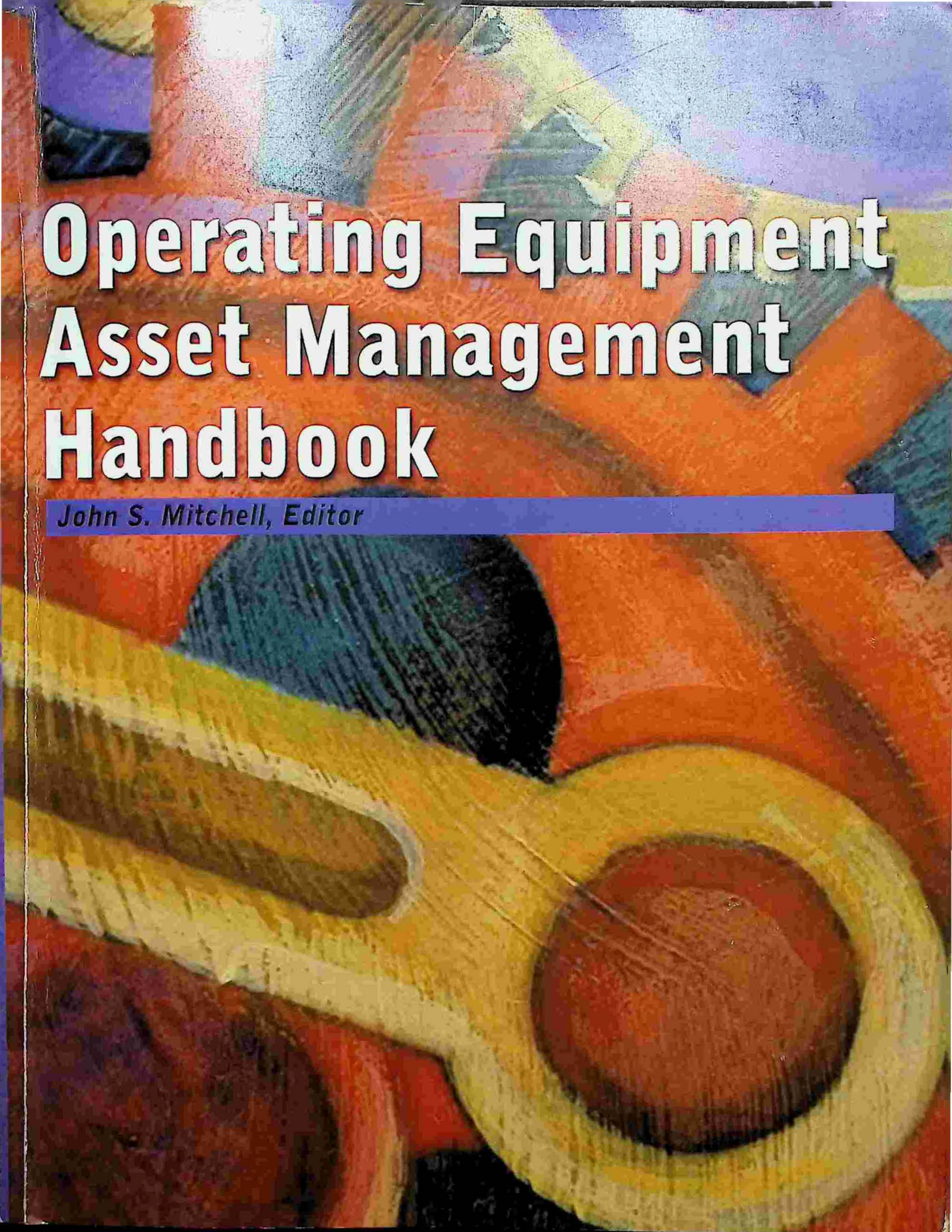

Operating Equipment Asset Management Handbook

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XI. FUNDAMENTALS OF FLUID ANALYSIS FOR INDUSTRIAL MACHINERY

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Illustrations:

A. Introduction

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. 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, the opportunities surround what is commonly referred to as proactive maintenance.

Carefully monitoring and controlling the conditions of the oil (nurturing) can systematically eliminate many of the root causes of failure. Case studies of highly successful organizations show that oil analysis plays a central role in this nurturing activity. For oil analysis to succeed, the user organization must first define the goals of the effort.

Some people view 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 for 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 finetunes it through continuous improvement.

Detecting Machine Faults and Abnormal Wear Conditions

In the past, success in fault detection using oil analysis was limited primarily to reciprocating engines, power train components, and aviation turbine applications. The 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, industry reports have revealed widespread success using wear debris analysis to detect machine anomalies in stationary industrial lubrication oils and hydraulic fluids. The rapidly growing base of knowledge coming from the burgeoning oil analysis and tribology community has contributed to this success. Figure 11.1 provides a simplistic overview of the application of oil analysis—specifically wear debris analysis—in machine health monitoring. Specific methods are discussed later in this chapter.

Condition-Based Oil Changes

Each year, huge amounts of oil are disposed of prematurely; all at a great cost to the world's economy and ecology. This waste has caused a growing number of companies to discontinue the practice of scheduled oil changes and implement comprehensive condition-based programs in their place. This, of course, is one of the principle roles of oil analysis.

By monitoring the symptoms of oil, we are able to respond to the true and changing conditions of the oil. Figure 11.2 illustrates this point. And, in some cases, reconditioning the oil—including the reconstructing depleted additives—may be practical. Some oil analysis tests even provide a prediction of residual life of the oil and additives. Some distressed oils can be conveniently fortified or changed without disruption of production. In addition, those fluids that degrade prematurely can be reviewed for performance robustness in relation to the machine stressing conditions.

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. Figure 11.3 demonstrates this concept.

When a proactive maintenance strategy is applied, three steps are necessary to ensure that its benefits are achieved. Proactive maintenance, by definition, involves continuous monitoring and controlling of machine failure root causes; therefore, 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 (e.g., particles, moisture, heat, or coolant) and additive degradation.

However, 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 second step often involves an audit of how fluids become contaminated and then systematic elimination of these entry points. Often better filtration and the use of separators are required.

The third step is vital—providing the feedback loop of an oil analysis program. When exceptions occur (e.g., over target results), this feedback allows remedial actions to be commissioned immediately. Using the proactive maintenance strategy, contamination control becomes a disciplined activity of monitoring and controlling high fluid cleanliness, rather than a crude activity of trending dirt levels.

Finally, when the life extension benefits of proactive maintenance are flanked 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. This unique, early detection of machine faults and abnormal wear is often considered the exclusive domain of oil analysis in the maintenance field.

B. Oil Sampling Methods

The success of an oil analysis program depends heavily on proper oil sampling. Experience has taught that correct sampling cannot rely solely on human instincts or judgment. In addition, published manuals on oil analysis often contain inaccurate or outdated methods. The sampling practice must be learned from those experienced in the trade.

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

1. Selecting the Ideal Sampling Point

In circulating oil systems, such as the one shown in Figure 11.4a, the best (primary) location is a live zone of the system upstream from filters where particles from ingression and wear debris are the most concentrated. Usually this means sampling on fluid return or drain lines. Figure 11.4b shows 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.

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 11.4c shows various options for sampling pressurized fluid lines. Where possible, always avoid sampling 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 11.5). A vacuum pump to assist the oil flow may be required for high viscosity lubricants, as shown in Figure 11.4d.

2. 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 concentrations. In contrast, sampling from ports positioned at right angles to the path of the fluid flow in high velocity, low viscosity fluids results in 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, as shown in Figure 11.5. Alternatively, drop-tube vacuum samplers could be used, as demonstrated in Figure 11.6a. 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. To prevent cross contamination and mixing of fluids, never reuse suction tubes.

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 the casing. The optimal location for valves is near return lines and where turbulence is highest. Installing a short length of stainless steel tubing inward from the valve is also helpful.

3. 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." Atmospheric contamination that contacts the oil sample cannot be distinguished from the original contamination.

Avoid sampling methods that involve removing the bottle cap, especially where 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, which is illustrated in Figure 11.6b.

1. *Step One:* Obtaining a good oil sample begins with a bottle of the correct size and cleanliness. The bottle must be at a known level of cleanliness and 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—in other words, 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.

2. *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. 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 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.

3. ***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 containing 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.

4. ***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 pocketknife. This permits air to escape during sampling.

5. ***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.

6. ***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.

C. 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 arresting the problem on the run probably is no longer possible; the machine may have to be torn down 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 for successfully performing oil analysis will be described later; however, insufficient oil sampling frequency is sure to reduce the effectiveness of the effort. "You can't hear an alarm unless you are listening for an alarm" or "You can't catch a fish unless your hook's in the water" both demonstrate this notion. Too often we hear about oil samples being taken every six months or annually, yet vibration readings are taken on the same machinery every month.

