in light transmitted through the tube between the beginning of the sample flow and the end of the flow. The instrument is first "zeroed" with the portion of sample that reaches the detection system. This will help compensate for differences in the oils' colors. Ferro-magnetic particles are pulled out of suspension by the magnet and deposited on the bottom of the glass tube, as well as in the light paths of the two detectors. The detectors then measure the percent transmittance difference caused by the accumulation of ferro-magnetic particles. As a function mostly of its placement, the first detector will be "looking" through an accumulation of particles ranging from sub-micron to over 100 microns, and is reported as *Direct Read Large* or DRL, whereas the second detector will be "looking" through an accumulation of particles generally less than 5 microns in size, and is reported as *Direct Read Small* or DRS. The numbers generated are an empirical value ranging from 0.0 to 180.0. Larger numbers can be obtained by sample dilution.



The second ferrography procedure is called an **Analytical Ferrograph**. Again, a small portion of the sample is diluted with a solvent, but this time it is flowed over a glass slide sitting on a strong permanent magnet. The magnet pulls out ferro-magnetic particles and aligns them along its magnetic field vectors for easy viewing. The larger particles will be pulled out first, followed by increasingly smaller ferro-magnetic articles. Some non-magnetic particles will also be scattered along the slide in a non-magnetically aligned manner. This makes identification of ferrous particles relatively easy. The slide is then examined under a microscope, various particle types are identified and quantified, and a wear judgment is made.

Advantages

- Particles as large as 400 microns can be seen both in the Direct Read Ferrograph and the Analytical Ferrograph.
- A good analyst can usually pinpoint the type of wear that is occurring when doing an Analytical Ferrograph.
- Other non-magnetic particles are also trapped in the light path when ferrous particles are present. They can also be seen on the slide.
- Direct Read Ferrography results are easily trended.

Disadvantages

- The Direct Read Ferrograph cannot distinguish different metals.
- When no ferro-magnetic particles are present, the Direct Read Ferrography may miss other particles.
- The Analytical Ferrograph is time consuming, and hence expensive.
- Results of the Analytical Ferrography are not easily trended and are subject to the analyst's judgment and expertise.

Particle Count

Particle Count analysis, as the name implies, counts the number of particles in a given size range in a given volume of sample. We use three different particle counting methods: Laser Light Scattering, Flow Degradation Curve Analysis, and Microscopic Examination/Count. All three of these methods are capable of counting the number of particles on a given size range. The number of particles and size distributions are then used to determine the *Class of Cleanliness*. Three different classifications are used throughout the industry: ISO 4406 or NAS 1638. Each of these classification types has different size groupings and ratings.

Laser Light Scattering

An oscillating laser beam scans a known volume of sample over a given period of time. By measuring the intensity of scattered light and the intensity of incident light in a known period of time, a particle count by micron size can be determined.

Advantages

- The instrument is sensitive to particles down to approximately 4 microns.
- Results are easily converted to any of the three standard reporting classifications.

Disadvantages

- The instrument reads even minute air bubbles as particles.
- The instrument is sensitive to changes in the oils color.
- Large particles may settle out before being counted in low viscosity fluids.
- It may be time consuming when analyzing very "dirty" oil.

Flow Degradation Curve Analysis

This instrument uses a calibrated sensor screen, through which contaminated fluids are passed under pressure. This produces a distinctive flow decay curve, which is then analyzed by a proprietary computer formula, and particle count results are produced. This instrument and formula were developed by Diagnetics, Inc. of Tulsa, OK.

Advantages

- Results are not affected by air bubbles, water, or color.
- Results are comparable with other accepted methods.
- Tests are relatively quick and simple.

Disadvantages

- Equipment Cost.
- Compressed air-supply required.
- Frequent sensor screen replacement.

