Chapter 19

Successful Oil Analysis Practices In the Industrial Plant*

Every industrial organization has experienced the consequences of shoddy maintenance: contract penalties, junked parts, injuries, catastrophic damage, ballooning costs, missed shipping dates, irate customers, and sickly quarterly financial reports. Gone are the days when a machine had a predictable service life, after which it was replaced, continuing the cycle. Today, machinery and equipment can be maintained to achieve useful operating lives many times those attainable just a few years ago. For oil lubricated machinery there are many opportunities in what is commonly referred to as proactive maintenance.

By carefully monitoring and controlling the conditions of the oil (nurturing), many of the root causes of failure are systematically eliminated. Case studies of highly successful organizations show that oil analysis plays an important, central role in this nurturing activity. But first, in order for oil analysis to succeed the user organization must define what the goals will be.

Some people see oil analysis as a tool to help them time oil changes. Others view it in terms of its fault detection ability. Still, others apply it to a strategy relating to contamination control and filter performance monitoring. In fact, when a program is well designed and implemented, oil analysis can do all of these things and more. The key is defining what the goals will be and designing a program that will effectively meet them. One might refer to it as a ready-aim-fire strategy. The *ready* has to do with education on the subject of oil analysis and the development of the program goals. The *aim* uses the knowledge from the education to design a program that effectively meets the goals. The *fire* executes the plan and fine-tunes through continuous improvement.

DETECTING MACHINE FAULTS AND ABNORMAL WEAR CONDITIONS

In the past, success in fault detection using oil analysis has been primary limited to reciprocating engines, power train components, and aviation turbine applications. The generally small sumps associated with this machinery concentrated wear metals and the rapid circulation of the lubricating oils kept the debris in uniform suspension making trending more dependable.

In recent years, there has been widespread reported success with wear debris analy-

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*Contributed by James C. Fitch, Noria Corporation, Tulsa, Oklahoma sis for detecting machine anomalies in stationary industrial lubrication oils and hydraulic fluids as well. There are many explanations for this but much of it has to do with a rapidly growing base of knowledge coming from the burgeoning oil analysis and tribology community. Table 19-1 provides a simplistic overview of the application of oil analysis, specifically wear debris analysis, in machine health monitoring. The various specific methods are discussed in later sections of this chapter.

Table 19-1. Application of lube oil analysis.

	Root Cause Detection	Incipient Failure Detection	Problem Diagnosis	Failure Prognosis	Post Mortem
What Oil Analysis Is Telling You	When something is occurring that can lead to failure - root cause conditions	When an early-stage fault exists that is otherwise going unnoticed - e.g., abnormal wear	What the nature of a problem is that has been observed. - Where is it coming from? - How severe is it? - Can it be fixed?	That a machine is basically worn out and needs to be fixed or replaced	What caused the machine to fail? Could it have been avoided?
What You Monitor	Particles, moisture viscosity, tempera- additives, oxidation, TAN/TBN, soot, glycol, FTIR, RBOT	Wear debris density temperature, particle count, moisture, elemental analysis, viscosity, analytical ferrography	Wear debris, elemental analysis, moisture, particle count, temperature viscosity, analytical ferrography, vibration analysis	Elemental analysis, analytical ferrography, vibration analysis, temperature	Analytical ferrography, ferrous density, elemental analysis
Maintenance Mode	Proactive	Predictive	Predictive	Breakdown	Breakdown

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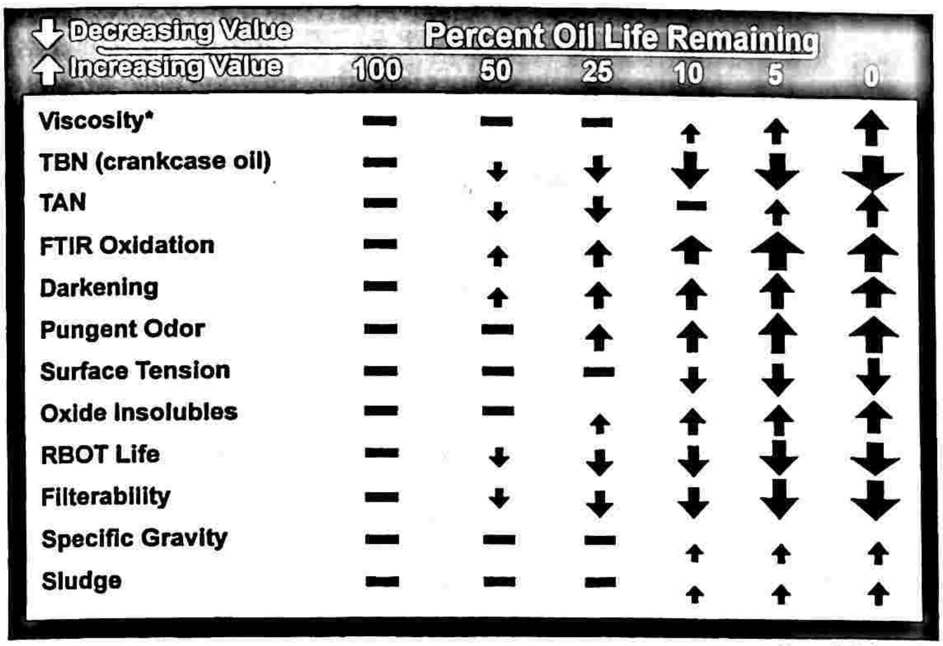
DOING CONDITION-BASED OIL CHANGES

Each year huge amounts of oil are disposed of prematurel, all at a great cost to the world's economy and ecology. This waste has given rise to a growing number of companies to discontinue the practice of scheduled oil changes by implementing comprehensive condition-based programs in their place. This, of course is one of the principal roles of oil analysis. One might say your oil is talking, but are you listening?

By monitoring the symptoms of oil when it tires and needs to be retired we are able to respond to the true and changing conditions of the oil (see Table 19-2). And, in some cases it might be practical to consider reconditioning the oil, including the reconstructing depleted additives. Some oil analysis tests even provide a forward-looking prediction of residual life of the oil and additives. Distressed oils, in cases, can be conveniently fortified or changed without disruption of production. And, those fluids that degrade prematurely can be reviewed for performance capability in relation to the machine stressing conditions.



↓ Decreasing Value ↑ Increasing Value	Percent Oil Life Remaining					
	100	50	25	10	5	0
Viscosity*	—	—	—	↑	↑	↑
TBN (crankcase oil)	—	↓	↓	↓	↓	↓
TAN	—	↓	↓	—	↑	↑
FTIR Oxidation	—	↑	↑	↑	↑	↑
Darkening	—	↑	↑	↑	↑	↑
Pungent Odor	—	—	↑	↑	↑	↑
Surface Tension	—	—	—	↓	↓	↓
Oxide Insolubles	—	—	↑	↑	↑	↑
RBOT Life	—	↓	↓	↓	↓	↓
Filterability	—	↓	↓	↓	↓	↓
Specific Gravity	—	—	—	↑	↑	↑
Sludge	—	—	—	↑	↑	↑

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Table 19-2. Changing parameters and their effect on remaining life of lube oil.

MONITORING AND PROACTIVELY RESPONDING TO OIL CONTAMINATION

While the benefits of detecting abnormal machine wear or an aging lubricant condition are important and frequently achieved, they should be regarded as low on the scale of importance compared to the more rewarding objective of failure avoidance (see Figure 19-1).

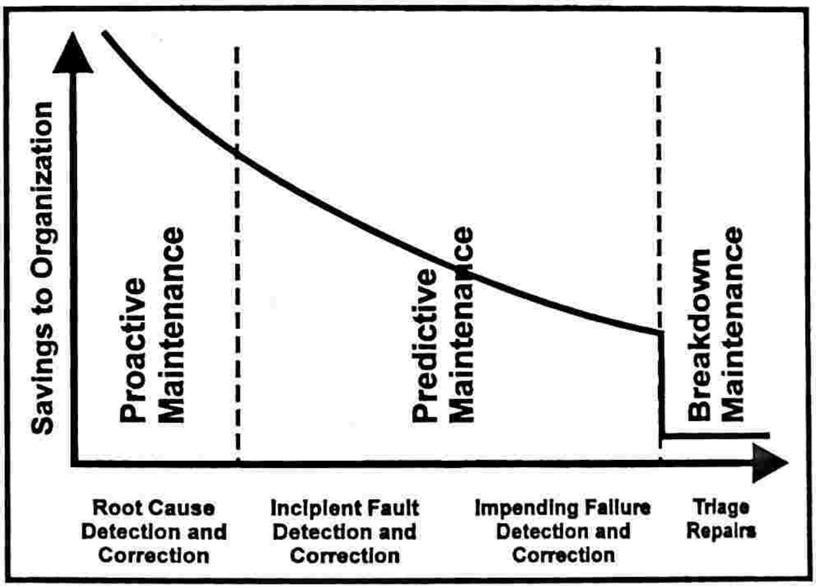

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Figure 19-1. Some maintenance strategies are more costly than others.

Whenever a proactive maintenance strategy is applied, three steps are necessary to ensure that its benefits are achieved. Since proactive maintenance, by definition, involves continuous monitoring and controlling of machine failure root causes, the first step is simply to set a target, or standard, associated with each root cause. In oil analysis, root causes of greatest importance relate to fluid contamination (particles, moisture, heat, coolant, etc.) and additive degradation.

However, the process of defining precise and challenging targets (e.g., high cleanliness) is only the first step. Control of the fluid's conditions within these targets must then be achieved and sustained. This is the second step and often includes an audit of how fluids become contaminated and then systematically eliminating these entry points. Often better filtration and the use of separators will be required.

The third step is the vital action element of providing the feedback loop of an oil analysis program. When exceptions occur (e.g., over target results) remedial actions can then be immediately commissioned. Using the proactive maintenance strategy, contamination control becomes a disciplined activity of monitoring and controlling high fluid cleanliness, not a crude activity of trending dirt levels.

Finally, when the life extension benefits of proactive maintenance are combined with by the early warning benefits of predictive maintenance, a comprehensive condition-based maintenance program results. While proactive maintenance stresses root-cause control, predictive maintenance targets the detection of incipient failure of both the fluid's properties and machine components like bearings and gears. It is this unique, early detection of machine faults and abnormal wear that is frequently referred to as the exclusive domain of oil analysis in the maintenance field.

OIL SAMPLING METHODS EXAMINED

The success of an oil analysis program depends heavily on proper oil sampling. Experience has taught that when it comes to correct sampling a person cannot rely on his or her instincts or judgment. Instead, the sampling practice needs to be learned from those experienced in the trade. It is even common to find published manuals on oil analysis teaching wrong or out-dated methods.

From a practical standpoint, optimum performance in oil sampling depends directly on succeeding in the following three areas:

Selecting the Ideal Sampling Point

In circulating oil systems such as the one shown in Figure 19-2, the best (primary) location is a live zone of the system upstream of filters where particles from ingression and wear debris are the most concentrated. Usually, this means sampling on fluid return or drain lines. Figures 19-3 and 19-4 show different options for sampling low pressure return lines. In the case of vented vertical drains from bearing housings there is not a solid flow of oil (air and oil share the line) making sampling more difficult. In such cases, a hardware adapter called a sample trap can be effectively installed to "trap" the oil for easy sampling (see Figure 19-5).

In those applications where oil drains back to sumps without being directed through a line (e.g., a diesel engine and wet-sump bearing and gear casings), the pressure line downstream of the pump (before filter) must be used. Figure 19-4 shows various options for sampling pressurized fluid lines. Where possible, always avoid sampling

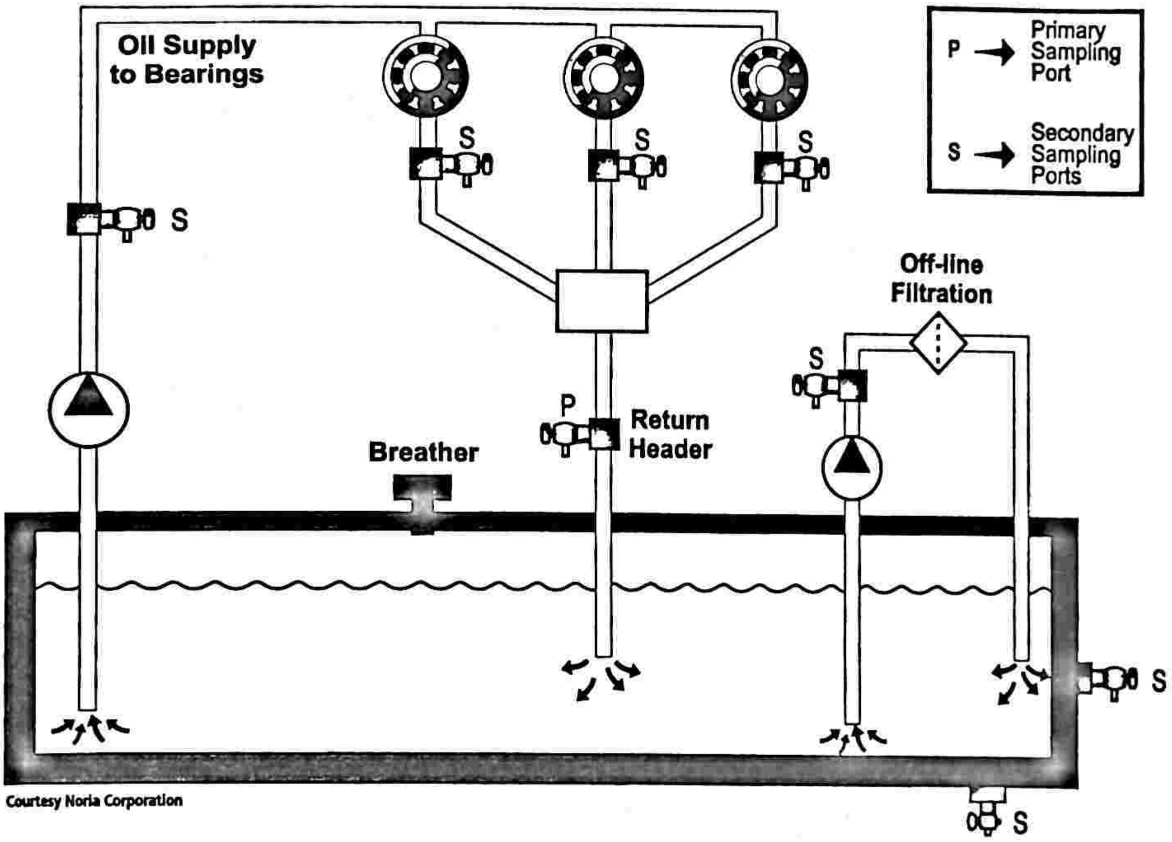

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Figure 19-2. Circulating oil system indicating recommended sampling points.