Scheduled sampling intervals are common in oil analysis. The frequency may be keyed to drain intervals or operating hours. The following table lists commonly recommended intervals based on operating hours for different machine classes.

Recommended Oil Sampling Frequencies

	Hours
Diesel engines - off highway	150
Transmission, 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/duty	300
Gear boxes - low speed/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

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 should be considered.
- ☐ ***Fluid Environment Severity:*** Operation and fluid environment conditions influence the frequency and rate of failure progress. These include pressures, loads, temperature, speed, contaminant ingression, and system duty cycle.
- ☐ ***Machine Age:*** For most machines, the chances of failure are greatest for machines approaching break-in and after major repairs and overhauls. Likewise, the risk increases as a machine approaches the end of its expected life.
- ☐ ***Oil Age:*** Infant oils and old age oils are the highest risk. Infant oils are those that have just been changed and are less than 10 percent into expected life. Old age oils show trends that suggest additive depletion, the onset of oxidation, or high levels of contamination.

D. Selection of Oil Analysis Tests

After proper oil sampling has been mastered, the oil must be analyzed. Each test that is conducted by an oil lab adds cost to the program; therefore, an optimum selection of tests must 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 to obtain further information that could identify the cause or source of the problem. Exception tests might, for instance, include specialized tests for confirming oil oxidation or abnormal machine wear. Figure 11.7 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 function 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 fixture on 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, which ultimately leads to failure and downtime. For most machines, solid contamination is the number one cause of wear-related failure. Likewise, particles, moisture, and other contaminants are the principal root cause of additive and base stock failure of lubricants. Basic tests—such as particle counting, moisture analysis, glycol testing, and fuel dilution—are valuable and should be performed 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 larger and larger particles as wear advances, the size, shape, and concentration of these particles tell a revealing story of the internal-state condition of the machine.

Streamlining oil analysis can be effectively 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 conditions.

E. Monitoring Changing Oil Properties

Today there are a growing number of organizations transforming their lube programs from scheduled oil changes to condition-based 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.

Plants commonly interpret oil analysis results independent of the lab. The lab is relied on to provide accurate and timely data, leaving the interpretation of the data and the corresponding response to plant personnel who are familiar with the equipment, the application, and the operating conditions. Modern oil analysis software can greatly assist such programs.

To reduce oil consumption, two plans must be implemented. The first plan is proactive in nature and relates to the operating conditions in which the oil exists. Improving the oil's operating conditions will increase its expected life many fold. For example, with mineral oils, a reduction in operating temperature of just 10 degrees C can double the oil's oxidation stability and double the oil change interval. An upcoming section discusses the proactive maintenance benefits of controlling oil contamination.

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

There are numerous modes of degradation of lubricating oil. These change the fluid's many properties. Our intent is to recognize the change by monitoring the correct properties; overly extensive monitoring is wasteful. A discussion of common oil degradation modes and the properties that can best reveal them is presented below. In all cases, we must obtain a base signature of the normal properties in the new oil to benchmark the trended change. These reference properties should remain as a permanent fixture 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 liquid. Viscosity is critical to oil film control and is a key indicator to a host of ailing conditions related to the oil and the machine. As such, it is often considered a critical "catch-all" property in oil analysis. Essentially, when viscosity remains in a controlled narrow band, we can assume that many things that could go wrong, in fact, are not. Conversely, when viscosity falls outside of the band, an exception test is usually needed to identify the nature and cause of abnormality. Therefore, monitoring viscosity serves as a first-line detection defense for many problems.

The importance of viscosity is reflected in the fact that it is often monitored onsite by the reliability team. It is used as an acceptance test for new oil deliveries and to verify that 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. Figure 11.8 illustrates this concept.

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. Kinematic viscosity can also be represented by Saybolt Universal Seconds (SUS). Figure 11.9 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 a 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.

Onsite 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 11.10 shows an absolute viscometer designed for plant-level use. It employs a capillary in its tip, through 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 of which are detrimental to good lubrication. Oxidation is uncommon in applications where oils are relatively cool, dry, and clean. 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), monitoring the progress of oxidation is the only option. Monitoring the depletion of oxidation inhibitors provides an early, forecastable trend; however, it may not be practical in some applications.

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

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. FTIR is addressed in Figure 11.11.
2. Total acid number (TAN) is sensitive to both mass-transfer and decomposition depletion of ZDDP inhibitors. Interpretation of the trend requires practice and a good new-oil reference.
3. Elemental spectroscopy can show reliable mass-transfer depletion trends in ZDDP inhibited oils.
4. Rotating Bomb Oxidation Test (RBOT) provides a highly forecastable trend on additive depletion. The time needed to run this test makes it expensive; therefore it is usually saved for exception testing or special circumstances.
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 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, with oxidation, the worst things get, the faster they get worse. If the goal is a condition-based oil change, this translates to the need to monitor sufficiently frequently 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 for detecting and trending oil oxidation are listed below.

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. Oxidation results in the polymerization of the base oil and the discharge of oxide insolubles, causing the viscosity to increase.
4. Color-bodies form in oxidized oils, resulting in a marked darkening of the oil's color.
5. Oxidized oils emit 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 recip compressors or hot surfaces in IC engines and turbo machinery. Another common cause of localized thermal failure is associated with entrained air that is permitted to compress, similar to air bubbles passing through a high-pressure hydraulic pump. The air bubble implosion causes heat to concentrate, generating microscopic specs 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 because the majority of the physical properties of the oil are unaffected. For instance, there is generally no change in viscosity, TAN, or FTIR for oxidation. However, sophisticated labs that have experience with hydraulic fluids employ specialized tests such as ultracentrafuge, 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 attributable to a number of causes. However, the most common reasons include overloading, inadequate oil supply, failure of a heat exchanger, and 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, 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). This test takes a week to gestate; therefore, it is generally impractical for routine used oil analysss. 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. A review of how additives deplete during normal use and aging offers a good starting point.

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 easiest 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 example, 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.

Figure 11.12 describes common methods used to monitor additive depletion. Note 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).

F. 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. Contamination 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. Although attempting to totally eradicate contamination from in-service lubricants is impractical, controlling contaminant levels within acceptable limits is possible 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, particle contamination and moisture are widely recognized as the most destructive to the oil and machine.

Particle Contamination

No single property of lubricating oil challenges the reliability of machinery more than suspended particles. Particles are essentially 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 they cause can be continuous. Many studies have shown convincing evidence of the greater damage associated with small, rather than large particles. However, most maintenance professionals have misconceptions about the size of particles and the harm they cause.

These misconceptions relate to the definition people apply to what is clean oil and what is dirty oil. This definition also 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 (e.g., improve cleanliness). For example, monitoring cholesterol does not save us from heart disease; the things we do to lower the cholesterol may. 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, we can frequently and easily achieve the new cleanliness targets. Concerns that filtration costs will increase are not often realized because of the greater overall control, particularly 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 a large assortment of common problems also can be routinely detected. As such, particle counting is another important "catch all" type of 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 of oils are checked and verified on a frequent basis, a phenomena 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 come from the careless practices of operators and craftsmen, the combined effect of monitoring with a modicum of training can go along ways toward 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, as shown in Figure 11.13. 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 corresponding to the three range numbers.

Although numerous methods are 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 Figure 11.14. 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.

Oil analysis laboratories use many different types of automatic particle counters. Likewise, there are 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, as shown in Figure 11.15. Pore blockage-type particle counters have a more narrow size range sensitivity; 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. This is shown in Figure 11.16.

Figure 11.17 shows how particle count trends vary depending on the machine application and the presence of an onboard 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. In systems with no continuous filtration (e.g., a splash fed gearbox), the equilibrium is not effectively established (i.e., there is no continuous particle removal). This causes the particle concentration to continuously rise. However, contamination control can be achieved by periodic use of portable filtration systems like 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 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 shown in Figure 11.18, also influences the saturation point.

With few exceptions, the chemical and physical stability of lubricants are 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 result. 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 water is well-known for promoting corrosive attack on sensitive machine surfaces, discharging harmful abrasives into the oil like rust.

The omnipresence of water in the environment precludes completely excluding it from entering and combining with the oil. However, its presence can be greatly minimized and controlled through effective maintenance practices. A proactive maintenance program needs to be established to control water. This should start with setting a target dryness level for each different oil application. By investigating the sources of water ingression, a plan can be implemented to eliminate the water. Occasional removal by water absorbent filters and vacuum dehydrators may also be necessary.

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 degrees 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 this procedure is 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. This concept is illustrated in Figure 11.19.

Other widely used methods to detect water include:

1. Dean & Stark apparatus – occasionally used by laboratories; 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 – 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.

G. Wear Particle Detection and Analysis

While 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—in other words, the symptoms of failure. The oil serves as the messenger of information on the health of the machine. 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; the particles' size, shape, color, orientation, and elements define the cause, source, and severity of the condition.