Microscopic Count

This method employs the use of a gridded filter through which 100 ml of fluid, diluted with solvent, is passed. Particles greater than 1 micron are trapped on the patch, which is then examined under a microscope. Each patch contains 100 grids. The accepted method of counting and sizing particles is to first examine the patch to make sure particles are evenly distributed across all the grids. Then select ten representative grids and manually count the particles in each size range. The ten results are averaged and multiplied by 100 to give results in particles/100 ml according to their size range.

Advantages

- Careful patch examination will probably produce the most accurate results of these three methods.
- Results are unaffected by air bubbles, water, or fluid color.

Disadvantages

- Very time consuming and tedious.

Data Interpretation

Metals

We report 20 different metals. Some are wear metals, some contaminants, and some are metallic additives. Many of these metals fall into more than one category. Below is a list of each category, along with each metal's most common source.

Wear Metals

Iron	Most common of the wear metals. Sources include cases, cylinder walls, valve guides, rocker arms, ball and roller bearings, bearing races, springs, gears, and shafts.
Lead	Bearing metal. Other sources include solder, paint, and grease.
Copper	Present in the form of an alloy, therefore usually found with tin (bronze), or zinc (brass). Sources include main or rod bearing thrust bearing, wrist pin bushing, gears, turbo-charger bushings, thrust plates, and roller bearing cages.
Chromium	Plating metal. Sources include piston rings, some cylinder liners, and chromium plated spacers.
Aluminum	Primary construction metal. Sources include cases, spacers, shims, washers, pistons, bearing cages in planetary gears, and some bearing surfaces.
Nickel	Alloying metal in hardened steel.Sources include shafts, valve train, and turbine blades.
Silver	Plating metal. Sources include some bearings, some engine wrist pin inserts, and silver solder joints in piping.
Tin	Bearing metal. Sources include babbitt bearings, oil seals, and solder.
Titanium	Alloying metal in hardened steel. Sources include shafts, valve trains, turbine blades, and compressor.
Antimony	Alloying metal in some babbitts. Source as wear metal is almost always bearings.

Additive Metals

Copper	One of the newest metallic additives. Generally found in the 100 to 200 ppm range.
Silicon	Anti-foam additive. Generally found in the 10 to 25 ppm range in gear oils, and some engine oils.
Boron	Part of the detergent package. Used to cut down NO_X emissions. Generally found in the 100 to 200 ppm range.
Sodium	Probably coming from one of the metallic additive salts. Usually found below 30 ppm.
Zinc	Anti-wear, anti-corrosion. Is part of the ZDDP (Zinc Dialkyl Dithio Phosphate) additive package in most engine oils. Found anywhere from 100 to 3000+ ppm, depending on the manufacturer.
Calcium	Anti-corrosion. Calcium levels from 150 ppm to over 2% are present in some oils, depending on the manufacturer.
Barium	Anti-corrosion, anti-wear. Is currently being eliminated due to its toxicity Levels used to run as high as 3000 to 5000 ppm in some oils. Barium is rarely found above 50 ppm in newly formulated lubricants.
Magnesium	Anti-corrosion, anti-wear. Generally found below 50 ppm.
Molybdenum	Extreme pressure anti-wear. Used in lubricants where heavy loads are expected. Can be found from 20 ppm up to 5000+ ppm, depending on the manufacturer and oil type.
Antimony	Extreme pressure additive. Only present in a few special gear oils.
Phosphorous	Anti-wear, anti-corrosion,detergent. Part of the ZPPD package. Most often, phosphorus will be within plus or minus 50% of the zinc level when part of a ZPPD package.

Contaminant Metals

Silicon	The most common contaminant. Sources include airborne dust, grease, sealants, and coolant leaks.
Boron	Coolant additive. Most common source is coolant leak.
Sodium	Salts in water. Most common source is coolant leak.
Zinc	Sometimes used as coolant additive. Sources include coolant leak, galvanized piping, and grease.
Calcium	Found in high concentration in ground water and open cooling systems. Most common source is coolant leak where cooling tower water is used.
Barium	Used in drilling fluids. Usually found in oil field equipment with water contamination.
Potassium	Normally a coolant additive. When present in lubricating oil, it is almost always indicative of a coolant leak.