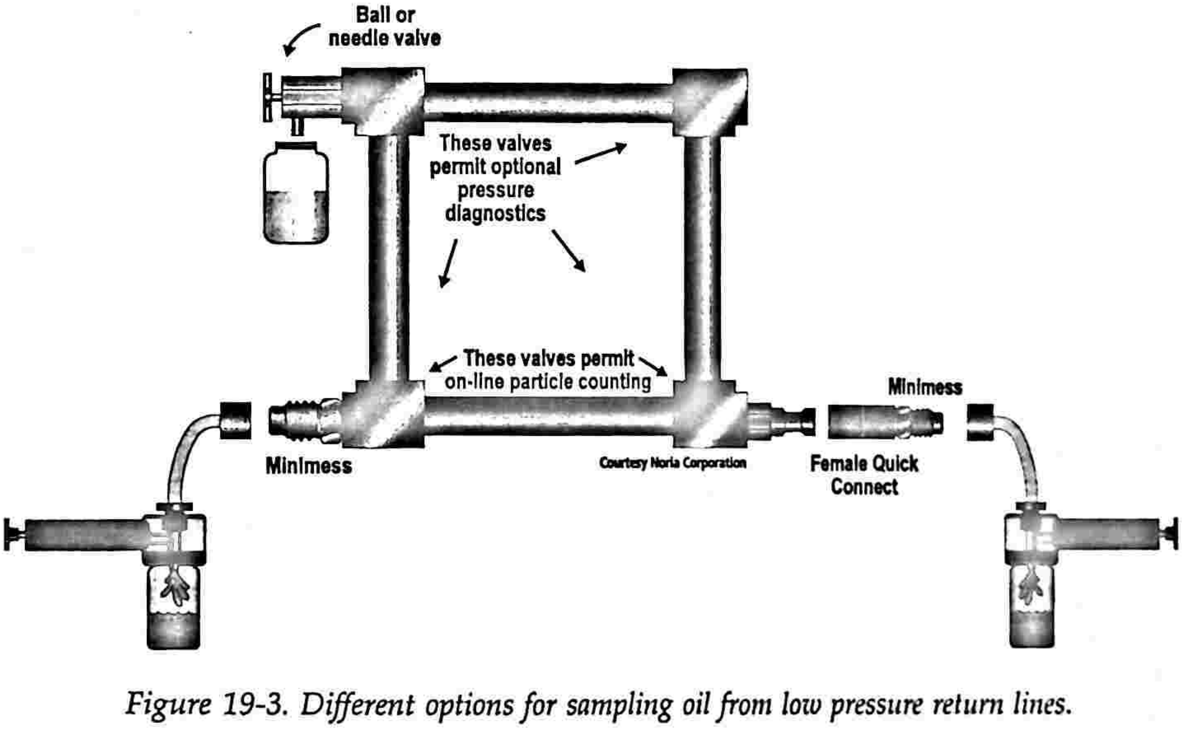

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Figure 19-3. Different options for sampling oil from low pressure return lines.

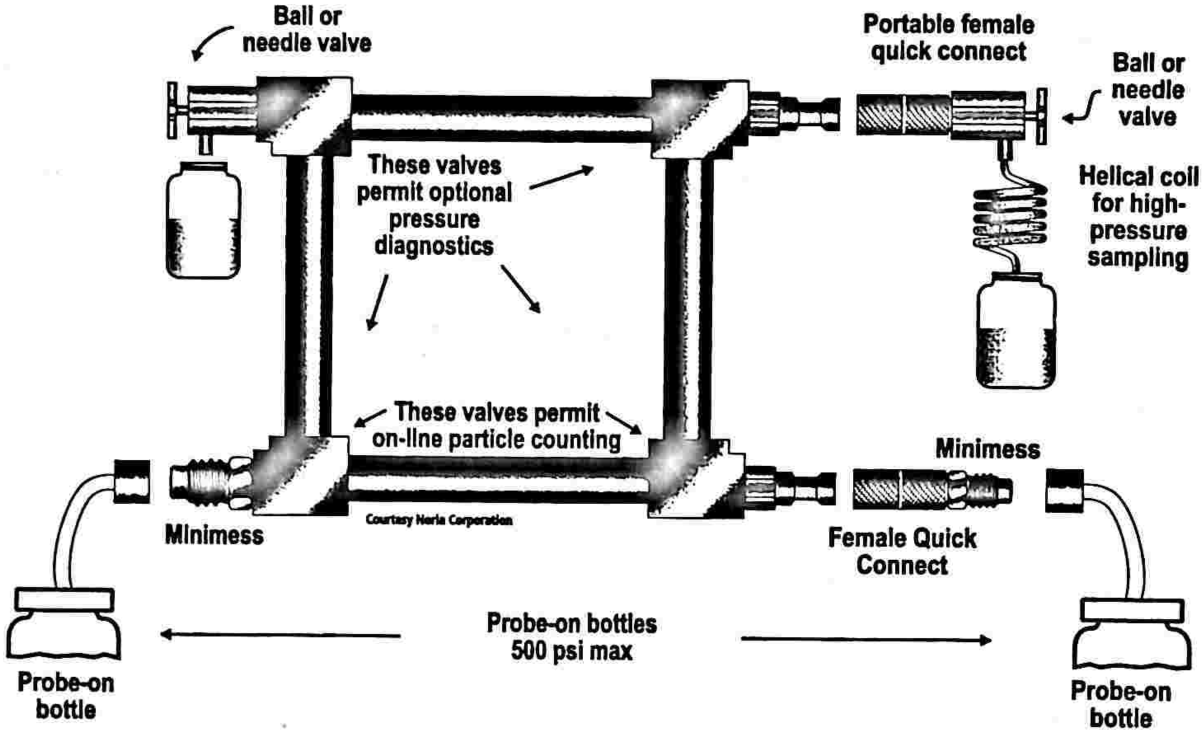

Figure 19-4. More options for taking lube oil samples.

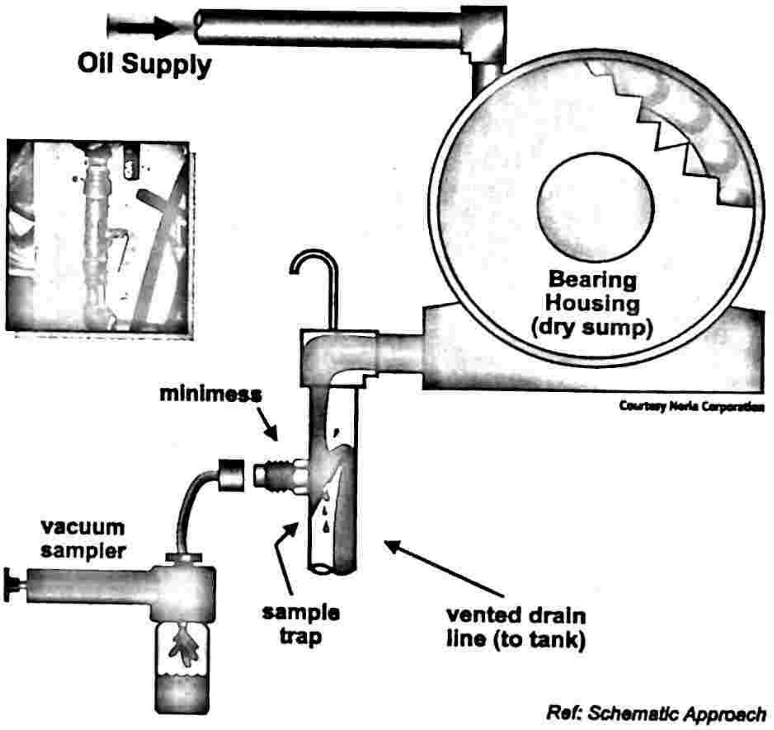

Figure 19-5. Sample trap installed in drain line below bearing housing.

from dead zones such as static tanks and reservoirs. Splash, slinger ring, and flood-lubricated components are best sampled from the drain or casing side using a short inward-directed tube attached to a sample valve (see Figure 19-6). It may be necessary to use a vacuum pump to assist the oil flow for high viscosity lubricants.

Procedure for Extracting the Sample

Once a sampling point is properly selected and validated, a sample must be extracted without disturbing the integrity of the data. When a sample is pulled from turbulent zones such as at an elbow, particles, moisture, and other contaminants enter the bottle at representative concentra-

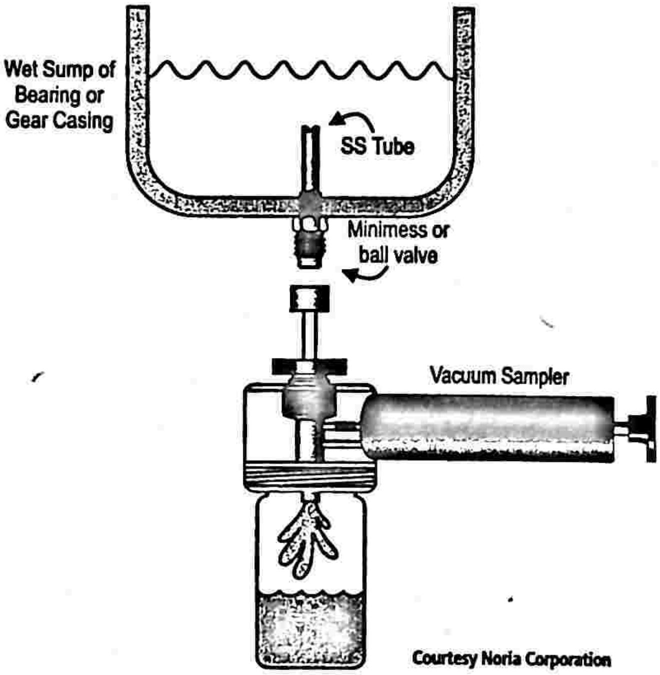

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Figure 19-6. Vacuum sampler arrangement.

tions. In contrast, it is well-known that sampling from ports positioned at right angles to the path of the fluid flow in high velocity, low viscosity fluids causes particle fly-by. In such cases, the higher density particles follow a forward trajectory and fail to enter the sampling pathway.

Machines should always be sampled in their typical work environment, ideally while they are running with the lubricant at normal operating temperature. Likewise, during (or just prior to) sampling, machines should be run at normal loads, speeds, and work cycles. This helps to ensure that the wear debris that is typically generated in the usual work environment and operating conditions is present in the fluid sample for analysis.

Sampling valves should be flushed thoroughly prior to sampling. If other portable sampling hardware is employed, these devices need to be flushed as well. Once the flushing is complete the sample bottle can be filled. However, never fill a sample bottle more than three-fourths full. The headspace in the bottle (ullage) permits adequate agitation by the lab.

With many non-circulating systems, static sampling may be the only option. Often this can be done effectively from drain ports if a sufficient volume of fluid is flushed through prior to the actual sample (see Figure 19-6). Alternatively, drop-tube vacuum samplers could be used (Figure 19-7). Care should be taken to always sample a fixed distance into the sump. Using a rod with a marked standoff from the bottom of the tank is a reliable way to do this. Flushing of the suction tube is also important. Never reuse suction tubes to avoid cross contamination and mixing of fluids.

Static sampling using a vacuum sampler can be improved by installing a quick-connect sampling valve to which the vacuum tube is attached. Often this will require drilling and tapping, preferably in the wall of the sump or casing. It is best if the valve can be located near return lines and where turbulence is highest. Generally, it is desirable to install a short length of stainless steel tubing inward from the valve.

Don't Contaminate the Contaminant

One of the main objectives of oil analysis is the routine monitoring of oil contamination. Therefore, in order to do this effectively, considerable care must be taken to avoid "contaminating the contaminant." Once atmospheric contamination is allowed to contact the oil sample, it cannot he distinguished from the original contamination.