Elemental Spectroscopy

Figure 11.20 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 the head, 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 special 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, and aluminum. By comparing the major, minor, and trace metals to the metallurgical chart of the machine, we can establish a fingerprint of the probable sources of the wear. Many of the laboratories perform wear metal interpretation with the help of sophisticated software programs and extensive metallurgical databases. Figure 11.21 applies to wear metal interpretation.

Most oil analysis laboratories offer elemental spectroscopy as standard with all samples analyzed. The spectrometers and technology vary somewhat, creating 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 unmeasureable. This particle-size bias leads to occasional errors—some serious (false negatives).

One popular way to reduce the particle-size error is to use rotrode filter spectroscopy. This capability is available with spark-emission spectrometers at many of the large commercial laboratories. A more complete vaporization of larger particles is achieved (possible sensitivity to 20 microns) by pushing the particles into the interstices of the disc electrode. 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 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. Typically the ferrous surface is the most important from the standpoint of machine reliability. As a result, the oil analyst must have a thorough understanding of the ferrous particle concentration at all sizes. This is particularly important, considering the particle-size bias associated with elemental spectrometers. Therefore, to ensure that abnormal wear of iron and steel surfaces does not go undetected, most commercial and onsite laboratories use ferrous density analyzers. These instruments provide a first line of defense by detecting free-metal ferrous debris reliably. Example instruments include:

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

Analytical Ferrography

Elemental spectroscopy and ferrous density analysis are just two of many methods for detecting 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 the fault to a single component
2. Identify the cause,
3. Assess how severe or threatening the condition is
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 to 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 regiment of frequent sampling (e.g., putting the hook in the water).

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 achieved recent 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 via particle counting, ferrous density analysis, and elemental spectroscopy in defining a response to items 1-4 above. Figure 11.22 presents a general overview of the combined detection and analysis process. Analytical ferrography is represented by microscopic analysis in the figure.

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 that does this is called a ferrogram maker. Beneath the slide is a strong magnet. Ferromagnetic particles become quickly pinned down onto the slide and oriented to the vector lines of the magnetic field. Non-magnetic debris deposit gravimetrically in random fashion, with the exception of larger and heavier particles, which settle first. Approximately 50 percent of the non-magnetic particles wash down the slide and do not deposit. A ferrogram of cutting wear is shown is Figure 11.23.

In cases where low levels of ferromagnetic particles are detected, but high non-ferrous debris is found (by a particle counter or elemental analysis), a filtergram is preferred. Unlike the ferrogram, the filtergram does not use a magnet; therefore, all particles are randomly deposited without size, weight, or magnetic bias. This is accomplished by passing an aliquot of solvent-diluted oil through a membrane of about three-micron pore size. No particles are lost from observation except those too small to be retained by the membrane. The single disadvantage of the filtergram is the difficulty of distinguishing ferrous debris from non-ferrous. The skillful eye of an experienced technician can usually overcome this drawback. An example of red iron oxide particles (rust) can be seen in the filtergram in Figure 11.24.

H. 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. A failure to gain knowledge about these many internal machine details as a reference base for use in interpreting oil analysis 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. Types of bearings in use and their metallurgy
2. Input and output shaft speeds/torques
3. Type of gears in use, speeds, loads, gear metal hardness, surface treatments, alloying metals
4. Type and location of frictional surfaces (e.g., cams, pistons, bushings, swash-plates, etc.) and the metallurgy of surface treatments
5. Type and location of coolers and heat exchangers and type of fluids used
6. Fluid flow circuit diagrams/schematics
7. Identification and location of the types of seals in use, both external and internal
8. Possible contacts with process chemicals and types
9. Lubricant flow rates, lubricant bulk oil temperatures, bearing drain and inlet temperatures, and oil pressures
10. Detailed lubricant specification and compartment capacity
11. Filter performance specification and location

In many cases, oil analysis data can be inconclusive when used alone. When combined with sensory inspection information, however, a reliable, more certain, determination can be made. Likewise, the application of companion maintenance technologies (like vibration and thermography) can help support a conclusion prior to expensive machine teardown or repair.

I. Importance of Training

When a well-intentioned oil analysis program fails to produce the expected benefits, indifference among plant personnel is often thought to be a main contributing factor. Although this is occasionally true, in reality the problem is 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.

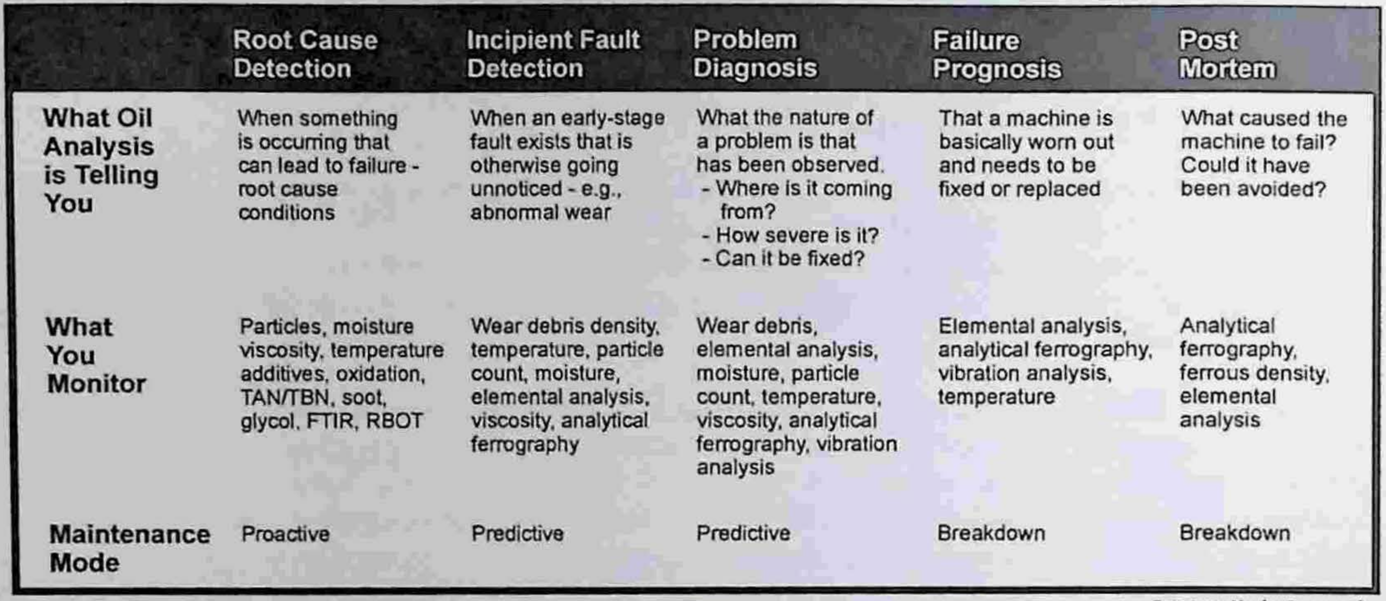
This level of understanding can be accomplished through a liberal amount of training and education. This should not simply be concentrated on a single individual—it should include all of those personnel who benefit from and contribute to machine reliability. In fact, training and education should occur at several different levels, 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 use
2. Mechanical failure analysis
3. Proactive maintenance and root cause analysis
4. Troubleshooting 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 machine fault detection

Once these fundamentals are in place, oil analysis can move forward enthusiastically, beginning with the development of oil analysis mission and goals. Rapid-fire corrections can be carried out in response to oil analysis exceptions and measures can be taken to preempt their reoccurrence. In time, unscheduled maintenance will become rare and oil analysis exceptions will be few, as the idealized machine operating environment becomes controlled.