Physical Data

The physical data consists of several tests: *viscosity*, *TAN*, *TBN*, *infrared analysis*. Other assumed tests such as odor and color are also conducted whenever warranted.

Viscosity

Viscosity may very well be the most important physical data test that is routinely run. Many things affect an oil's viscosity. As lube oil degrades, polymers are formed which increase the viscosity. Oil that is under heavier-than-normal loads will react to form friction polymers in the presence of a catalyst, such as copper or iron. Temperatures outside of the oil's useful range will also act on the lubricant to form polymers, and the oil becomes 'cooked', driving off the lighter ends, and leaving behind coke or carbon residue. Except in extreme cases, the viscosity will increase measurably, long before any of this happens.

Contaminants will also change an oil's viscosity. Glycol, for instance, will form globs in the oil, with a consistency of soft tar balls. Obviously, the lubricant can no longer perform the function of maintaining a film between two wear surfaces, and metal to metal contact begins.

Water will usually initially decrease an oil's viscosity. Shortly thereafter, the viscosity will increase as the water becomes emulsified with the oil, and the oil begins to form polymers. In many instances, this is a very short process, and is never seen by running monthly viscosity tests.

Other contaminants such as dirt and wear metal particles can also increase the oil's viscosity. The dirt can act as an abrasive and introduce abrasion wear particles into the oil. Where the abrasion is occurring, the temperature rises, and all the ingredients for polymerization are present: heat, a catalyst, and the oil.

Viscosity is also affected by fuel dilution or process gas dilution. Usually a decrease in viscosity indicates fuel dilution where engines are concerned, and product dilution where light end hydrocarbons are concerned. In either case, the lube oil will lose its ability to maintain a film between two wear surfaces, and metal to metal contact will occur.

TAN

As the oil degrades, a number of different types of acids can be formed. The particular types of acids present are not as important as how much there are. Acids are categorized into strong acids and weak acids. The major difference between the two is how fast the acid will corrode metal surfaces. Most of the oil degradation acidic by-products fall into the strong acid category. They will attack babbitt bearings and aluminum surfaces first, creating pits. Once corrosion pits are formed, a whole regiment of wear mechanisms can begin, including fatigue spalling, cracking, etc.

Lubricants with high metallic additive packages will generally have a high TAN base line (0.3 - 0.7). These acids are weak acids, and generally cause no damage to aluminum or babbitt surfaces.

We measure *total acid*, which includes both strong and weak acids. An increase of the Total Acid Number from the base line of any lubricant usually indicates an increase of strong acids.

The TAN can also be affected by contaminants. Chlorides, for example, can form hydrochloric acid in oil. Sulfur compounds can form sulfuric acids. Both of these are very damaging to babbitt and aluminum.

When an acidic lube oil comes in contact with the case, which is usually cast iron, a slow corrosion process begins. Once a corrosion begins, the problem is only resolved by removing the source of the acid (i.e., changing the oil).

TBN

TBN refers to the ability of the lube oil to neutralize acids. In equipment that is particularly subject to acidic attack, mainly engines, a high TBN is desirable. A TBN of 3.0 or better for engine oils is usually considered adequate protection. TBN's may start off as high as 20.0, and degrade to 3.0 before the lubricant should be change. Most new engine oil lubricants have a TBN in the 5 to 10 range.

Additives such as calcium, magnesium, and others contribute to an oil's TBN.

Infrared

Infrared analysis is very useful when checking engine oils for oxidation and nitration by-products. Four major types of oxidation by-products are formed when oil degrades. All four form carbon-oxygen double bonds which can be seen on the infrared spectrum. The level of oxidation, or *oxidation number*, should never exceed three. At a level of four, the lube oil will begin to polymerize, and form acids beyond the capacity of the oil to neutralize. Some additives will also contain carbon-oxygen double bonds, and the baseline must be considered when determining the degradation level of an engine oil.