Avoid sampling methods that involve removing the bottle cap, especially where

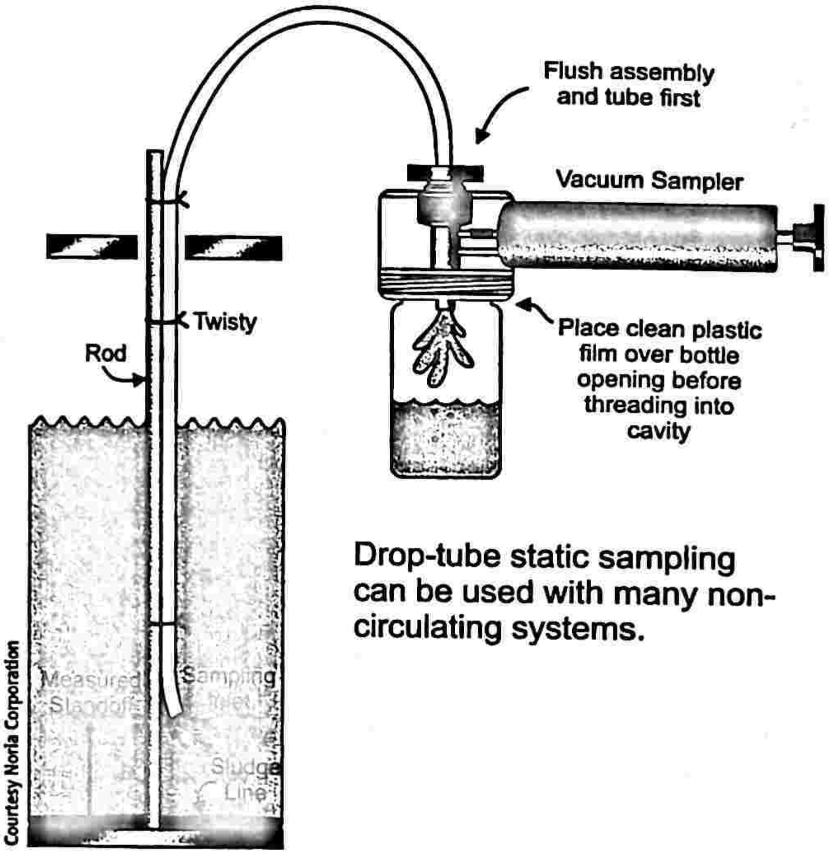

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Figure 19-7. Drop-tube static sampling arrangement.

significant atmospheric contamination is present. One effective method that ensures that particles will not enter the bottle during sampling is a procedure called "clean oil sampling." It involves the use of common zip-lock sandwich bags and sampling hardware such as vacuum pumps and probe devices. Below is an outline description of this procedure:

Step One

Obtaining a good oil sample begins with a bottle of the correct size and cleanliness. It is understandable that the bottle must be at a known level of cleanliness and that this level should be sufficiently high so as not to interfere with expected particle counts. Some people refer to this as signal-to-noise ratio, i.e., the target cleanliness level of the oil (signal) should be several times the expected particle contamination of the bottle (noise). For more information on bottle cleanliness refer to ISO 3722.

Step Two

Before going out into the plant with the sample bottles place the capped bottles into very thin zip-lock sandwich bags, one per bag (Figure 19-8). Zip each of the bags such that air is sealed into the bag along with the bottles. This should be done in a clean-air indoor environment in order to avoid the risk of particles entering the bags along with the bottles. After all of the bottles have been bagged, put these small bags (with the bottles) into a large zip-lock bag for transporting them to the plant or field. Sampling hardware such as vacuum pumps and probe devices should be placed in the large bag as well.

Step Three

After the sampling port or valve has been properly flushed (including the sampling pump or probe if used) remove one of the bags holding a single sample bottle. Without opening the bag, twist the bottle cap off and let the cap fall to the side within the bag. Then move the mouth of the bottle so that it is away from the zip-lock seal. Do not unzip the bag.

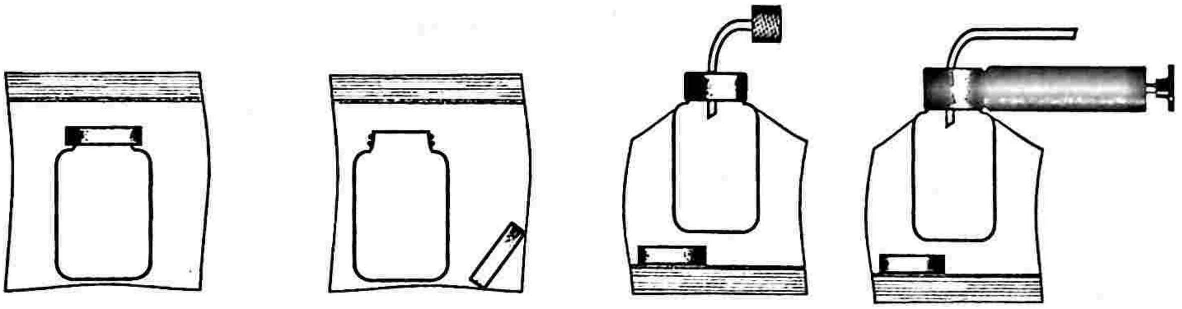

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Figure 19-8. Zip-Lock® bags prevent contamination of samples.

Step Four

Thread the bottle into the cavity of the sampling device (vacuum pump or probe). The plastic tube will puncture the bag during this process, however, try to avoid other tears or damage to the bag (turn the bottle, not the probe or pump, while tightening). If a probe device is used, it is advisable to break a small hole in the bag below the vent hole with a pocket knife. This permits air to escape during sampling.

Step Five

The sample is then obtained in the usual fashion until the correct quantity of oil has entered the bottle. Next, by gripping the bottle, unscrew it from the cavity of the pump or probe device. With the bottle free and still in the bag, fish the cap from the bottom of the bag onto the mouth of the bottle and tighten.

Step Six

With the bottle capped it is safe to unzip the bag and remove the bottle. Confirm that the bottle is capped tightly. The bottle label should be attached and the bottle placed in the appropriate container for transport to the lab. Do not reuse the zip-lock bags.

Three levels of bottle cleanliness are identified by bottle suppliers: clean (fewer than 100 particles >10 µm/ml), superclean (fewer than 10), and ultraclean (fewer than 1). Selecting the correct bottle cleanliness to match the type of sampling is important to oil analysis results.

OIL SAMPLING FREQUENCY

The objective of oil analysis, like condition monitoring in general, is to find bad news. The objective of proactive maintenance is not to have any bad news to find. The machine and oil will generally give off silent alarms when problems first occur. In time, as the severity increases, these alarms are no longer silent and even the most rudimentary condition monitoring methods can reveal the problem. Of course, at this point, a great deal of damage may have already occurred. And, it is likely too late to arrest the problem on the run; the machine may have to be taken apart and repaired.

One of the extraordinary benefits of oil analysis is its incredible sensitivity to these silent alarms and the detection of incipient failures and faults. The methods of doing this —successfully—are still to be discussed. However, it is a very basic principle that you cannot hear an alarm unless you are listening for an alarm—restated, you can't catch a fish unless your hooks in the water. Too often we hear about oil samples being taken every six months or annually; yet, on the same machinery we see vibration readings taken every month.

Scheduled sampling intervals are common in oil analysis. The frequency may be keyed to drain intervals or operating hours. Table 19-3 conservatively recommended intervals based on operating hours for different machine classes. Proper selection of sampling frequencies considers machine and application-specific criteria such as those below:

Penalty of Failure

Safety, downtime costs, repair costs, and general business interruption costs must be considered.

Fluid Environment Severity

Operation and fluid environment conditions influence both frequency and rate of failure progression. Influencing factore include pressures, loads, temperature, speed, contaminant ingression, and system duty.

Machine Age

In general, the chances of failure are greatest for machines going through break-in and after major repairs and overhauls. Likewise, the risk increases as a machine approaches the end of its expected life.

Table 19-3. Conservatively recommended oil sampling intervals for different equipment categories.

	Hours
Diesel engines - off-highway	150
Transmissions, differentials, final drives	300
Hydraulics - mobile equipment	200
Gas turbines - industrial	500
Steam turbines	500
Air/gas compressors	500
Chillers	500
Gear boxes - high speed, heavy duty	300
Gear boxes - low speed, heavy duty	1000
Bearings - journal and rolling element	500
Aviation reciprocating engines	25-50
Aviation gas turbines	100
Aviation gear boxes	100-200
Aviation hydraulics	100-200

Oil Age

Infant oils and old oils are at highest risk. Infant oils are those that have just been changed and are less than 10% into expected life. Old oils are showing trends that suggest additive depletion, the onset of oxidation, or high levels of contamination.

SELECTION OF TYPE OF OIL ANALYSIS

Once proper oil sampling has been mastered it is time to analyze the oil. Because each test that is conducted by an oil lab adds cost to the program, it is important that an optimum selection of tests be defined. There are generally two types of tests; routine and exception. A routine test is a scheduled test that is repeated with each scheduled sample such as tests for viscosity, moisture, and particle count.

An exception test is triggered by a previously non-complying condition or test result. It is conducted to either confirm a conclusion (diagnosis/prognosis) or seek further information that might identify the cause or source of the problem. Exception tests might, for instance, include specialized tests for confirming oil oxidation or abnormal machine wear. Table 19-4 shows how routine tests can be combined with exception tests to provide comprehensive test bundles by machine application.

To be thoroughly effective, a well-designed oil analysis program must encompass three categories of routine tests: (1) fluid properties, (2) fluid contamination, and (3) fluid wear debris.

Fluid Properties Analysis

This essential type of oil analysis helps ensure the fundamental quality of the lubricating fluid. The standard to which a used oil's properties should be routinely compared are the new oil's properties; a listing of each of the new oil properties should be a standard feature of used oil analysis reports. Examples of common tests include viscosity, total acid number, total base number, infrared for oxidation, emission spectroscopy for additive elements, flash point, specific gravity, and rotating bomb oxidation test (RBOT).

Fluid Contamination Analysis

Despite the use of filters and separators, contaminants are the most common destroyers of machine surfaces that ultimately lead to failure and downtime. For most machines, solids contamination is the number one cause of wear-related failures. Likewise, particles, moisture, and other contaminants are the principal root cause of additive and base stock failure of lubricants. It is important to perform basic tests such as particle counting, moisture analysis, glycol testing, and fuel dilution as directed by a well-designed proactive maintenance program.

Fluid Wear Debris Analysis

Unlike fluid properties and contamination analysis, wear debris analysis relates specifically to the health of the machine. Owing to the tendency of machine surfaces to shed increasing numbers of progressively larger particles as wear advances, the size, shape, and concentration of these particles tell a revealing story of the internal or state condition of the machine.

Table 19-4. Selecting oil analysis tests by application.

Test or Procedure	Paper Machine Oils	Motor & Pump Bearings	Diesel & Gas Engine	Hydraulics	Air & Gas Compressors	Chillers and Refrigeration	Transmissions, Final Drives, Differentials	Industrial Gear Oils	Steam Turbine Oils	Gas Turbine Oils	EHC Fluids
1. Particle Count	O,L	O,L	L	O,L	O,L	O,L	L	O,L	O,L	L	O,L
2. Viscosity											
a. 40°C	O,L	O,L	-	O,L	O,L	O,L	L	O,L	L	L	O,L
b. 100°C	-	-	L	-	-	-	-	-	-	-	-
3. TAN	L	E(5a)	-	L	L	L	L	L	L	L	O,L
4. TBN	-	-	L	-	-	-	-	-	-	-	-
5. FTIR											
a. Ox/Nit/Sul	L	L	L	L	L	L	L	L	L	L	-
b. Hindered Phen	-	L	-	L	L	-	-	L	L	-	-
c. ZDDP	-	L	-	L	L	-	L	L	-	-	-
d. Fuel Dil/Soot	-	-	L	-	-	-	-	-	-	-	-
6. Flash Point	-	-	E(2b,5d)	-	L*	-	-	-	-	E(2b,5d)	-
7. Glycol-ASTM Test	-	-	E(14b)	-	-	-	-	-	-	-	-
8. Ferrous Density	E(1)	E(1)	L	O,L	O,L	O,L	L	O,L	E(1)	E(1)	O,L
9. Analytical Ferrography	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)	E(8,14a)
10. RBOT	-	-	-	-	L	-	-	-	L	L	-
11. Crackle	O,L	O,L	L	O,L	O,L	L	O,L	O,L	O,L	-	O,L
12. Water by KF	E(11)	E(11)	E(11)	E(11)	E(11)	E(11)	E(11)	E(11)	E(11)	-	E(11)
13. Water Separability	L	-	-	-	L**	-	-	-	L	-	-
14. Elemental Analysis											
a. Wear Metals	L,E(1)	L,E(1)	L	L,E(1)	L,E(1)	L,E(1)	L	L,E(1)	L,E(1)	L	L,E(1)
b. K, Na, B, Si	L	L	L	L	L	L	L	L	L	L	L
c. Additives	L	L	L	L	L	L	L	L	L	L	L

*Gas Compressors Only **Air Compressors Only

Courtesy Noria Corporation

O = On-site routine test (small on-site lab or portable instrument)
L = Fully equipped oil analysis laboratory
E = Exception test keyed to a positive result from the test in parenthesis

Cost-effective oil analysis can generally be done when on-site oil analysis tools are available. For many machines, the particle counter serves as the best first line of defense. Only when particle counts exceed preset limits is exception testing performed. The best exception test is ferrous density analysis, such as a ferrous particle counter. When ferrous levels are high, a failure condition exists, triggering yet further testing and analysis. In addition to on-site particle counting, on-site moisture analyzers and viscometers also assess important root cause contributors.