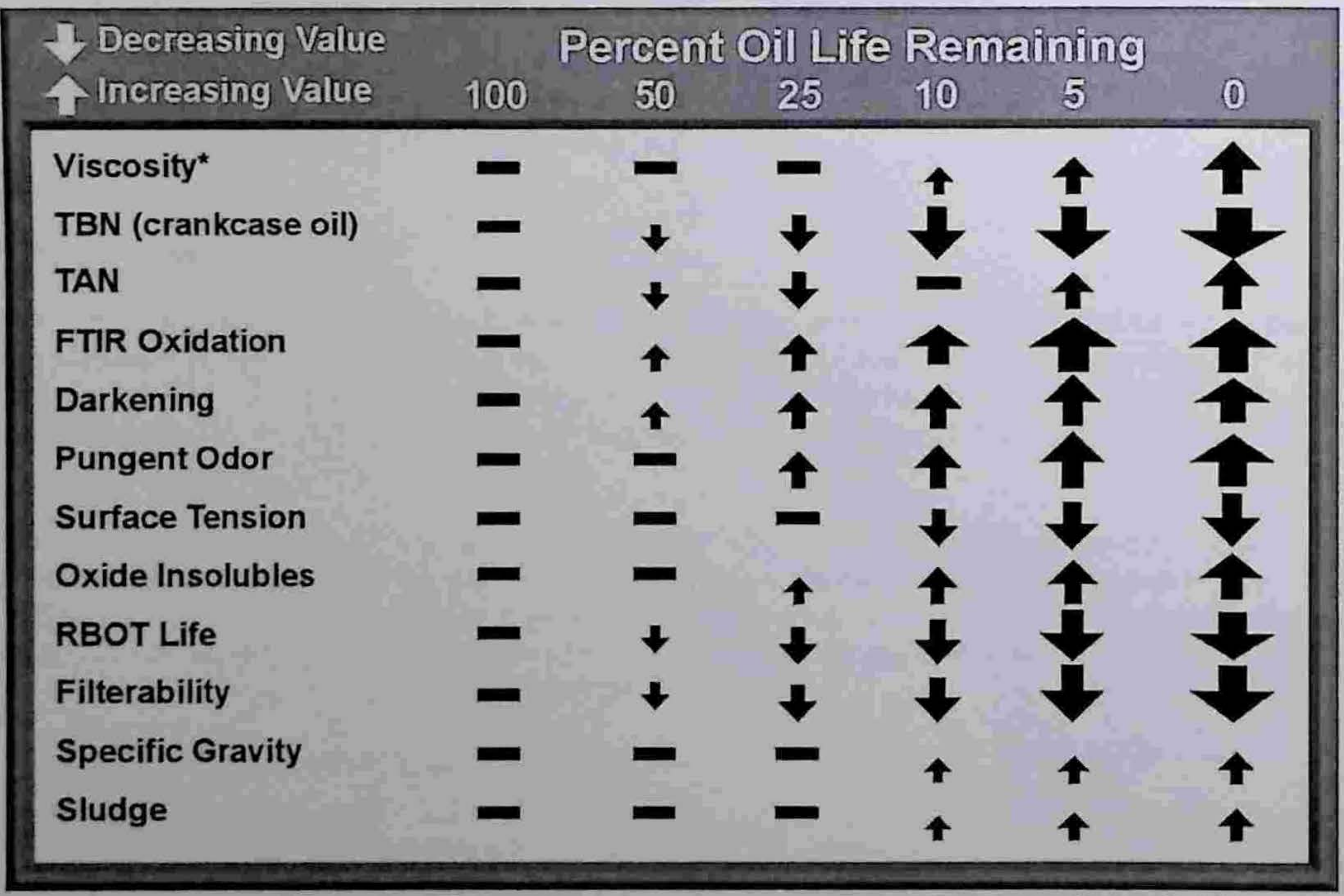
Finally, as the many elements of oil analysis and proactive maintenance merge together into a cohesive maintenance activity, the benefits should be promoted. Unlike many applications of new technology, proactive maintenance seeks non-events as its goal and reward. These non-events include oil that continues to be fit-for-service, machines that do not break down, and inspections that do not need to be performed. This quiet existence is the product of a highly disciplined activity; however, at times, it can be misunderstood and its value underestimated by the casual observer. Therefore, the close association of the activities of proactive maintenance with the benefits of proactive maintenance must be measured, monitored, and displayed for all to view.



	Root Cause Detection	Incipient Fault 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, temperature 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