Oxidation by-products are measured at a wavelength of 1704 to 1715 cm. Esters and di-esters show at a wavelength of 1736 cm and mask the oxidation peak. When using an ester additive type oil in an engine, the oxidation number is not useful for determining degradation. The TAN would be a more appropriate number of degradation.

Nitration by-products show on the infrared scan at a 1602 to 1610 cm. Increases in the nitration number are usually an indication of an improper air-to-fuel ratio which forms nitrates and other nitrose compounds. These compounds act as intermediates to the oxidation reaction and can cause excessive sludge and varnishing. Generally, the nitration number should be below three (3).

Other Contaminants

Water is perhaps the largest single cause of major equipment failure. While some oils such as engine oils with high additive packages can tolerate a relatively high-water content (1000 ppm), other oils such as turbine and compressor oils cannot. Levels of water in the 100 ppm range can cause acids to form and bearing corrosion to occur.

Other contaminants such as coolant leaks, airborne dirt, and product are usually noted by reviewing the other standard test (such as emission spec or viscosity). Paper filter parts, for example, would be picked up on the blotter test, as well as on a Direct Read Ferrography. Coal dust would be picked up on the blotter test. Sometimes further investigation is needed to identify the source of the contaminant.

Ferrography

Direct Read Ferrography

Direct Read Ferrograph results consist of DRL and DRS, which refers to large and small particles, respectively. This test is **not** a particle count, although it is similar to one. While the name of the test implies that only ferro-magnetic particles are 'counted,' in fact many non-ferro-magnetic particles are usually included. This is actually beneficial as filter by-pass and/or filter breakdown is also usually seen by the direct read ferrograph results, as well as gross contamination by such things as airborne dirt and sand blasting material.

DRF numbers will vary according to the type of equipment in question. Normally operating centrifugal compressors will have a DRF below five, while some normally operating engines will have a DRF above 100. Trend analysis is important when interpreting Direct Read Ferrography numbers.

The relationship between the DRS and DRL can also give some insight to a possible problem. If the DRS and DRL are relatively close in numbers, then corrosion is the most likely cause. If the DRL is twice the DRS or more, then a wear situation exists that should be examined more thoroughly.

Analytical Ferrograph

When doing an analytical ferrographic analysis, a close working relationship with the customer is essential. Understanding the metallurgy of the lubricated components, as well as the lubricant itself, will help the analyst make a correct wear judgment.

The Analytical Ferrograph report lists 16 general wear particle types. Each particle type is given one of four possible ratings: *none*, *few*, *moderate*, or *heavy*. This rating is based upon the relative number of that type of particle present, the type of equipment the lubricant is being used in, as well as the judgment of the analyst. Within each rating except *none*, one of three levels of severity is assigned, which is indicated by the position of the "X" in the rating box (the right-most is the most severe). Some wear particles may fit into more than one category. (*Laminar particles*, for instance, certainly can also be classified as *severe wear particles*.) A *wear judgment* is also made by the analyst based upon the cumulative ratings, along with the analyst's knowledge of the lubricated surface or surfaces. *Comments* are then added to explain the wear judgment and also to pass along information not readily gleaned from the main report body. Photo-micrographs are then presented of actual particles, along with a description, to further explain what was present on the ferrogram. Below is a list of the particle type headings found on the analysis report along with their definitions:

Normal Rubbing Wear Particles

Most lubricated surfaces generate particles in normal operation, especially steel or iron surfaces. These particles are generally under 5 microns in the major dimension for iron and steel, and may be up to 15 microns for some copper alloys. They show no signs of severe or abnormal wear such as striation marks, tortuous shape, or severe discoloring from excessive heat. An oxide layer may appear on some of the surfaces, depending on the age of the particle and the operating conditions, however, these oxide layers are usually slight. *Normal rubbing wear particles* will usually have a thickness to length ratio of less than 1 to 5. While this type of particle is considered normal, an excessive amount usually indicates a shortened life expectation of the lubricated component in question.