MONITORING CHANGING OIL PROPERTIES

Today there are a growing number of organizations transforming their lube programs from scheduled to condition-based oil changes. In fact, many companies claim that they easily pay for the cost of oil analysis from savings achieved through reduced lubricant consumption. Such progressive goals as these place a greater burden of precision on the selection of oil analysis tests and alarm limits to reveal non-complying lubricants.

It is not uncommon for plants to interpret oil analysis results independent of the lab. Essentially, the lab is relied on to provide accurate and timely data, leaving both interpretation and response to the plant; i.e., personnel close to the equipment with knowledge of application and operating conditions. The use of modern oil analysis software can greatly assist in this such programs.

In order to reduce oil consumption, two plans must be implemented. The first plan is proactive in nature and relates to the operating conditions the oil lives in. By improving the oil's operating conditions its expected life can increase many fold. For instance, with mineral oils the reduction of operating temperature of just 10 degrees C can double the oil's oxidation stability and double the oil change interval in many instances. An upcoming section discusses how proactive maintenance by controlling oil contamination can lead towards oil life extension.

The second plan to reducing oil consumption is predictive in nature and relates to the timing of oil changes. Basically, through oil analysis, key physical properties can be trended to help forecast the need of a future oil change. Restated, by listening to the oil, it will tell us when it needs to be changed. And, if the need of an oil change occurs prematurely, then an assessment of the oil's operating conditions (cleanliness, dryness, coolness, etc.) and oil formulation should be made. The nature of the degradation will provide basic clues defining the solution.

There are numerous modes of degradation of lubricating oil. These change many of the properties of the fluid. In order to recognize the change it is important that the correct properties be monitored, realizing that overkill is wasteful. What follows is a discussion of common oil degradation modes and the properties that can best reveal them. In all cases, it is important to get a base signature of the properties of the new oil so as to benchmark the trended change. These reference properties should remain as a permanent record on the oil analysis report and include additive elements, neutralization numbers, -infrared units (unless spectral subtraction is used), RBOT minutes, viscosity, flash temperature, VI, and color.

Viscosity Stability

Viscosity is often referred to as the structural strength of a liquid. It is critical to oil film control plus is a key indicator to a host of ailing conditions relating to the oil and machine. As such, it is often considered a critical "catch-all" property in oil analysis. Essentially, when viscosity remains in a controlled narrow band one can assume that a great many things that could be going wrong are, in fact, not going wrong. Conversely, when viscosity falls outside of the band an exception test is usually needed to identify the nature and cause of an abnormality. Monitoring viscosity thus represents a first line of defense against many problems.

Because viscosity is so important it is often monitored on-site by the reliability team. It is used as an acceptance test for new oil deliveries and to verify the correct lubricant is in use. When viscosity changes with in-service lubricants, the cause is either oil degradation or oil contamination. Oil degradation relates to changes to the base oil and additive chemistry (molecular changes). Contamination of an oil can either thicken or thin the oil depending on the viscosity and emulsifying characteristics of the contaminant (see Table 19-5).

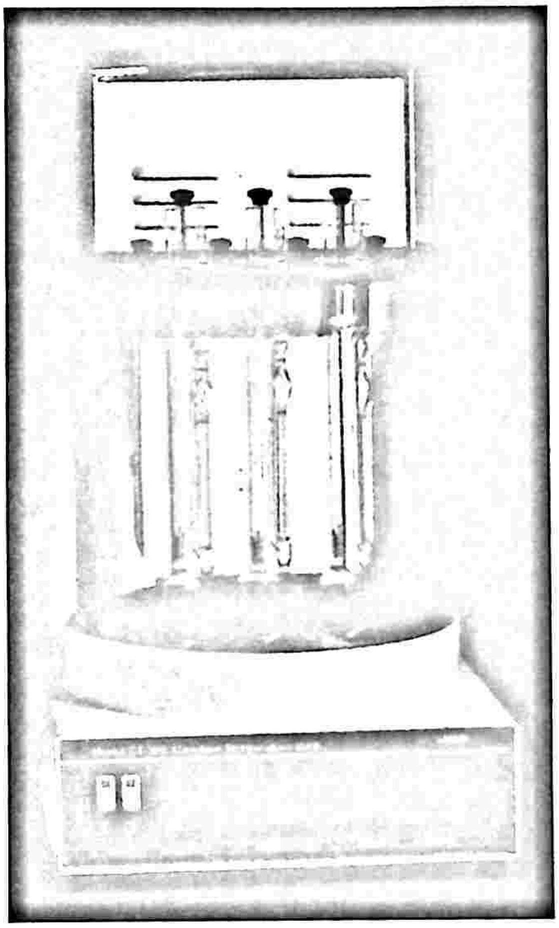
In oil labs, viscosity is typically measured using kinematic viscometers. ISO viscosity grades shown on lubricant spec sheets are based on kinematic viscosity in centistokes (cSt) at 40 degrees C. Another way to represent kinematic viscosity is Saybolt Universal Seconds (SUS). Figure 19-9 shows a photo of a common U-tube kinematic viscometer. In this device, the oil is allowed to drain by gravity through a capillary at constant temperature. The drain time (efflux time) is measured and translated into centistokes. Viscosity varies nearly proportionally to drain time. Because gravity is involved, kinematic viscosity characterizes both the oil's resistance to flow (absolute viscosity) and specific gravity.

On-site oil analysis labs frequently use absolute viscometers to obtain a precise indication of base oil condition. Unlike kinematic viscometers, absolute viscosity measures only an oil's resistance to shear or flow (not specific gravity). Figure 19-10 shows an absolute viscometer designed for plant-level use. It employs a capillary in its tip, through

Table 19-5. The origin of viscosity changes.

	Decreases Viscosity	Increases Viscosity
Changes to base oil (molecular changes)	• Thermal cracking of oil molecules • Shear thinning of VI improvers	• Polymerization • Oxidation • Evaporative losses • Formation of carbon & oxide insolubles
Additions to base oil (contamination)	• Fuel • Refrigerant • Solvents • Wrong oil (low viscosity)	• Water (emulsions) • Aeration • Soot • Antifreeze (glycol) • Wrong oil (high viscosity)

Figure 19-9. U-tube kinematic viscometer.



Courtesy Cannon Instruments

which the oil flows under constant pressure and temperature. An inline plunger moves outward with the flow. The speed of this plunger, measured electronically, varies nearly proportionally to absolute viscosity.

Viscosity is typically trended at 40 degrees C although for high temperature applications, such as crankcase lubricants, a 100-degree C trend is sometimes preferred. Both temperatures are needed to determine the oil's Viscosity Index (VI). However, the VI rarely is trended for routine condition monitoring. Monitoring viscosity at 40-degrees C, for most industrial applications, will provide the most reliable early indication of base oil degradation and oxidation.

Oxidation Stability

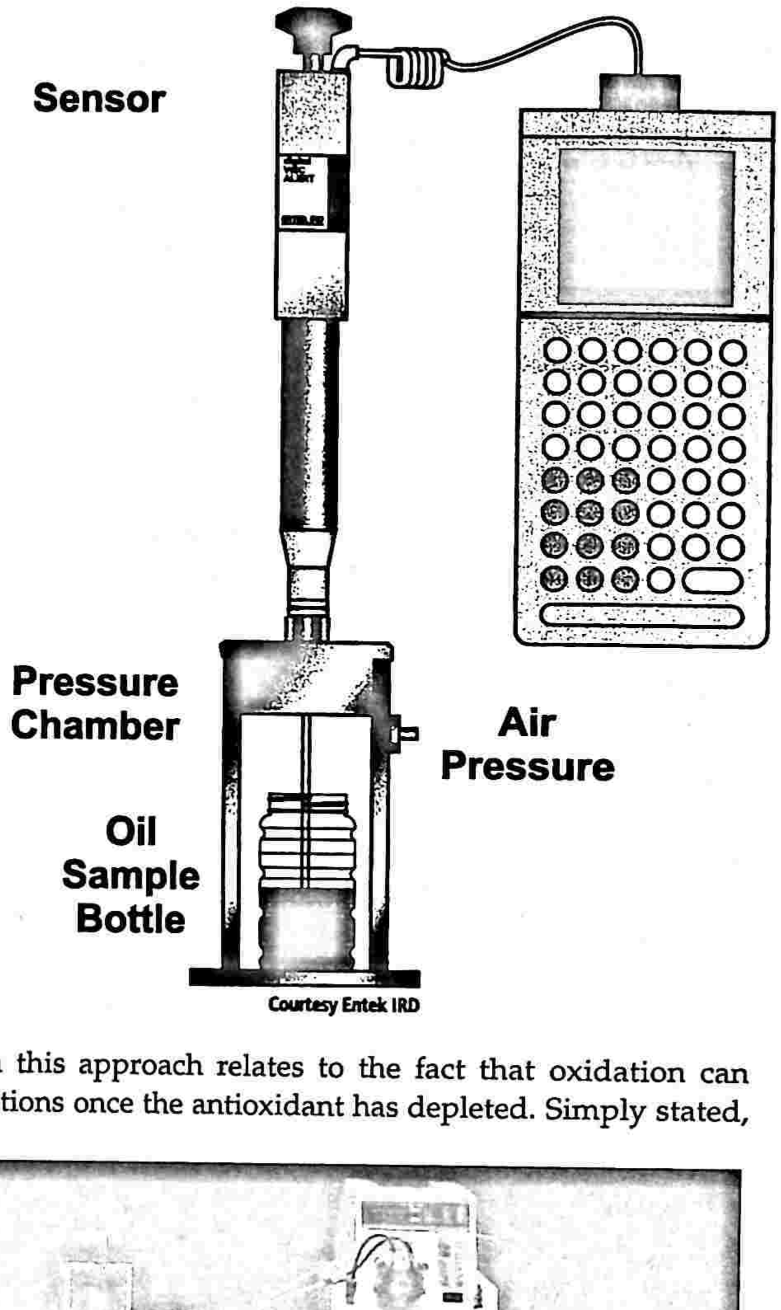
When an oil oxidizes the base oil thickens and discharges sludge and acidic materials; all detrimental to good lubrication. Oxidation is uncommon in applications when conditions are such that oils are relatively cool, dry, and clean. And, this is especially true for low viscosity oils such as hydraulic fluids and turbine oils that have higher oxidation stability. However, when operating conditions are severe, oil oxidation can be a recurring problem. Where a proactive solution cannot be applied (controlling oxidation root causes or the use of resistant synthetics) it is best to monitor the progress of oxidation. Monitoring the depletion of oxidation inhibitors provides an early, forecastable trend, but this may not be practical in some applications.

The technologies used to monitor the depletion of oxidation inhibitors include:

1. Infrared spectroscopy (FTIR) can pick up trendable changes in phenolic and ZDDP inhibitors. However, only a few of the laboratories report additive depletion with FTIR because of unreliable reference oils and occasional inferences from contaminants. See Figure 19-11.

2. Total acid number (TAN) is sensitive to both mass-transfer and decomposition depletion of ZDDP inhibitors. Interpretation of the trend takes practice and a good new-oil reference.

3. Elemental spectroscopy can show reliable mass-transfer depletion trends in ZDDP inhibited oils.



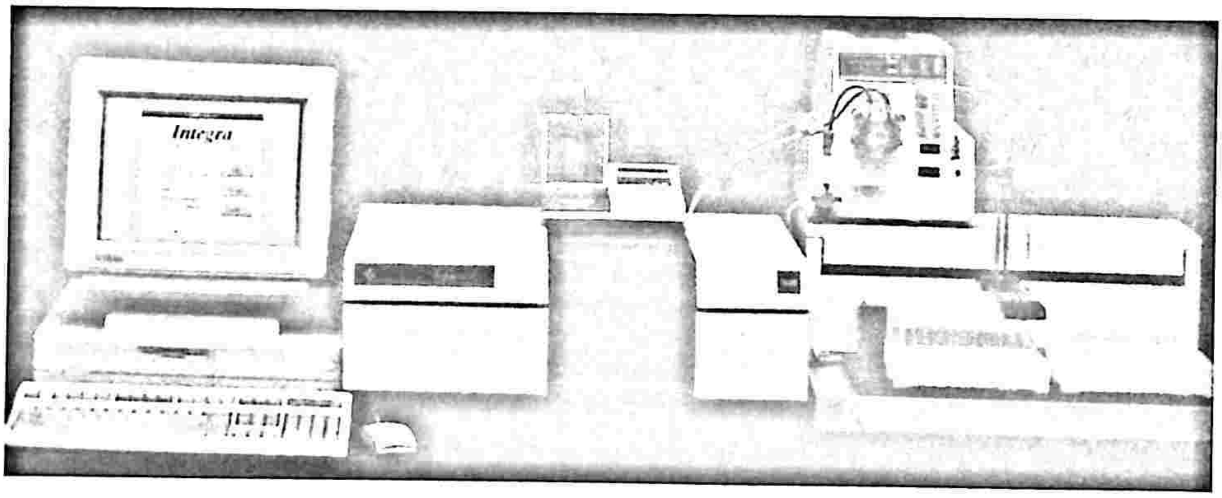
Courtesy Entek IRD

Figure 19-10. Absolute viscometer for plant use.

4. Rotating Bomb Oxidation Tests (RBOT) provide a highly forecastable trend on additive depletion. Because of the time needed to run this test it is expensive and usually saved for exception testing or special circumstances. (See Table 19-6)

5. Voltametry is a new technology that has shown particular promise in trending the depletion (mass transfer and decomposition) of phenolic and ZDDP inhibitors.