Courtesy Noria Corporation

Figure 11.1

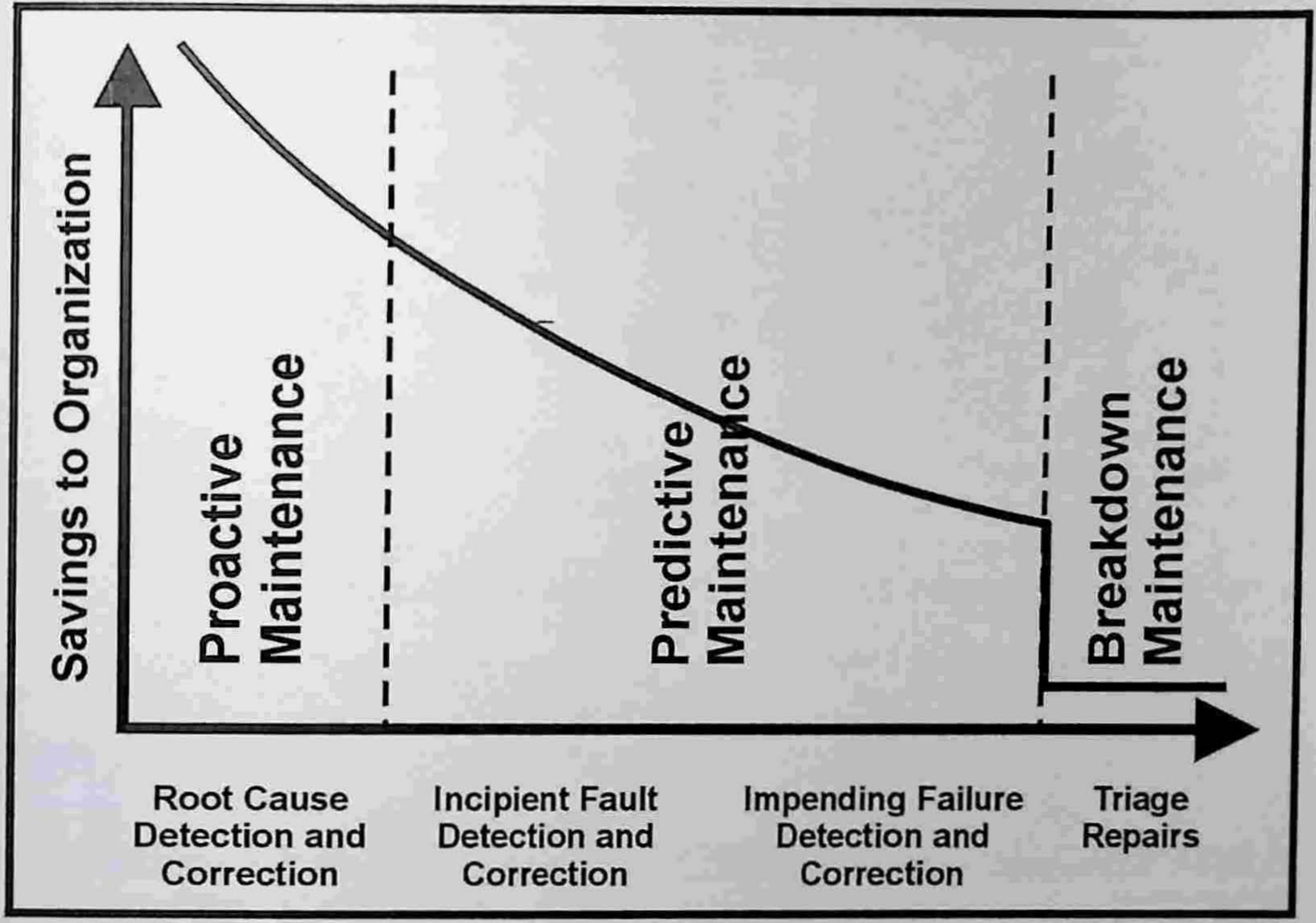


↓ Decreasing Value
↑ Increasing Value

	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	—	—	—	↑	↑	↑

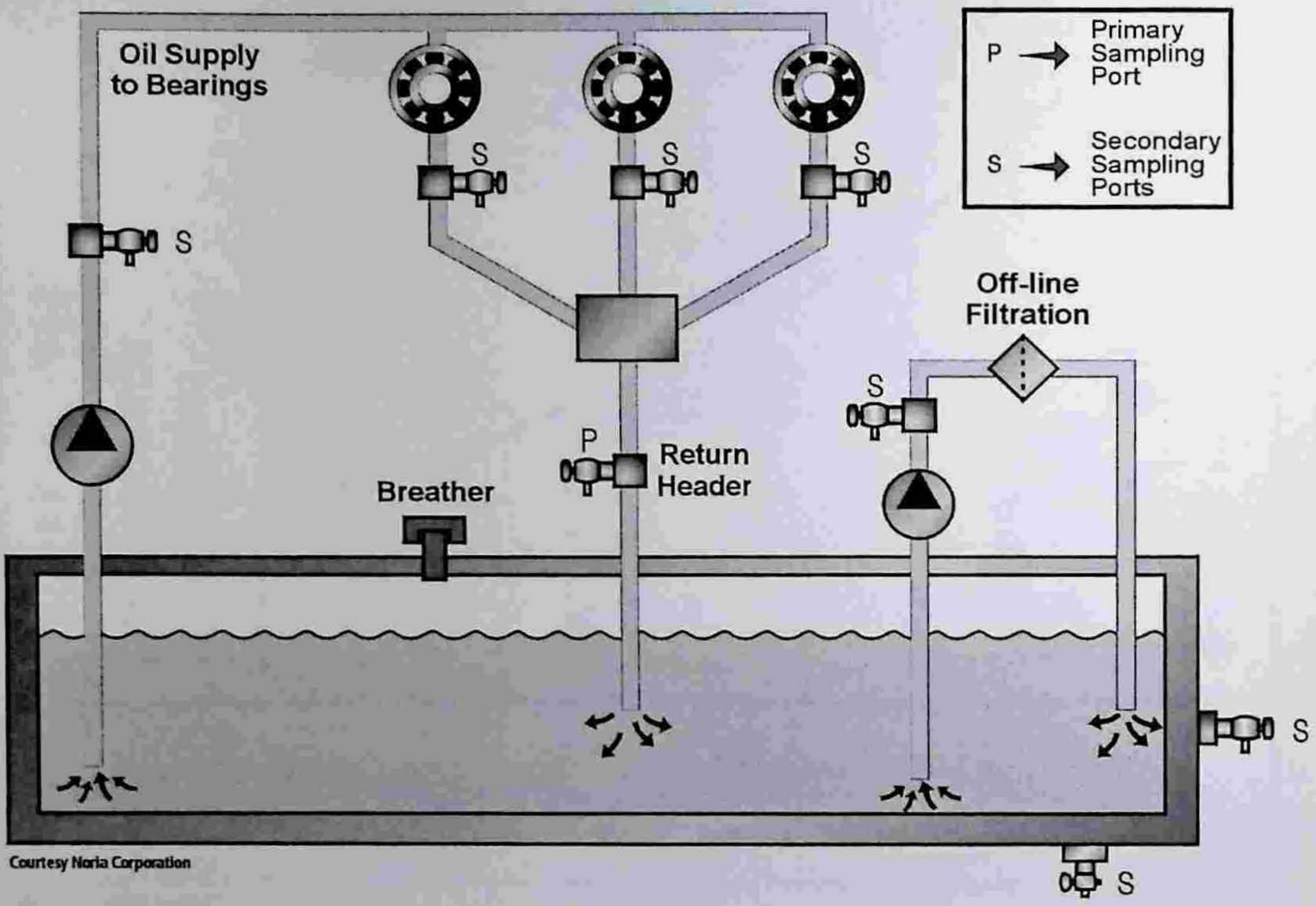
Courtesy Noria Corporation

Figure 11.2



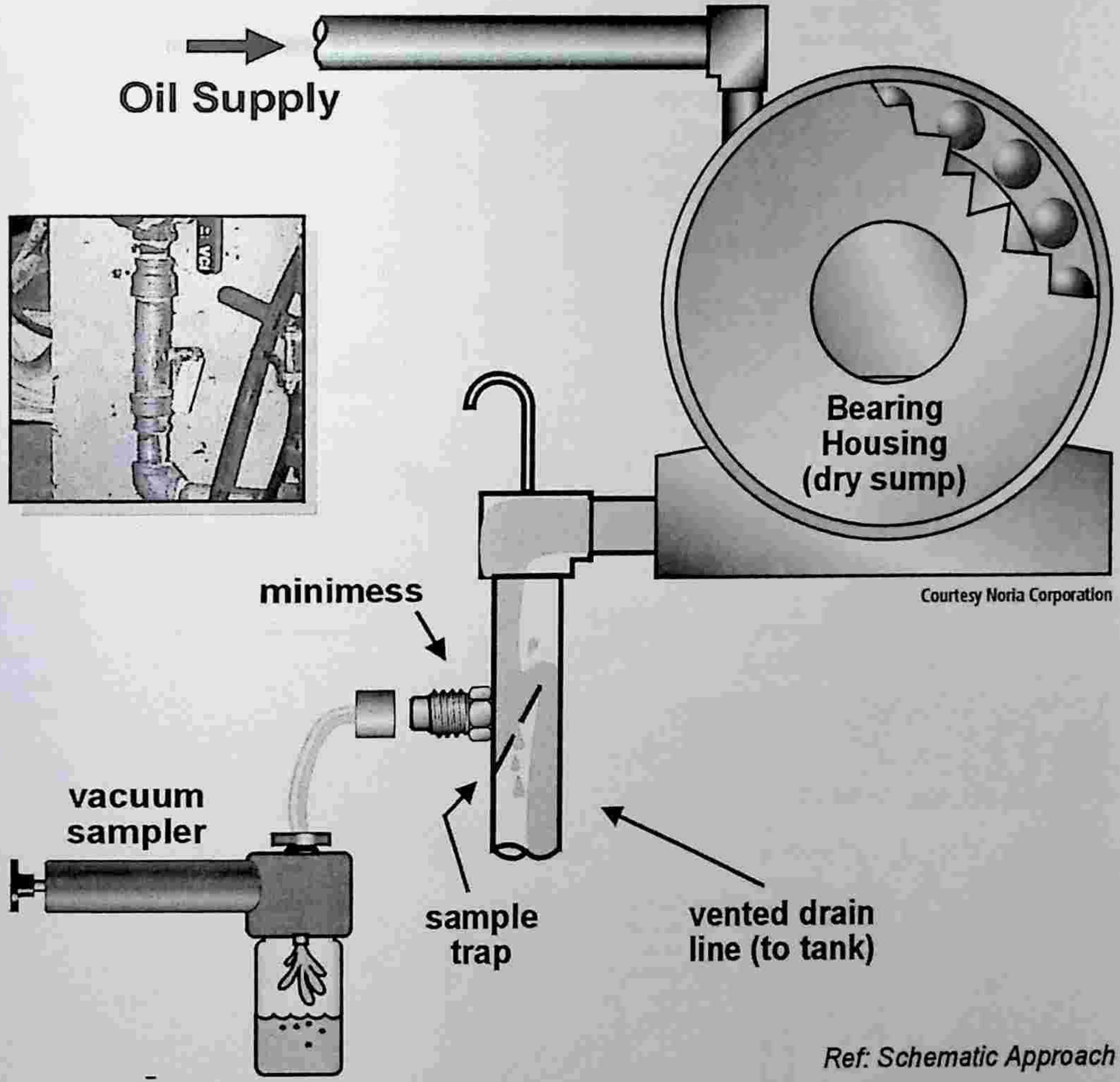