Severe Wear Particles

These are generally considered to be any metal particle which was generated by the machine component and which falls outside of the *normal rubbing wear particle* category. It includes fatigue spalling particles, misalignment cutting wear particles, laminar and spherical particles from rolling elements, and most babbitt metal particles. This is a broad category that includes particles that fit into the next four or five categories.

Cutting Wear Particles

Two types of cutting wear particles are rated together in this category: small cutting wear particles which result from abrasion, and longer, more tortuous shaped cutting wear particles which result from misalignment. The difference is usually noted in the comments. Particles that are generally called *shavings* are included here. Cutting wear particles resulting from misalignment usually are striated (marked with long sliding gouges), and in the case of some metals such as copper and carbon steel, they are most often curled. More brittle metals will not necessarily be curled; however, they will be striated. Cutting wear particles resulting from abrasion are generally less than 5 microns, while those resulting from misalignment may reach hundreds of microns for less brittle metals.

Chunks

Chunks are considered to be those particles larger than 5 microns, whose length-to-width ratio is 1 or 2, and whose major dimension to thickness ratio is also 1 *or* 2. They are literally 'chunks' of metal. Usually generated at fatigue cracks, either in roller elements or gear teeth. By the nature of gear meshing, the pitch line can also be considered a 'rolling element', and fatigue cracks are often formed in this area due to excessive load.

Laminar Particles

Laminar particles are large, flat, round shaped particles. It is generally believed they are formed by particles which are repeatedly passed between two rolling elements, literally flattening them out. This category includes wear particles that temporarily attach themselves to roller bearings or gear pitch lines by a welding action, then flatten out and break the weld. There origin is not certain; however, their presence always indicates some rolling element damage. Whether they cause the damage or were created by the damage is not always clear. Their width-to-thickness ratio is in the order of 25-1, and are generally 20 to 40 microns wide.

Spheres

Spheres are generated at rolling element fatigue cracks.The exact mechanism of their generation is unclear; however, large numbers of ferrous spheres in the 1 to 5 micron size range indicate fatigue cracks. They literally grow from the bottom of the crack, and it is believed that their spherical shape comes from equal multi-directional pressure forces coupled with heat generated by compressing the metal during overload conditions. Larger (10+ microns) spheres are usually a result of contamination by such things as welding slag.

Dark Metallo-Oxide Particles

These are dark ferrous-oxide particles which are generated as a result of excessive heat. Uneven load distribution, lubricant starvation, or inadequate lubricant contribute to the formation of dark metallo-oxides where sliding surfaces are concerned. They are generally in the 5-15 micron range, and are ferro-magnetic. This helps to differentiate them from such particles as carbon, which are not ferro-magnetic. Larger dark metallo-oxides are usually a result of contamination, are not as ferro-magnetic, and contain any number of other constituents such as sodium, silicon, manganese, sulfates, etc. The term *black ferrous oxides* indicates ferrous-wear-generated dark oxides, and usually is noted in the comments.

Red Oxide Particles

These are rust particles which are either a result of water being present or the completion of the oxidation process of *black ferrous oxides*. The difference manifests itself in the size of the particles. Those caused by water are large, and those resulting from lubricant starvation remain small (usually ten microns or less). In either case, the presence of excessive red oxides indicates a problem that needs attention.

Corrosive Wear Debris

Non-Ferrous Metal Particles

These are all the metals that do not line up magnetically on the ferrogram. They include chromium, aluminum, copper, etc. This is a broad classification. Often some stainless steels are mistaken for non-ferrous metals. Heat treating a slide in steps up to 1000 °F and observing the temperature color generated can usually allow stainless steels to be identified. Other metals, such as copper, aluminum, and chromium, can often be identified with the help of heat treating the ferrogram.

Inorganic Non-Metallic/Birefringent

This category includes particles which cannot be identified as metallic and will disrupt polarized light. The inorganic nature of these particles is determined by heating to 625 °F, at which temperature most organics will char, shrivel, or evaporate. They generally indicate contamination.