If trending the depletion of oxidation inhibitors is not practical then oxidation itself must be monitored. The problem with this approach relates to the fact that oxidation can progress rapidly in stressful conditions once the antioxidant has depleted. Simply stated,



Courtesy Biorad

Figure 19-11. Infrared spectroscopy (FTIR) is used to determine additive depletion.

Additive	Monitoring Method	Effectiveness
ZDDP (antioxidant, antiwear, and corrosion inhibitor)	FTIR - (@ ≈950 wavenumbers)	Fair (early detection)
	FTIR - oxidation (1750 wn)	Good (later detection)
	RBOT	Excellent (early detection)
	TAN (downward trend)	Fair (early detection)
	TAN (upward trend)	Good (later detection)
	Voltametry	Excellent (early detection)
	Elemental Spectroscopy	Excellent (early detection)
Rust Inhibitors	Elemental Spectroscopy	Fair (early detection)
Foam Inhibitors	Elemental spectroscopy	Fair (interferences from dirt)
Sulfur Phosphorus - EP	Elemental spectroscopy	Excellent
Molybdenum Disulfide - EP	Elemental spectroscopy	Good
Borate - EP	Elemental spectroscopy	Excellent
VI Improver	Viscosity at 40°C and 100°C	Excellent
Dispersants	Blotter spot test	Good
Detergents	TBN	Excellent
	Elemental Spectoscopy	Excellent
Hindered Phenol (antioxidant)	FTIR	Fair

Courtesy Noria Corporation

Table 19-6.

with oxidation, "the worse things get the faster they get worse." If the goal is a condition-based oil change, this translates to the need to monitor with sufficient frequency to catch the problem in the incipient stages, not after the oil throws sludge and destructive lubrication has occurred.

The most common and reliable methods to detect and trend oil oxidation are the following:

1. If a reliable new oil reference is available to the laboratory, infrared analysis (FTIR) is dependable for mineral oils and many synthetics including organic and phosphate esters. The acids, aldehydes, esters, and ketones formed during oxidation are detected by FTIR in mineral oils and PAO synthetics.

2. Total acid number (TAN) will quantify the growing acid constituents in oxidizing oils.

3. Because oxidation results in polymerization of the base oil and the discharge of oxide insolubles, the viscosity will increase.

4. Color-bodies form in oxidized oils resulting in a marked darkening of the oil's color.

5. Oxidized oils give off a sour or pungent odors, similar to the smell of a rotten egg.

Thermal Stability and Varnish Tendency

The thermal failure of an oil can be localized or uniform. Localized thermal failure occurs when the bulk oil temperature remains generally suitable for the selected lubricant but oil is exposed to hot surfaces such as the discharge valves of reciprocating compressors, or hot surfaces in internal combustion engines and turbomachinery. Another common cause of localized thermal failure is associated with entrained air that is permitted to compress, such as occurs to air bubbles passing through a high-pressure hydraulic pump. The air bubble implosion causes heat to concentrate generating microscopic specks of carbon. These carbon insolubles later condense on machine surfaces, forming what is commonly called varnish.

The varnish tendency of an oil is often difficult to detect due to the fact that the majority of the physical properties of the oil are unaffected. For instance, oxidation may occur without change in viscosity, TAN, or FTIR. However, sophisticated labs having experience with hydraulic fluids will employ specialized tests such as ultracentrifuge, FTIR for nitration, and submicron membrane tests. Other, less reliable, indicators include oil color and paper chromatography (blotter spot test).

The uniform thermal failure of an oil results from excessively high operating temperatures due to any of a number of reasons. However, the most common reasons include overloading, inadequate oil supply, failure of a heat exchanger, and the use of a high watt-density tank heater. When any of these conditions occur, the oil fails by evaporation (thickening), carbonization (coking, carbon stones, etc.), or cracking (thinning) in extreme cases. Regardless of origin, the uniform thermal failure of the oil is serious and threatens the reliable operation of the lubricated machine.

An oil's thermal stability it often measured using the Cincinnati Milacron test (ASTM D 2070-91). However, because this test takes a week to complete, it is generally impractical for routine used-oil analysis. Other ways to evaluate thermal failure include viscosity analysis, ultracentrifuge, total insolubles, and oil color. Less reliable indicators include oil odor (either a burnt, rancid odor or no odor at all) and paper chromatography.

Additive Stability

Additive monitoring is one of the most challenging and evasive areas of used-oil analysis. The reasons for this are many and complex. As a starting point, it is worthwhile to review how additives deplete during normal use and aging.

It is generally accepted that there are two forms of additive depletion, both are common and can occur simultaneously. The first form of depletion is known as decomposition. Here the additive mass stays in the oil but its molecular structure changes resulting in an assortment of transformation products (other molecules). In some instances, the transformation products may possess properties similar to the original additive, but in most cases performance is degraded or is completely lost. This sacrificial form of depletion is common to what happens over time to oxidation inhibitors, as described previously under "oxidation stability."

The second form of additive depletion is called mass transfer. This type of depletion is often the most easy to detect because the entire mass of the additive transfers out of the bulk oil. And, as such, any measurable property of the additive leaves as well. For instance, if the additive is constructed with phosphorous, a downward trend of phosphorous in the used oil is a reliable indication of its mass transfer depletion. Conversely, an unchanging level of phosphorous in used oil in no way confirms that decomposition depletion has not occurred. With decomposition the elements of the additive remain suspended in the oil.

Mass transfer of additives occur in normal operation, usually as a result of the additive doing the job it was designed to do. For instance, when a rust inhibitor attaches itself to internal machine surfaces it depletes by mass transfer. It is common for additives to cling to various polar contaminants in the oil, such as dirt and water. The removal of these contaminants by filters, separators, and settling action causes a removal of the additive as well. And, over time, aging additives can form floc and precipitate out of the oil due to decomposition and long cold-temperature storage. The insolubles formed will migrate out, often ending up on the bottom of the sump or reservoir.

Table 19-6 describes common methods used to monitor additive depletion. It is worth restating that the use of elemental spectroscopy to trend additive depletion is only effective where mass transfer is involved. It is not uncommon, therefore, for oil labs to condemn an oil with only a 25 percent reduction in the concentration of telltale additive elements, e.g., zinc and phosphorous in the case of ZDDP.

MONITORING OIL CONTAMINATION

Contamination can be defined as any unwanted substance or energy that enters or contacts the oil. Contaminants can come in a great many forms, some are highly destructive to the oil, its additives, and machine surfaces. It is often overlooked as a source of failure because its impact is usually slow and imperceptible yet, given time, the damage is analogous to eating the machine up from the inside out. While it is not practical to attempt to totally eradicate contamination from in-service lubricants, control of contaminant levels within acceptable limits is accomplishable and vitally important.

Particles, moisture, soot, heat, air, glycol, fuel, detergents, and process fluids are all contaminants commonly found in industrial lubricants and hydraulic fluids. However, it is particle contamination and moisture that are widely recognized as most destructive to both oil and machine.

Particle Contamination

There is no single property of lubricating oil that challenges the reliability of machinery more than suspended particles. It would not be an exaggeration to refer to them as a microscopic wrecking crew. Small particles can ride in oil almost indefinitely and because they are not as friable (easily crumbled) as their larger brothers, the destruction can be continuous. Many studies have shown convincing evidence of the greater damage associated with small particles compared to larger. Still, most maintenance professionals have misconceptions about the size of particles and the associated harm caused.

These misconceptions relate to the definition people apply to what is clean oil and what is dirty oil. And, it is this definition that becomes the first of the three steps of proactive maintenance; the need to set appropriate target cleanliness levels for lubricating oils and hydraulic fluids. The process is not unlike a black box circuit. If we want a change to the output (longer and more reliable machine life) then there must be a change to the input (a lifestyle change, i.e., improve cleanliness). For instance, it's not the monitoring of cholesterol that saves us from heart decease, instead it's the things we do to lower the cholesterol. Therefore the best target cleanliness level is one that is a marked improvement from historic levels.

This leads us to the second step in proactive maintenance, the lifestyle change. By effectively excluding the entry of contaminants and promptly removing contaminants when they do enter, the new cleanliness targets are frequently easily achieved. Concerns that filtration costs will increase may not materialize due to the greater overall control, especially from the standpoint of particle ingression.

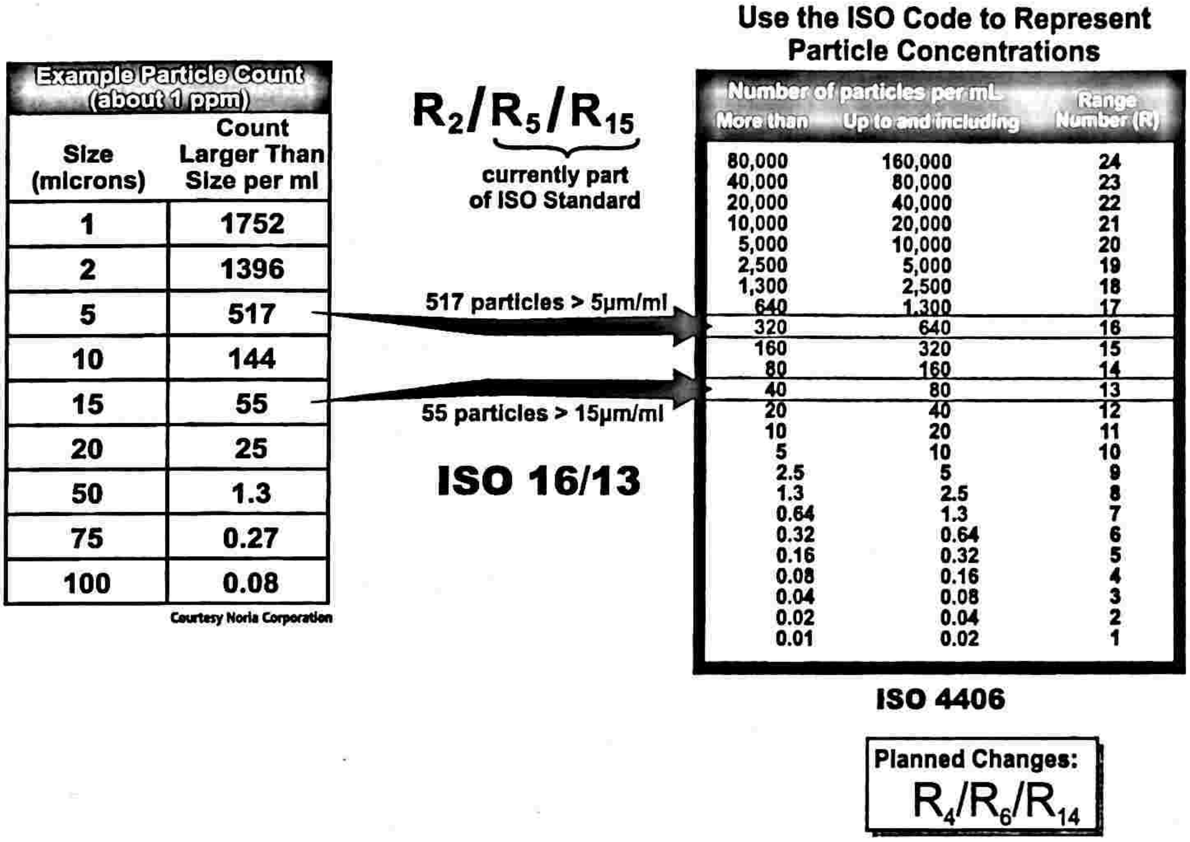
The third step of proactive maintenance is the monitoring step, i.e., particle counting. If this is done on a frequent enough basis, not only is proactive maintenance achieved but also a large assortment of common problems can be routinely detected. As such, particle counting is another important "catch all" type test, like viscosity analysis. Because of the obvious value, the particle counter is probably the most widely used onsite oil analysis instrument. It is not uncommon to find organizations testing the cleanliness of their oils as frequently as weekly.

The activity of routine particle counting has a surprising impact on step number two. When the cleanliness levels of lubricants are checked and verified on a frequent basis a phenomenon known as the "invisible filter" occurs, which is analogous to the saying, "what gets measured gets done." Because a great deal of dirt and contamination that enters oils comes from the careless practices of operators and craftsmen, the combined effect of monitoring with a modicum of training can go a long way towards achieving cleanliness goals.

The ISO Solid Contaminant Code (ISO 4406) is probably the most widely used method for representing particle counts in oils. The current standard employs a two-range number system (see Figure 19-12). The first range number corresponds to particles larger than 5 microns and the second range number for particles larger than 15 microns. From the chart, as the range numbers increment up one digit the represented particle count roughly doubles. At this writing, the ISO Code is undergoing revision that will likely add a third range number plus a change to the particle size the three range numbers will relate to.

While there are numerous different methods used to arrive at target cleanliness levels for oils in different applications, most combine the importance of machine reliability with the general contaminant sensitivity of the machine to set the target. This approach is shown in Table 19-7. The Reliability Penalty Factor and the Contaminant Severity Factor are arrived at by a special scoring system that is included with the Target Cleanliness Grid.