Courtesy Noria Corporation

Figure 11.3



Courtesy Noria Corporation

Figure 11.4a



Courtesy Noria Corporation

Ref: Schematic Approach

Figure 11.4.b

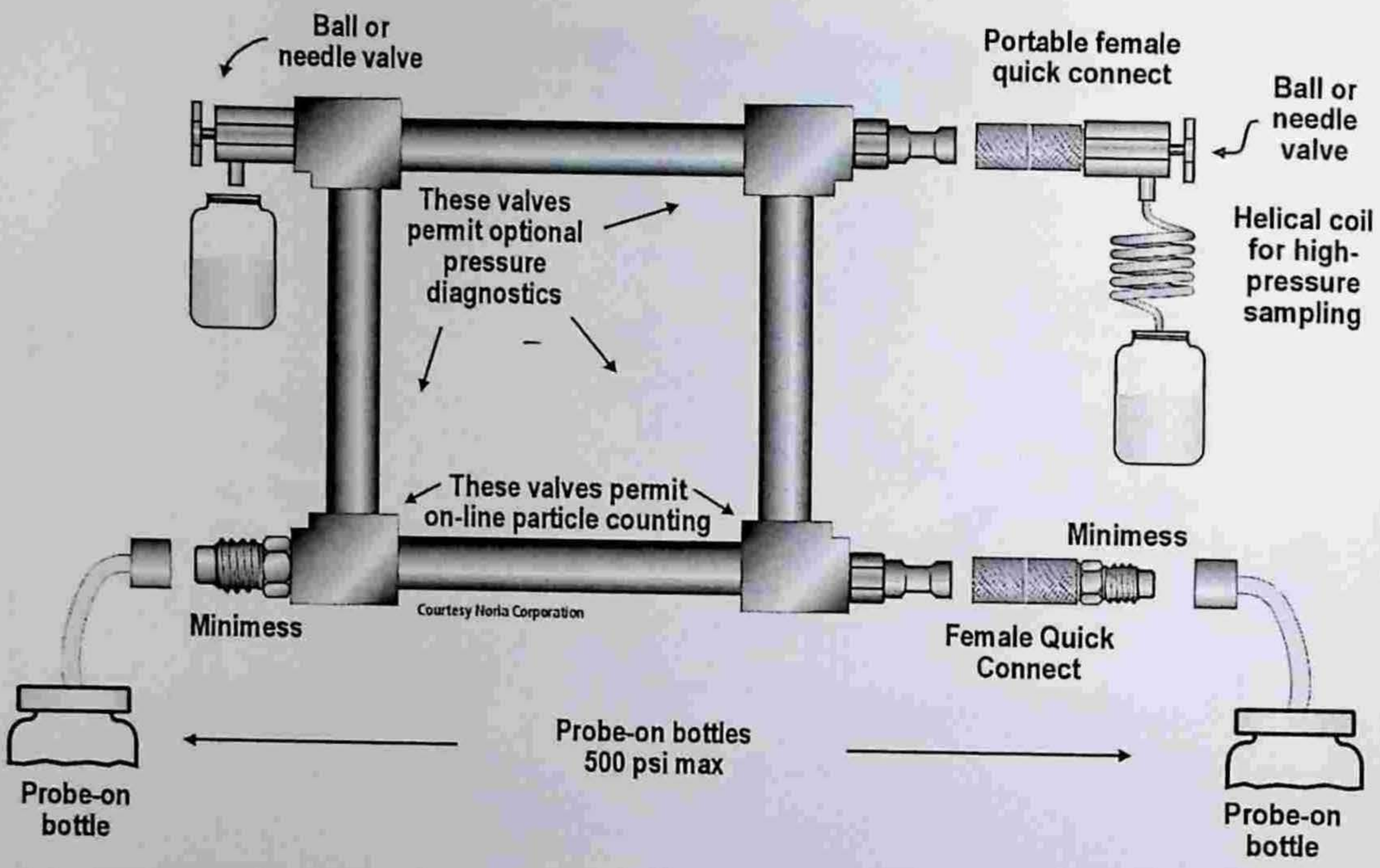


Figure 11.4c

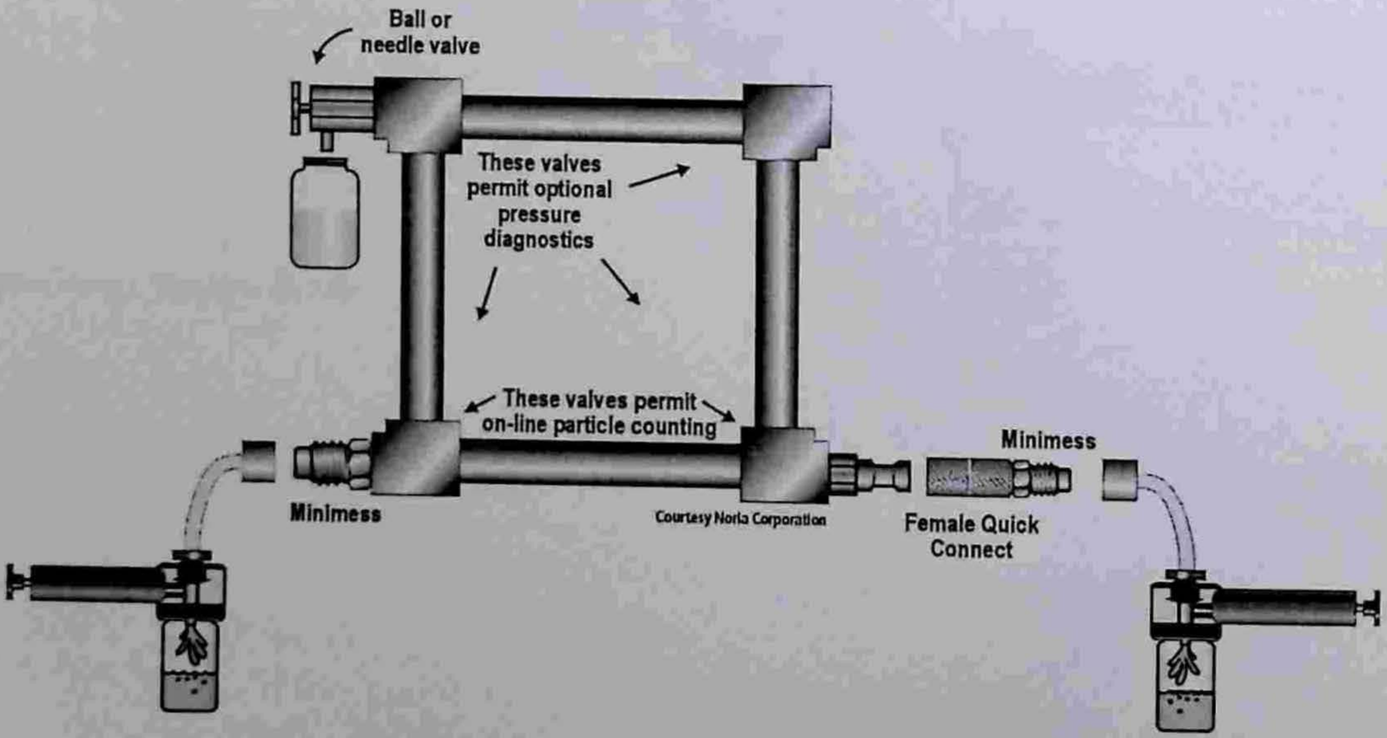
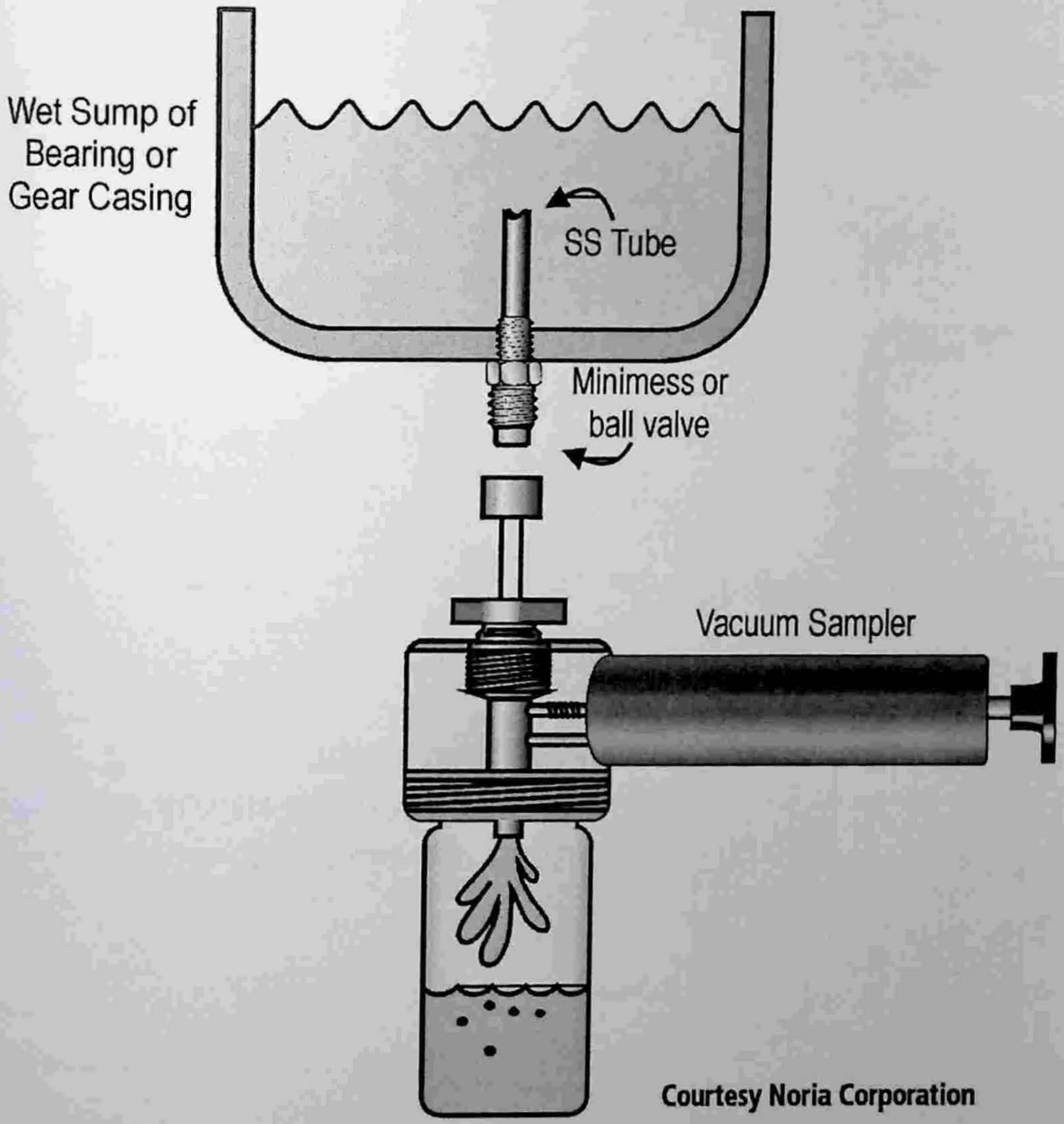
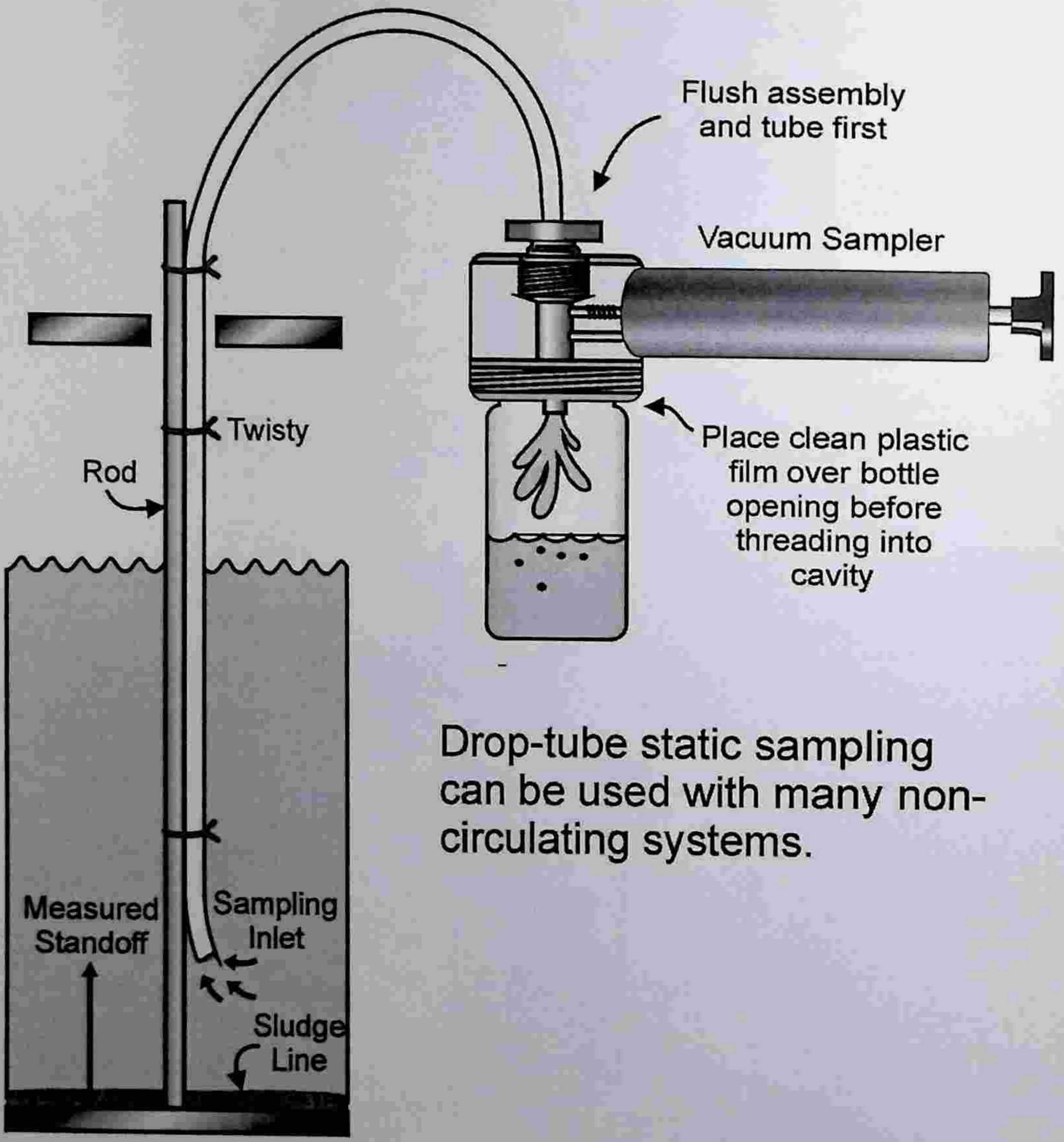