Organic Non-Metallic/Birefringent

This is the same as *inorganic non-metallic/birefringent*, except identified as organic by their reaction to heat.

Amorphous Non-Metallic

These are particles, or generally masses, with no particular shape. Usually they are organic in nature, such as certain polymers. Friction polymers would fall into this category.

Friction Polymers

These are polymers which are formed as a result of heat and a catalyst, such as iron or copper. In most heavy load situations, friction polymers are to be expected, and may even be beneficial. An excessive amount of friction polymers, however, can alter the viscosity of oil such that it becomes an ineffective lubricant for a particular situation.

Fibers

Fibers are usually a result of filter deterioration. Other sources include contamination, some gaskets, packing, and some seals.

Other

Anything of significance that cannot fit into one of the above categories will be listed here. A description of the particle along with a "best guess," if appropriate, will be given in the comments.

Considered Judgment of Wear Situation

The analyst, using his/her knowledge of the equipment, the lubricant, and the visual evidence presented on the ferrogram, will make a wear judgment.

Comments

The analyst attempts to describe the slide and point out anything that may be of interest.

Particle Count

An increase of one or two classes over the previous particle count result is generally significant. Possible sources of class increases include filter failure, increased wear, and contamination. When using the ISO 4406 classification (such as "15/13"), the first number refers to the range number for particles < 6 microns, and the second number refers to the range number for particles < 14 microns. Below are some generally recognized recommended cleanliness levels.

RECOMMENDED CLEANLINESS LEVELS

Service application	SAE Class Range	Max ISO	NAS Class
Numerical control hydraulics	3	15/13	6
General hydraulic systems and hydrostatic bearing	4	16/14	7
General lubrication systems	5	17/15	8

Causes of Concern

Trend Analysis

Because of differences in oils, equipment types, manufacturers, location, and operations, no simple, universal guideline can be established for deciding the limits for metals in most oils.

Once some historical data is collected on a particular piece of equipment, however, some "rules of thumb" can be established as to when there is cause to be concerned. If data is available on the "new oil", a solid judgement can be made as to the condition of the used oil.

In most cases, trending particular data is more important than absolute numbers. Typical significant month to month results changes are as follows:

Wear Metals	An increase of 5 - 10 ppm, or 100% increase, whichever is larger
Contaminant Metals	An increase of 10 - 20 ppm, or 100% increase, whichever is larger
Water	Any increase that puts water above 100 ppm for pumps and compressors, 1000 ppm for engines, and 300 ppm for gear boxes
TAN	An increase of 0.3 for most equipment, 1.0 for engines
TBN	A decrease of 50% from new oil
Viscosity	A 10% change
Direct Read Ferro	A 50% increase of DRL when above 20.0
Particle Count	An increase of one or two classes or ranges

Upper Limits

While upper limits for any piece of equipment should be established after enough historical data is collected, the following are some rules of thumb.

	PUMPS	COMPS	GEARBOXES	ENGINES
Iron	15	10	25-50	50
Lead	10	5	5	15
Copper	15	15	15	15
Chromium	-	5	-	10
Aluminum	10	5	15	20
Nickel	5	5	5	5
Tin	10	5	10	10
Silicon	20	15	25	25
Water	100	100	500	1000
Viscosity	10%	10%	10%	10%
DRL	15	10	50	50
TAN	+0.3	+0.3	+0.5	+1.0
TBN	--	--	--	-50%
Oxidation	--	--	+1	+3
% Insolubles	0.05	0.05	0.5	1.0

Report Totality

In many cases, certain combination of metals and physical properties are as important as absolute numbers and trends. For example, high iron and water usually indicate corrosion. High iron and nickel usually indicate hardened steel wear. High iron and increased DRL usually indicate roller bearing or gear wear. Increased copper in a centrifugal AC compressor usually indicates tube corrosion. As is evident, the combinations are endless; however, with some knowledge of the machine and wear surfaces, many different problems can be diagnosed.