There are many different types of automatic particle counters used by oil analysis laboratories. There are also a number of different portable particle counters on the market. The performance of these instruments can vary considerably depending on the design and operating principle. Particle counters employing laser or white light are widely used because of their ability to count particles across a wide range of sizes (see Figure 19-13). Pore blockage-type particles counters have a more narrow size range sensitivity,



Example Particle Count (about 1 ppm)

Size (microns)	Count Larger Than Size per ml
1	1752
2	1396
5	517
10	144
15	55
20	25
50	1.3
75	0.27
100	0.08

Courtesy Noria Corporation

$R_2/R_5/R_{15}$

currently part of ISO Standard

517 particles > 5µm/ml

55 particles > 15µm/ml

ISO 16/13

Use the ISO Code to Represent Particle Concentrations

Number of particles per mL		Range Number (R)
More than	Up to and including	
80,000	160,000	24
40,000	80,000	23
20,000	40,000	22
10,000	20,000	21
5,000	10,000	20
2,500	5,000	19
1,300	2,500	18
640	1,300	17
320	640	16
160	320	15
80	160	14
40	80	13
20	40	12
10	20	11
5	10	10
2.5	5	9
1.3	2.5	8
0.64	1.3	7
0.32	0.64	6
0.16	0.32	5
0.08	0.16	4
0.04	0.08	3
0.02	0.04	2
0.01	0.02	1

ISO 4406

Planned Changes:
$R_4/R_6/R_{14}$

Figure 19-12. ISO contaminant code (ISO 4406).

Target Cleanliness Grid (TCG)

Reliability Penalty Factor (RPF)
Cost, Safety, and Business Interruption Penalty From Failure

10	19/16/13	18/15/12	17/14/12	16/13/11	15/12/10	14/11/9	13/10/8	12/10/8	11/9/7	10/9/7
9	19/16/13	19/16/13	18/15/12	17/14/11	16/13/10	15/12/10	14/11/9	13/10/8	12/9/7	11/9/7
8	20/17/14	20/17/13	19/16/13	18/15/12	16/13/11	15/12/10	14/11/9	13/10/8	12/9/8	12/9/7
7	20/17/14	20/17/14	19/16/13	18/15/12	17/14/11	16/13/10	15/11/9	14/11/9	13/10/8	12/10/8
6	21/18/15	21/18/14	19/16/13	18/15/12	17/14/11	16/13/10	15/12/9	14/11/9	13/10/8	12/10/8
5	21/18/15	21/18/15	20/17/14	19/16/13	18/15/12	17/14/11	16/14/11	15/13/11	14/11/10	13/11/9
4	22/19/16	22/19/16	20/17/14	19/17/14	18/15/13	17/14/11	16/14/11	15/13/10	14/12/9	13/11/9
3	22/19/16	22/19/16	21/18/15	20/17/14	19/16/13	18/15/12	17/14/11	16/14/11	15/13/10	14/12/9
2	23/20/17	23/20/17	22/19/16	21/18/15	20/17/14	19/16/13	18/15/12	17/14/11	16/14/11	15/13/10
1	24/20/17	23/20/17	22/19/16	21/18/15	20/17/14	19/16/13	19/16/12	18/15/11	17/14/11	16/14/11
	1	2	3	4	5	6	7	8	9	10

Courtesy Noria Corporation

Table 19-7. Contaminant severity factor (CSF).

however, they are also popular because of their ability to discriminate between hard particles of other impurities in the oil such as water, sludge, and air bubbles (see Figure 19-14).

Figure 19-15 shows how particle count trends vary depending on the machine application and the presence of a built-in filter. Because particle counters monitor particles in the general size range controlled by filters, equilibrium is usually achieved, i.e., particles entering the oil from ingression minus particles exiting from filtration will leave behind a steady state concentration. When filters are properly specified and ingression is under control this steady state concentration will be well within the cleanliness target. Systems with no continuous filtration, e.g., a splash-fed gearbox, an equilibrium is not really established (there is no continuous particle removal). This causes the particle concentration to be continuously rising. Still, contamination control can be achieved by periodic use of portable filtration systems, such as a filter cart.

Moisture Contamination

Moisture is generally referred to as a chemical contaminant when suspended in lubricating oils. Its destructive effects in bearings, gearing, and hydraulic components can reach or exceed that of particle contamination, depending on conditions. Like particles, control must be exercised to minimize water accumulation and resulting destruction to the oil and machine.

Once in the oil, water is in constant search of a stable existence. Unlike oil, the water molecule is polar, which greatly limits its ability to dissolve. Water may cling to hydrophilic metal surfaces or form a thin film around polar solids co-existing in the oil. If a dry air boundary exists, water molecules may simply choose to migrate

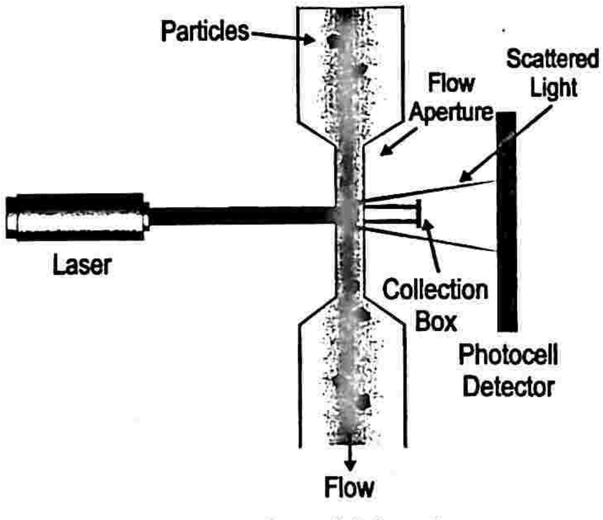


Figure 19-13. Particle counter.

Courtesy Noria Corporation

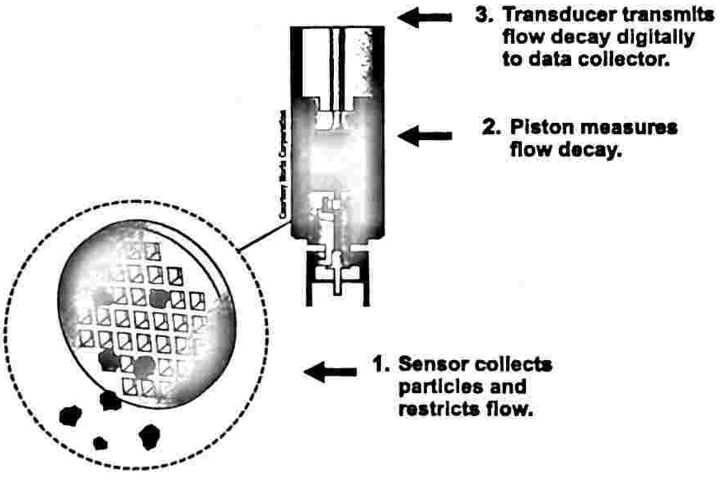
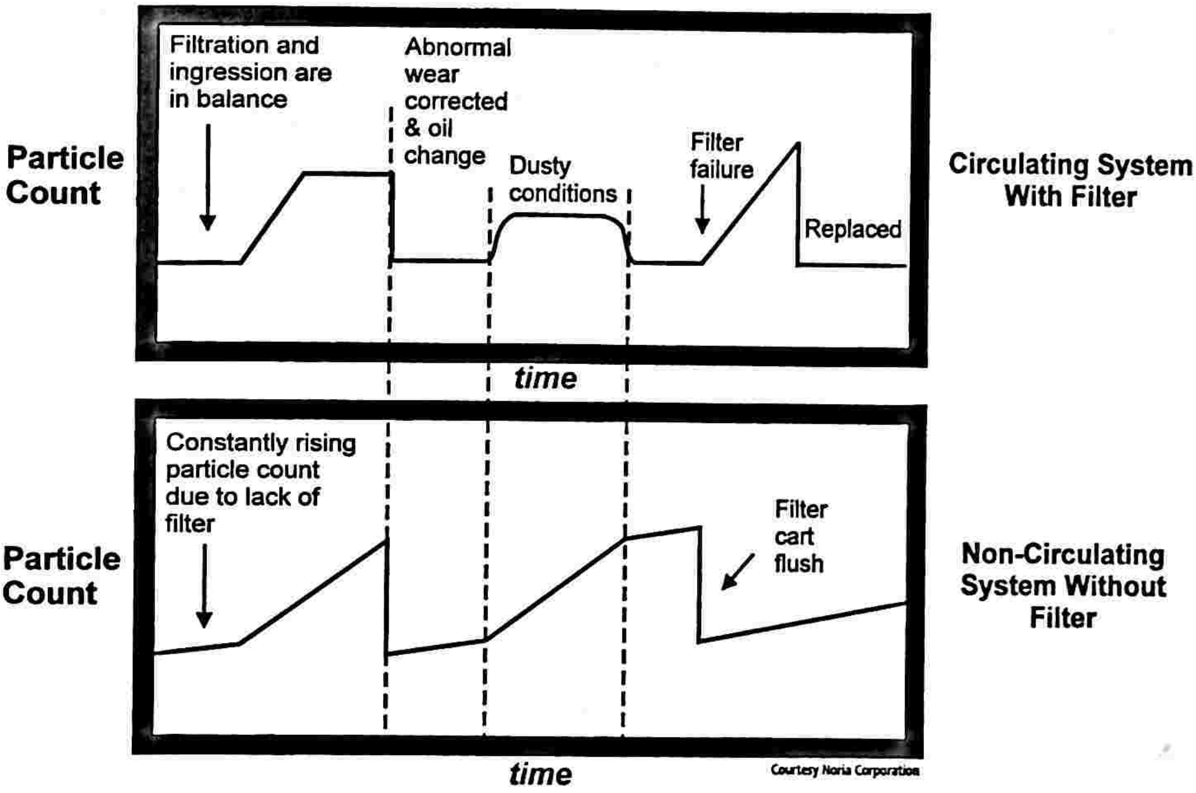


Figure 19-14. Pore blockage-type particle counter.



Courtesy Noria Corporation

Figure 19-15. Particle count trend graphs.

out of the oil to the far more absorbent air interface. If water molecules are unable to find polar compounds on which to attach, the oil is said to be saturated. Any additional water will create a supersaturated condition causing the far more harmful free and emulsified water. The temperature of the oil as is shown in Table 19-8 also influences the saturation point.

With few exceptions, the chemical and physical stability of lubricants is threatened by small amounts of undissolved suspended water. In combination with oxygen, heat, and metal catalysts, water promotes oxidation and hydrolysis. An overall degradation of the base oil and its additives results. The harmful effects of water on the life of rolling element bearings and other contact zones when boundary lubrication prevails are well documented. According to SKF, "free water in lubricating oil decreases the life of rolling element bearings by ten to more than a hundred times… " And, it is well know that water promotes corrosive attack on sensitive machine surfaces discharging harmful abrasives into the oil.

The omnipresence of water in the environment makes it difficult to completely exclude it from entering and combining with the oil. However, its presence can be greatly minimized and controlled through good maintenance practices. And, just like particle contamination, a proactive maintenance program needs to be established to control water. This should start with the setting of a target dryness level for each different oil application. By investigating the sources of water ingression a plan can be implemented to exclude the water. Occasional removal by water absorbent filters, vacuum dehydrators or air stripping units (see Chapter 17) may also be necessary.

Table 19-8. Make-up of water concentration in oil at different temperatures. (Courtesy Noria Corporation)

Temperature			100 ppm		Water Concentration 500 ppm		1000 ppm	
°F	**°C**		**D**	**F&E**	**D**	**F&E**	**D**	**F&E**
32	0							
		R&O	28	72	28	472	28	972
		Gear	100	0	100	400	100	900
68	20							
		R&O	72	28	72	428	72	928
		Gear	100	0	200	300	200	800
104	40							
		R&O	100	0	170	330	170	830
		Gear	100	0	500	0	500	500
140	60							
		R&O	100	0	350	150	350	650
		Gear	100	0	500	0	1000	0
158	70							
		R&O	100	0	500	0	520	480
		Gear	100	0	500	0	1000	0

D = Dissolved Water Amount (ppm)
F&E = Free and Emulsified Water (ppm)
R&O = ISO 32 Rust and Oxidation Inhibited oil (e.g., turbine oil).
Gear = Gear oil

A simple and reliable test for water is the crackle test (a.k.a. the sputter test). In the laboratory two drops of oil are placed on the surface of a hot plate heated to approximately 320 degree F. The presence of free or emulsified water in the oil will result in the formation of vapor bubbles and even scintillation if the water concentration is high enough. Although generally used only as a go/no-go procedure, experienced lab technicians have learned to recognize the visual differences associated with progressive concentrations of water contamination, see Figure 19-16.

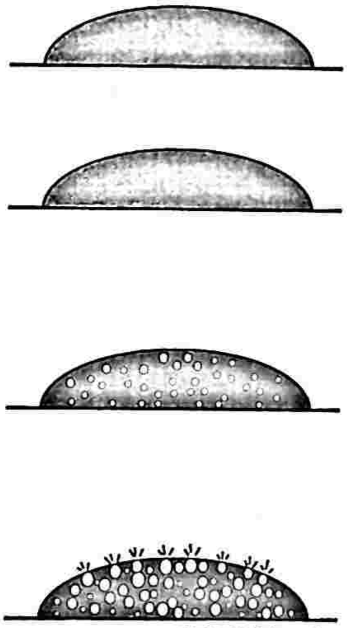
Other widely used methods to detect water include the following:

1. Dean & Stark apparatus is occasionally used by laboratories and involves a procedure of co-distilling the water out of the oil and establishing the water content volumetrically (ASTM D 4006).

2. Karl Fischer titration is commonly used by laboratories as an exception test should initial presence of water be detected by crackle or infrared analysis. Two Karl Fischer procedures exist, volumetric titration (ASTM D 1744) and coulometric titration (ASTM D 4928).

3. Infrared spectroscopy can reliably measure water concentrations down to about 0.1 percent. This lower limit may not be adequate for many oil analysis programs.