Figure 11.4d



Courtesy Noria Corporation

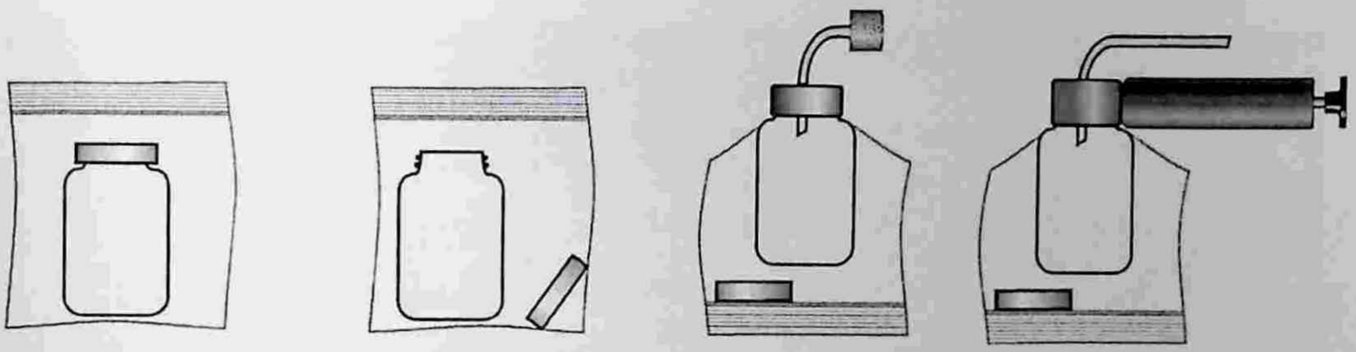
Figure 11.5



Drop-tube static sampling can be used with many non-circulating systems.