Centrifugal Compressors

Iron	Case corrosion
Iron/Tin	Bearing wear/corrosion
Aluminum	Bearing wear if aluminum bearings
Iron/Nickel	Major wear, most likely shaft
Copper	Tubing corrosion

Reciprocating Compressors

Iron	Case corrosion
Iron/Nickel	Cam, cam shaft wear/valve guides – stems
Tin	Bearing wear
Tin/Lead	Bearing wear
Tin/Lead/Copper	Significant bearing wear
Copper	Shims
Aluminum	Shims

Large Gear Boxes

Iron	Gear wear/bearing wear/case corrosion
Iron/Copper	Bearing wear/thrust plate wear
Iron/Nickel	Shaft wear

Small Gear Boxes (Cooling Tower/Mixers)

Iron	Gear wear/case corrosion
Iron/Copper	Bearing/bearing cage wear if roller bearings/bushings
Lead	Bearing wear/packing/seals
Iron/Lead	Bearing wear
Iron/Nickel	Shaft wear

Centrifugal Pumps

Iron	Usually case corrosion when the pump is in water or other corrosive liquid service. Check for the presence of H_2O.
Iron/Nickel	Main shaft wear
Iron/Lead/Tin	Bearing wear/corrosion
Tin/Lead/Copper	Significant bearing wear
Lead	Possible packing degradation, bearing wear

Gear Pumps

Iron	Case corrosion/gear wear
Copper	If roller bearings, bearing cage wear
Copper/Iron	If roller bearings, significant bearing/bearing cage wear

Diesel or Gas Engines

Iron	Block corrosion/cylinder wear
Chromium	Ring wear/liner wear
Iron/Chromium	Cylinder wear and ring wear
Iron/Nickel	Piston wear/cam wear/cam shaft wear valve wear/valve guides
Lead	Bearing wear/corrosion
Copper	Bushings/inserts

Hydraulics

Iron	Cylinder wear/corrosion
Copper	Line corrosion (fittings/bushings)

Proper Beginning and Ending

Sample Taking

Proper sampling is the essential foundation for any lube oil analysis program. The following are the keys to proper sampling:

Regularity

> Most critical plant equipment is sampled monthly. Extremely critical equipment may be sampled more often.

Systematic Sampling

> Samples should always be taken from the same point in the system, preferably from a petcock valve in the return line to the sump with the oil warm and the system operating. Sampling of new oil should be submitted periodically.

No Contamination

> Keep sample valves clean and run the sample directly into the sample bottle after flushing the sampling line with about 8 ounces of oil. If at all possible, do not sample from the oil reservoir drain plug.

Documentation

> Initially, data must be provided to adequately describe each piece of equipment to be sampled. Labels each month should be filled out accurately, including *sample date* and *hours on oil*.

Vehicles

> If samples are taken only at change intervals, samples of the drain oil may be submitted and results should be representative. Make sure the oil is fully warmed up and the engine runs for approximately 20 minutes before shutting it off and draining the oil. Always let the first quart or so go to drain before catching a sample. If between-change samples are to be taken, a *vampire oil sampling pump* is recommended. The pump is easy to use, and consecutive samples do not become contaminated. A section of tubing is coupled to the pump and fed down the dip-stick tube. Make sure the end of the tubing is not on the bottom of the oil pan, but approximately 2" off the bottom. Again, make sure the engine runs for 15-20 minutes before taking the sample. Never re-use a section of tubing, as the new sample may be contaminated with the previous sample.

Clearly, proper sampling is controlled by plant personnel.

Follow-Up

Just as proper sampling is the foundation of the oil analysis program, following up is equally essential:

- Establish an oil analysis program and integrate it into your overall PPM efforts.
- Develop a personal relationship with your service lab people.
- Ask your service lab personnel questions about the tests that are run and how to interpret the results.
- Keep accurate, organized files of your oil analysis reports.
- Act on warning and alarm situations and inform your service lab personnel of your findings.
- Review your files periodically with your service lab personnel to ensure the proper tests are being done for given situations.