Procedure: 2 drops of oil on a plate heated to 320°F



Observation	Approximate Water Present
No visible or audible change	No free or emulsified water
Very small bubbles (≈0.5 mm) produced and quickly disappear	0.05 - 0.1% 500 - 1000 ppm
Bubbles approximately 2 mm are produced, gather to center, enlarge to ≈4 mm, disappear quickly	0.1 - 0.2% 1000 - 2000 ppm
Bubbles ≈2-3 mm are produced growing to ≈4 mm, process repeats, possible violent bubbling and audible crackling	0.2 and more >2000 ppm

Courtesy Noria Corporation

Figure 19-16. Crackle test for water contamination.

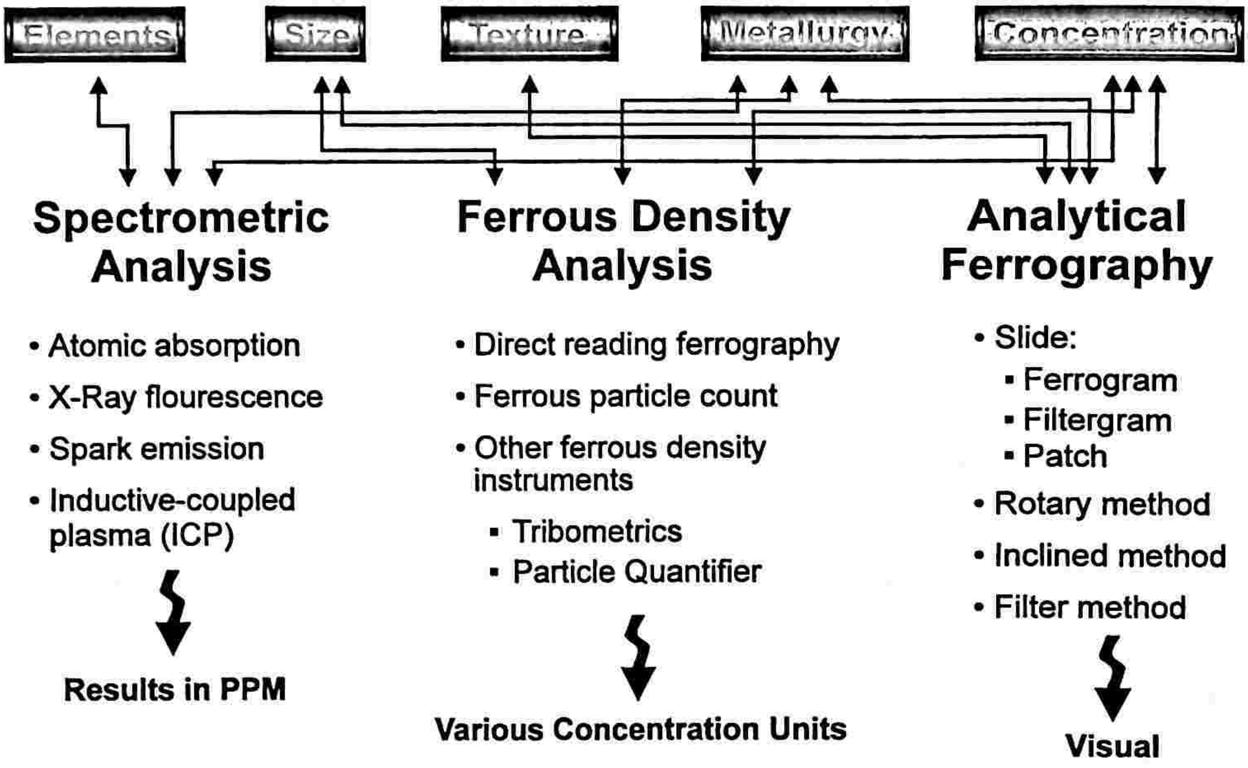
WEAR PARTICLE DETECTION AND ANALYSIS

Where the first two categories of oil analysis (fluid properties and contamination) deal primarily with the causes of machine failure (proactive maintenance), this category emphasizes the detection and analysis of current machine anomalies and faults, i.e., the symptoms of failure. The oil serves as the messenger of information on the health of the machine. Basically, when a machine is experiencing some level of failure the affected surfaces will shed particles, releasing them into the oil. The presence of abnormal levels of wear particles serves as problem detection where their size, shape, color, orientation, elements, etc. defines the cause, source, and severity of the condition.

Elemental Spectroscopy

Figure 19-17 illustrates the three common categories of wear particle detection and analysis. The oldest and most widely used of these methods is elemental analysis, done today primarily with optical emission spectrometers. The procedure involves applying high heat to the oil. Particles in the oil will totally or partially vaporize in the presence of heat, producing incandescent emission of light. The light is diffracted such that spectral intensities at different wavelengths can be measured. Specific wavelengths are associated with certain elements and the spectral intensities define the concentration of the elements.

The typical output from elemental spectroscopy is concentration units (parts per million) across 10 to 25 common elements such as iron, copper, lead, aluminum, etc. By comparing the major, minor, and trace metals to the metallurgical chart of the machine a



Courtesy Noria Corporation

Figure 19-17. Three common categories of wear particle detection

fingerprint of the probable sources of the wear can be established. Many of the laboratories do wear metal interpretation with the help of sophisticated software programs and extensive metallurgical databases (see Table 19-9).

Most oil analysis laboratories offer elemental spectroscopy as standard with all samples analyzed. Both spectrometers and technology vary somewhat, which translates to variations in detection range and sensitivity. The precision of these instruments is also influenced by the size of the wear particles suspended in the oils. During analysis, small particles vaporize more completely while large particles (> 10 microns) are almost not measurable. This particle-size bias leads to occasional errors, some serious (false negatives).

One popular way to reduce the particle-size error is to use electrode filter spectroscopy. This capability is available with spark-emission spectrometers at many of the large commercial laboratories. By pushing the particles into the interstices of the disc electrode a more complete vaporization of larger particles is achieved (possible sensitivity to 20 microns). A special fixture is required to process the sample through the electrode prior to analysis. Because the oil is washed through the electrode during preparation, a separate test is performed on the oil alone to measure dissolved metals and additive elements.

Ferrous Density Analysis

The most serious wear particles of all are generated from iron and steel surfaces. In fact, in most oil-lubricated pairs, at least one of the two surfaces is a ferrous surface. And, it is usually the ferrous surface that is the most important from the standpoint of machine reliability.

Table 19-9. Potential sources of metals in oil.

Iron
Steel
Cast iron
Rust
Wear debris
Mill scale
Ore dust
Fly ash
Paint
Paper mill dust
Asbestos
Talc
Zeolite
Cleaning detergent

Nickel
Alloy of stainless steel
Plating
Stellite (Cobalt-Nickel)
Alloy of
hard steels

Silver
Bearing overlay
Solder
Some needle bearings

Potassium
Coolant inhibitor
Fly ash
Paper mill dust
Road dust
Granite

Boron
Coolant inhibitor
EP additive
Oil drum cleaning agent
Boric acid (water treatment)

Chromium
Ring plating
Chrome plating
Paint
Stainless Steel

Silicon
Road dust
Sealant
Antifoam additive
Steel alloy metal
Synthetic lubricant
Wet clutch
Glass mfg
Coolant additive
Foundry dust
Filter fibers (glass)
Fly ash
Slag
Mica
Cement dust
Asbestos
Granite
Limestone
Talc

Lead
Babbitt
Journal bearing overlay
Gasoline additive
Paint
Solder

Sodium
Coolant inhibitor
Saltwater
Some additives
Grease
Base stocks (trace)
Dirt
Road dust
Salt (road salt)
Fly ash
Activated alumina
Paper mill dust

Copper
AW Additive
Bronze
Brass
Bearing cage
Cooler cores
Copper mining
Paint
Babbitt

Molybdenum
EP additive
Alloying metal
Rings

Calcium
Hard water
Salt water
Engine oil additive
Mining dust
Grease
Limestone
Slag
Rubber
Fuller's earth
Lignite
Cement dust
Road dust
Gypsum
Rust Inhibitor
Detergent

Zinc
AW additive
Brass
Plating
Galvanizing
Grease

Phosphorus
AW/EP additive
Surface finish on some gears
Cleaning detergent

Tin
Bearing cage (bronze)
Solder
Babbitt

Aluminum
Road dust
Bearing metal
Paint
Abrasives
Aluminum mill
Coal contaminant
Fly ash
Foundry dust
Activated alumina
Bauxite
Granite
Catalyst

Barium
Engine additive
Grease

Vanandium
Turbine blades
Valves

Titanium
Gas turbine bearings
Paint
Turbine blades

Cadmium
Journal bearings
Plating

Magnesium
Hard water
Engine additive
Turbine metallurgy
Seawater
Fuller's earth
Road dust

Courtesy Noria Corporation

This means that the oil analyst requires a dependable reading of the ferrous particle concentration at all sizes, an important issue considering the particle-size bias associated with elemental spectrometers. Therefore, in order to ensure that abnormal wear of iron and steel surfaces doesn't go undetected, ferrous density analyzers are widely employed, both in commercial and on-site laboratories. These instruments provide a first line of defense by reliably detecting free-metal ferrous debris. Example instruments include:

1. Direct Reading Ferrograph: reports results in Wear Particle Concentration units
2. Particle Quantifier: reports an index scale
3. Wear Particle Analyzer: output in micrograms/ml
4. Ferrous Particle Counter: assigns a percent ferrous to particle count ratio

Analytical Ferrography

Elemental spectroscopy and ferrous density analysis are just two of many different ways to detect problems in machinery. Thermography and vibration monitoring are also effective at detecting specific faults and modes of failure. Once there is an initial indication of a fault by any of these methods, the process must continue to:

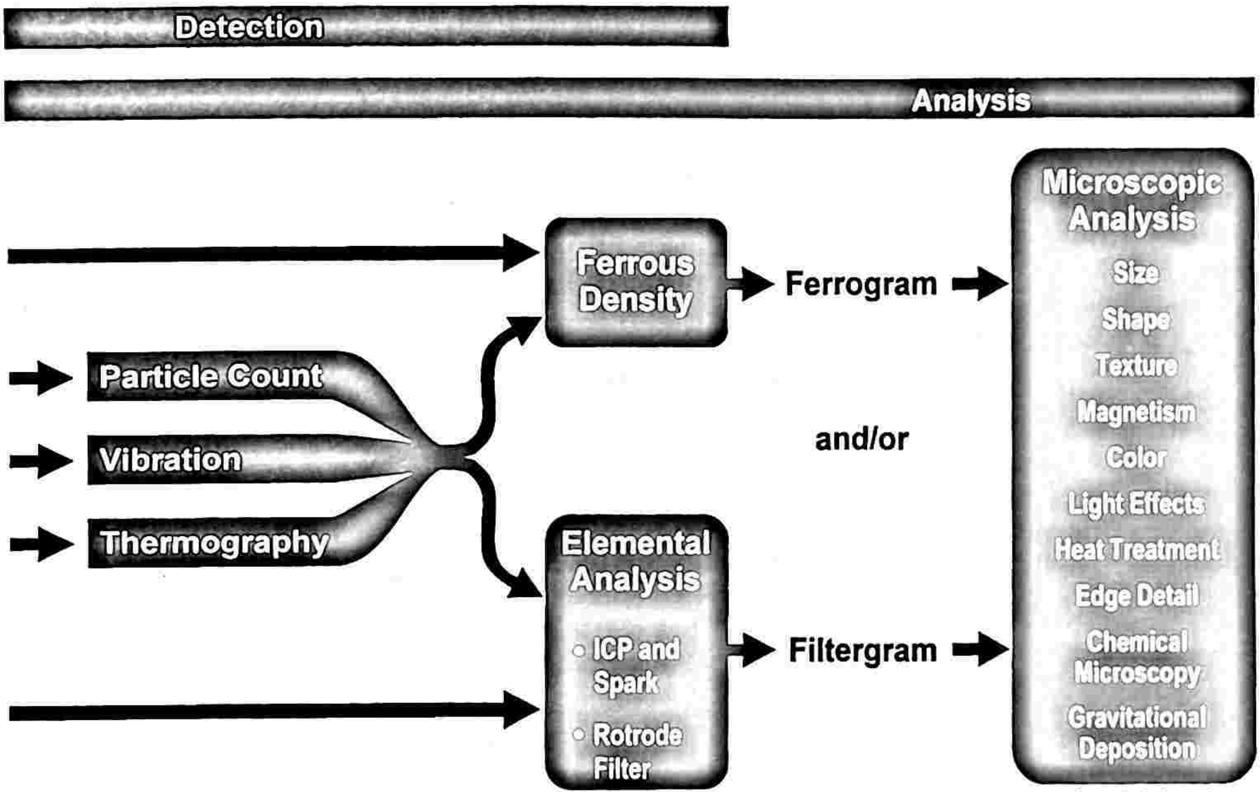
1. Isolate it to a single component
2. Identify the cause
3. Assess how severe or threatening the condition is, and, finally
4. Determine the appropriate corrective action

When problems are detected and analyzed early they can often be arrested without downtime or expensive repair. In fact, root causes of the most common problems are usually correctable on the run. The key is the timing of the detection. An important part of timing is a regimen of frequent sampling.

Successful analysis of a current wear-related problem requires many pieces of information and a skilled diagnostician. To this end, the practice of analytical ferrography has received recently prominence. Unlike other common instrumentation technologies, analytical ferrography is qualitative and requires visual examination and identification of wear particles. Numerous properties and features of the wear debris are inventoried and categorized. These include size, shape, texture, edge detail, color, light effects, heat treatment effects, apparent density, magnetism, concentration, and surface oxides.

This information is combined with other information obtained by particle counting, ferrous density analysis and elemental spectroscopy in defining a response to items 1-4 above. Figure 19-18 presents a general overview of the combined detection and analysis process. Here are analytical ferrography is represented by microscopic analysis. Two methods are commonly used to prepare the particles for viewing by the microscope.

If a high level of ferromagnetic debris is detected by ferrous density analysis then a ferrogram is typically prepared. The process involves slowly passing solvent-diluted oil down the surface of an inclined glass slide. The instrument involved is called a ferrogram maker. Beneath the slide is a strong magnet. Ferromagnetic particles become quickly



Courtesy Noria Corporation

Figure 19-18. Combined detection and analysis process.

pinned down onto the slide and oriented to the vector lines of the magnetic field.

Non-magnetic debris deposit gravimetrically in random fashion, although larger and heavier particles settle first. Approximately 50% of the non-magnetic particles wash down the slide and do not deposit. A ferrogram of wear is shown in Figure 19-19.

In those cases where low levels of ferromagnetic particles are detected but high nonferrous debris is found (by a particle counter or elemental analysis) a filtergram is preferred. Unlike the ferrogram, the filtergram does not use a magnet and therefore all particles are randomly deposited regardless of size, weight, or magnetic attraction. This is accomplished by passing an exact quantity of solvent-diluted oil through a membrane of about three-micron pore size. No particles are hidden from observation except those too small to be retained by the membrane. The single disadvantage of the filtergram is the difficulty of distinguishing ferrous from non-ferrous debris. The skillful eye of an experienced technician can usually overcome this drawback.

INTERPRETING TEST RESULTS

Most machines are highly complex, consisting of exotic metallurgy and intricate mechanisms. The numerous frictional and sealing surfaces usually employ varying contact dynamics and loads, all sharing a common lubricant. Failure to gain knowledge of the many internal machine details and using them as a reference base for interpreting

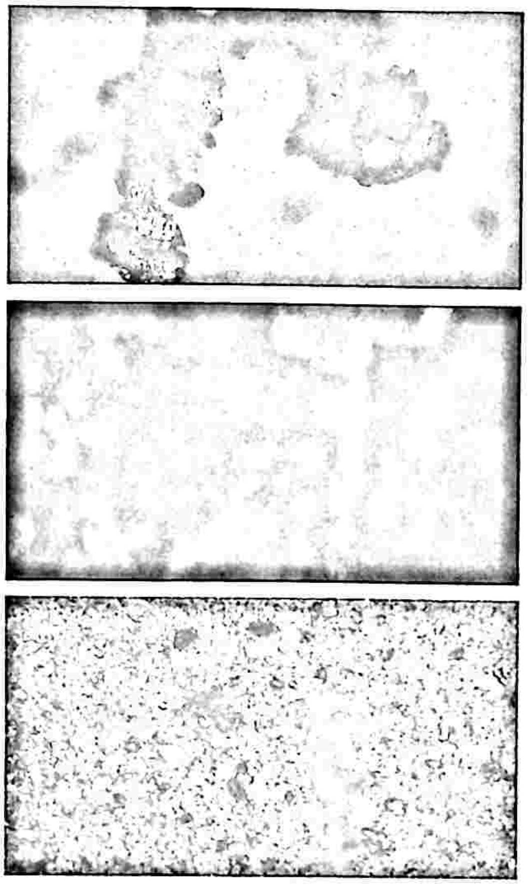


Figure 19-19. Pictured at right are examples of particles identified by analytical ferrography: cast iron, dense ferrous and products of corrosion magnified to 1,000 times normal size.

data may lead to confusion and indecision in response to oil analysis results. A good approach is to build a three-ring binder with index tabs for each machine type.

Include in this binder photocopied pages from the service and operation manuals plus other accumulated information. The following are examples of data and information to include:

1. Identify types of bearings in use and their metallurgy
2. Identify input and output shaft speeds and torques
3. Identify type of gears in use, speeds, and loads. Determine gear metal hardness, surface treatments, alloying metals
4. Locate and identify all other frictional surfaces, such as cams, pistons, bushings, swash-plates, etc. Determine metallurgy and surface treatments
5. Locate and identify coolers, heat exchangers and type of fluids used
6. Obtain fluid flow circuit diagrams/schematics
7. Locate and determine the types of seals in use, both external and internal
8. Identify possible contacts with process chemicals
9. Record lubricant flow rates, lubricant bulk oil temperatures, bearing drain and inlet temperatures, and oil pressures
10. Record detailed lubricant specification and compartment capacity
11. Record filter performance specification and location

In many cases oil analysis data can be inconclusive when used alone. However, combined with sensory inspection information, a reliable and more exact determination is possible. Likewise, the application of companion maintenance technologies (like vibration and thermography) can help support a conclusion prior to expensive machine teardown or repair. Table 19-10 represents a two-page summary of combined analytical and inspection/sensory indications of frequently encountered problems.

Table 19-10. Oil analysis data interpretation and problem identification.

Problem Area	Analytical Indications(a)	Inspection/Sensory Indications(b)
Wrong Lubricant	• Change in viscosity, VI, flash point, additive elements, FTIR(b) specta, TAN(c)/TBN(d) • Change in wear patterns	• Change in oil gage or bearing temperature • Bearing distress or noise • Hard turning of shaft
Antioxidant Depletion	• Decreasing TAN(c), RBOT oxidation life, and Zn/P content • Increasing viscosity, TAN(c), particle count • FTIR: decreasing antioxidant, increasing oxidation, sulphation, and/or nitration	• Oil darkening • Pungent odor • Hot running
Dispersancy Failure	• FTIR,(b) low TBN(d) • Increasing particle count, pentane insolubles • Defined inner spot on blotter test	• Filter inspection: sludge on media, filter in bypass • Black exhaust smoke • Deposits on rings and valves
Base Oil Deterioration	• Increasing viscosity, TAN(c), particle count, and/or ferrous particles • Decreasing TBN(d) • Change in VI and lower dielectric strength	• Poor oil/water separability • Air entrainment/foaming • Pungent odor, sludge/varnish formation • Blotter spot yellow/brown, oil darkening
Water Contamination	• Increasing viscosity, TAN(c), Ca, Ma, and/or Na • Rapid additive depletion/failure • Crackle test, VISA(e), KF(f), FTIR(b) • Reduced dielectic strength • Blotter test: sharp or star burst periphery on inner spot	• Oil clouding/opacity, water puddling/separating, sludging, foaming • Evidence of fretting wear/corrosion • Filter: paper is wavy, high pressure drop, short life. Ferrogram shows rust. • Valve stiction, orifice silting, bearing distress/failure, noisy pump/bearings
Coolant Contamination	• Increasing viscosity, copper, particle count, wear metal, Na, B, and/or K • FTIR(b): glycol • Crackle test, VISA(e), KF(f)	• Bearings dark charcoal color, distressed • Dispersancy failure, sludging, varnishing • Blotter test: sticky, black center • Filter plugs prematurely, oil has mayonnaise consistency, white exhaust smoke
Fuel Dilution	• Low oil viscosity, flash point • Additive and wear metal dilution (elemental analysis) • FTIR(b)/gas chromatography for fuel • Rising particle count and wear metals	• Rising oil levels and oil gage temperatures • Blotter test: halo around center spot • Blue exhaust smoke (collapsed rings), plugged air filter, defective injectors • Oil has diesel odor, overfueling conditions

(a) Not all of the identified indications would be expected for each problem area. (b) Fourier Transform Infrared Spectroscopy (c) Total Acid Number (d) Total Base Number (e) Vapor-Induced Scintillation Analysis (f) Karl Fischer

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(*Continued*)

Table 19-10. (Continued)

Problem Area	Analytical Indications (a)	Inspection/Sensory Indications(a)
Air Entrainment	• Increased viscosity, TAN(d), water, and/or FTIR(b) for oxidation • Silicon defoamant levels too high/low • Blotter test: coke-like carbon on patch	• Oil clouding/foaming, increase in oil gage temp. • Spongy/slow hydraulics, cavitation of pump/bearing, noisy operation
Abrasive Wear Conditions	• Increased silicon, aluminum, particle count and/or ferrous particles • Water contamination • Ferrogram has cutting wear, silica particles	• Scratch marking or/polishing of frictional surfaces • Cutting wear on blotter/patch/filter media • Filter/breather/seal failure
Corrosive Wear Conditions	• Increased TAN(d), particle count, spectrographic iron & bearing metals, water • Decrease in TBN(d) • Ferrogram shows submicron debris at ferrogram tail, rust particles, metal oxides	• Fretting, pitting and etching on contact surfaces • Transient electric currents, high engine blowby • Rust on patch or filter media
Failed Filter	• Increasing silicon/aluminum, particle count, ferrous particles, and/or elemental iron • Ferrograms show green looking particles, cutting wear, filter fibers	• Valve silt lock, noisy bearings • Unchanging or high delta P of filter • Frequent bearing failures, high levels of bottom sediment
Overheating	• Increasing ferrous particles, particle count, flash point, viscosity, or oil specific gravity • Ferrograms show friction polymers, oxides, bluing/tempering of particles, sliding wear particles, bearing particles, e.g., babbitt	• Bearing distress/failure • Hot spots and high bearing metal temp. • Evidence of coking/sludge • Burnt/rancid odor, high oil gage temp.
Misalignment, Imbalance, Overloading	• Ferrograms densely loaded with black-iron oxides, dark metallo oxides, severe cutting and sliding wear, tempered particles, large, chunky particles, or bearing metals • Increase in viscosity, TAN(d), particle count, and/or ferrous particles • Depletion of Zn and P	• Engine lugging/stalling, black exhaust • Raised oil, bearing metal, or jacket-water temperature • Dark, foul smelling oil, bearing distress/failure, hard turning of shaft • Abnormal vibration, noise • Blotter test: coke, metal chips • Metal chips on filter , highly loaded chip detectors
Impending Failure of Bearing, Gear, Pump, etc.	• Exponential increase in particle count and number of wear particle concentration • Increase in iron or bearing metals • Ferrogram shows rate increase in spheres, dark metallo oxides, particle bluing, spalling/chunks, severe sliding/galling particles, cutting wear	• Shaft wobble, vibration, acoustic changes, blue exhaust smoke, hot spots, hard turning shaft and/or high bearing metal temperatures • Patch/blotter shows coking

IMPORTANCE OF TRAINING

When a well-intentioned oil analysis program fails to produce the expected benefits it is often thought that a main contributing factor is an attitude of indifference among those involved. While this is occasionally true, the problem is generally much more fundamental and deep-rooted. Unless maintenance professionals have an understanding of the purpose and goals of oil analysis and are literate in the language of oil analysis, they cannot be expected to carry out its mission.

This mission is accomplished through a liberal amount of training and education. However, the effort should not simply be concentrated on a single individual but should involve all those that benefit from and contribute to machine reliability. Instead, training and education should be directed at several different functions including craftsmen, operators, engineering, and management. Below are a few subjects for which seminars and training classes are generally available:

1. Lubrication fundamentals and their application
2. Mechanical failure analysis
3. Proactive maintenance and root cause
4. Analysis and toubleshooting of hydraulic systems
5. Lubrication and maintenance of bearings and gear units
6. Oil analysis fundamentals
7. Oil analysis data interpretation
8. Filtration and contamination control
9. Wear particle analysis and machine fault detection

Once these fundamentals are in place, oil analysis can move forward enthusiastically, beginning with the development of its mission and goals. And, instead of indifference to oil analysis exceptions, rapid-fire corrections are carried out and measures are taken to preempt their recurrence. In time, unscheduled maintenance is rare and oil analysis exceptions become fewer as the machine operating environment becomes more controlled.

Finally, as the many elements of oil analysis and proactive maintenance merge together into a cohesive maintenance activity, the benefits should not be allowed to go unnoticed. Unlike many applications of new technology, proactive maintenance seeks non-events as its goal and reward. These non-events include oil that continues to be fit-for-service, machines that don't break down, and inspections that don't have to be performed. This quiet existence is the product of a highly disciplined activity but, let us remember, the activity risks being thought of by the casual observer as unneeded. Therefore, the plant's expenditures for proactive maintenance and the highly attractive benefits of proactive maintenance must be measured, monitored, and the outcome displayed for all to view.

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APPENDICES

Appendix A

Lubrication Program*

Work Process Manual

Lubrication Program Work Process Manual

Overview

Introduction

The purpose of this guide is to provide a detailed process for use by plants in developing, implementing, maintaining and improving their industrial lubrication programs. It is a compilation and organization of existing published material, input from maintenance and reliability professionals, and experience gained by the author during his tenure as a Reliability Engineer and consultant.

Audience

This guide is intended for all individuals who are involved with any of the four phases necessary to establish industrial lubrication programs.

Purpose

To significantly reduce the amount of time required by maintenance and reliability professionals to establish effective lubrication programs.

Program Goal

The goal of every lubrication program should be to ensure that all equipment receives and maintains the required levels of lubrication such that no equipment fails due to inadequate or improper lubrication.

Note to the Reader

The step descriptions in this manual should be read in conjunction with the work process diagrams.

In this document

This document contains the following information:

Title	See Page
Step Descriptions	3
Work Process Diagrams	Appendix A

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Practical Lubrication for Industrial Facilities

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