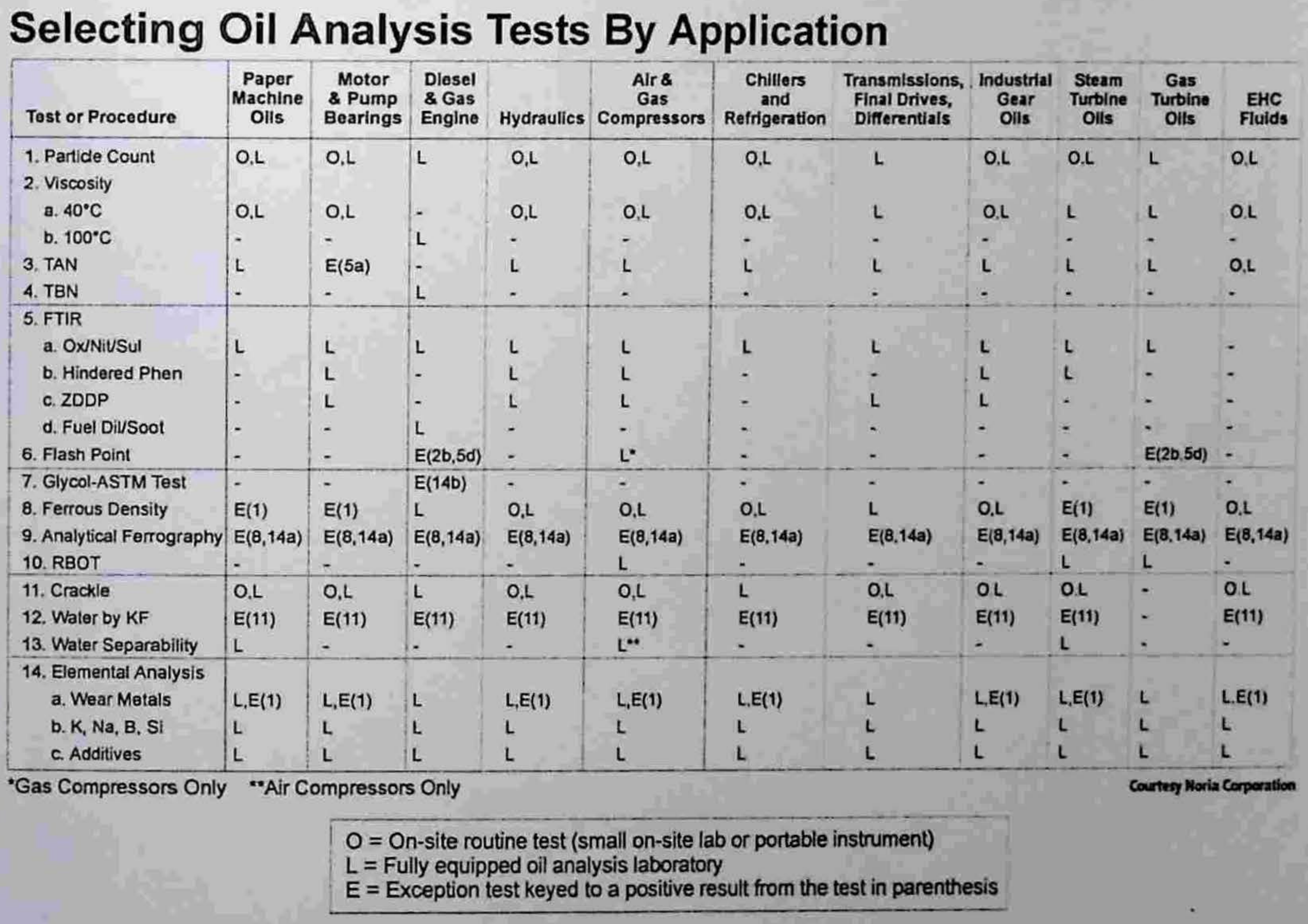
Courtesy Noria Corporation

Figure 11.6a



Courtesy Noria Corporation

FIGURE 11.6B



Selecting Oil Analysis Tests By Application

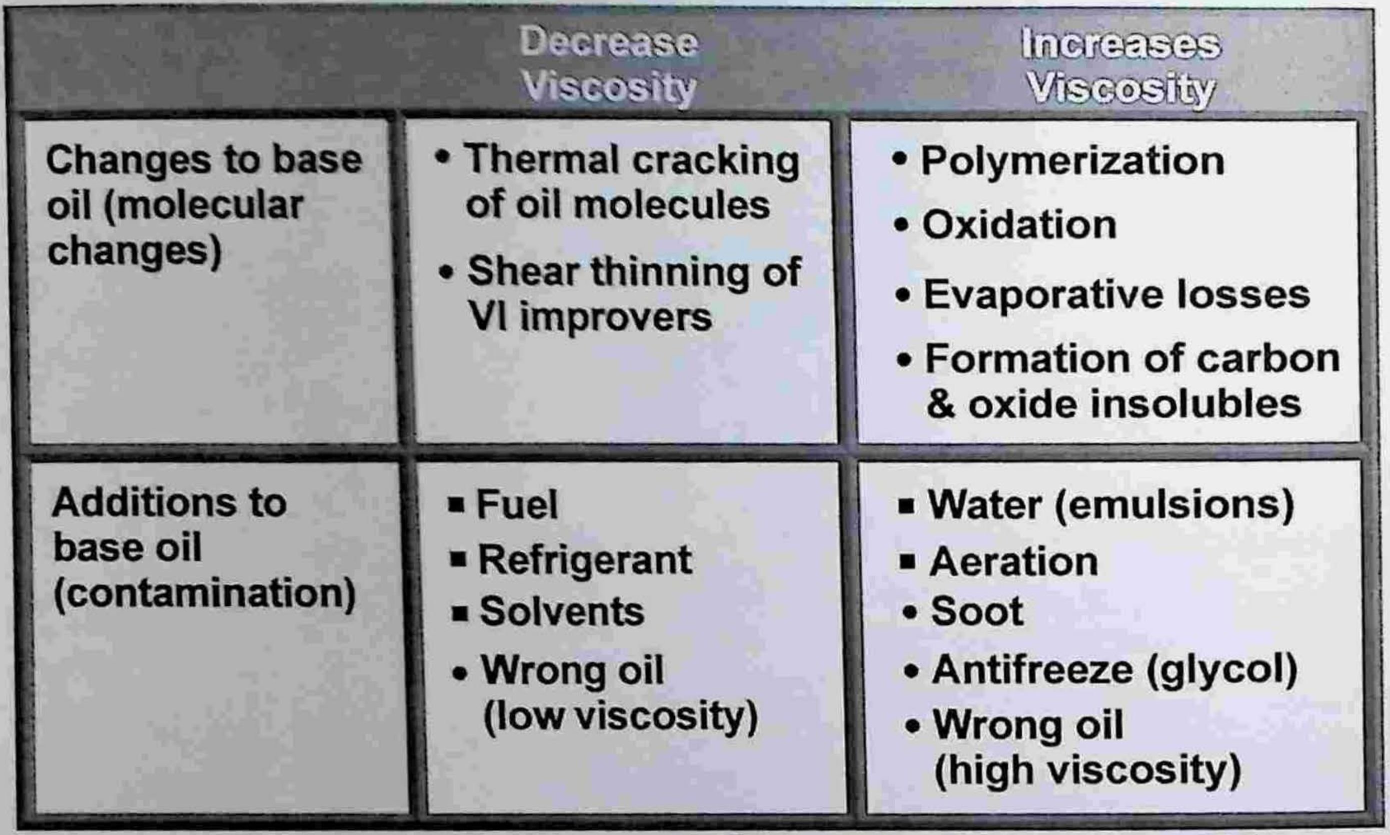
Test or Procedure	Paper Machine Oils	Motor & Pump Bearings	Diesel & Gas Engine	Hydraulics	Air & Gas Compressors	Chillers and Refrigeration	Transmissions, Final Drives, Differentials	Industrial Gear Oils	Steam Turbine Oils	Gas Turbine Oils	EHC Fluids
1. Particle Count	O,L	O,L	L	O,L	O,L	O,L	L	O,L	O,L	L	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

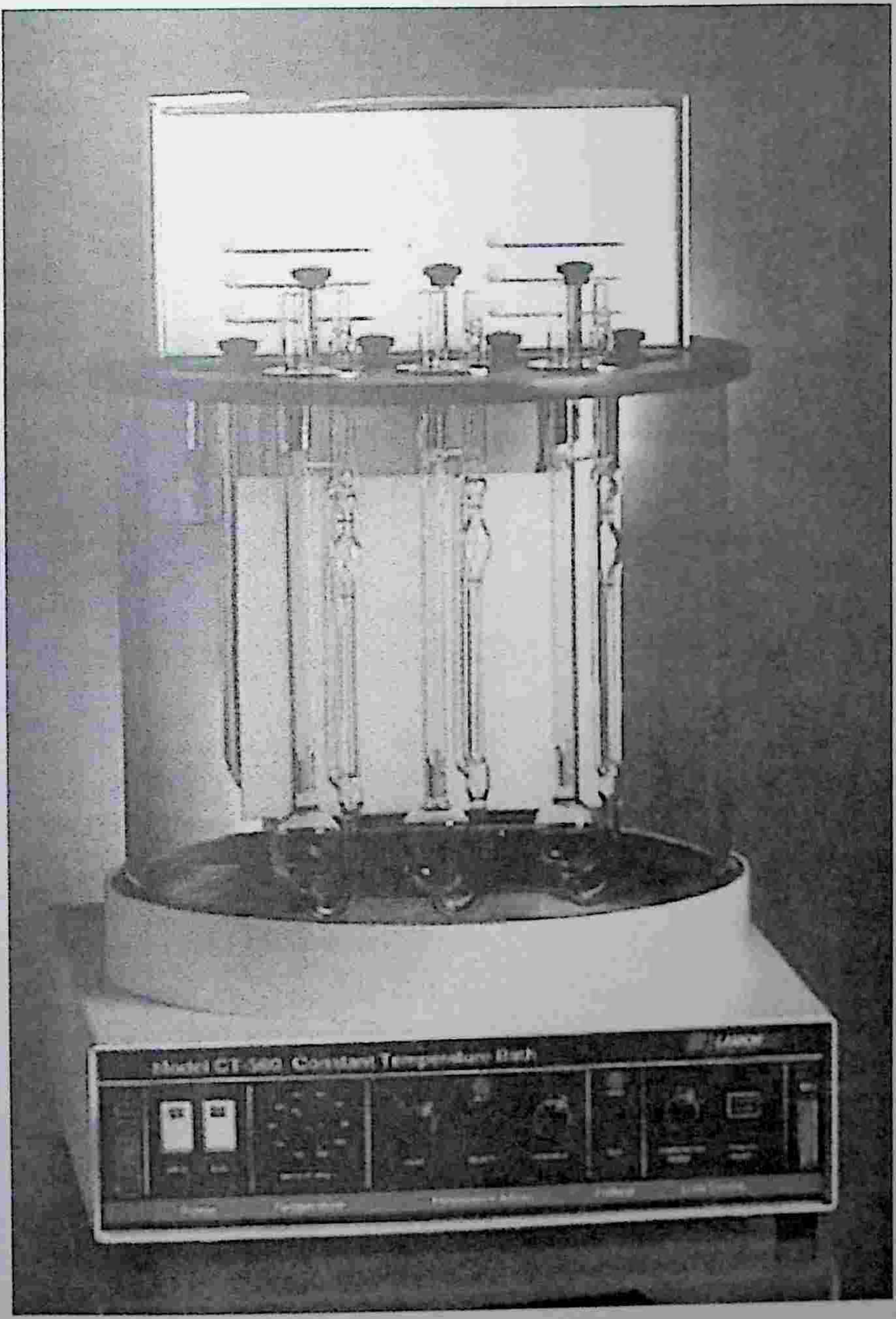
FIGURE 11.7



	Decrease 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)

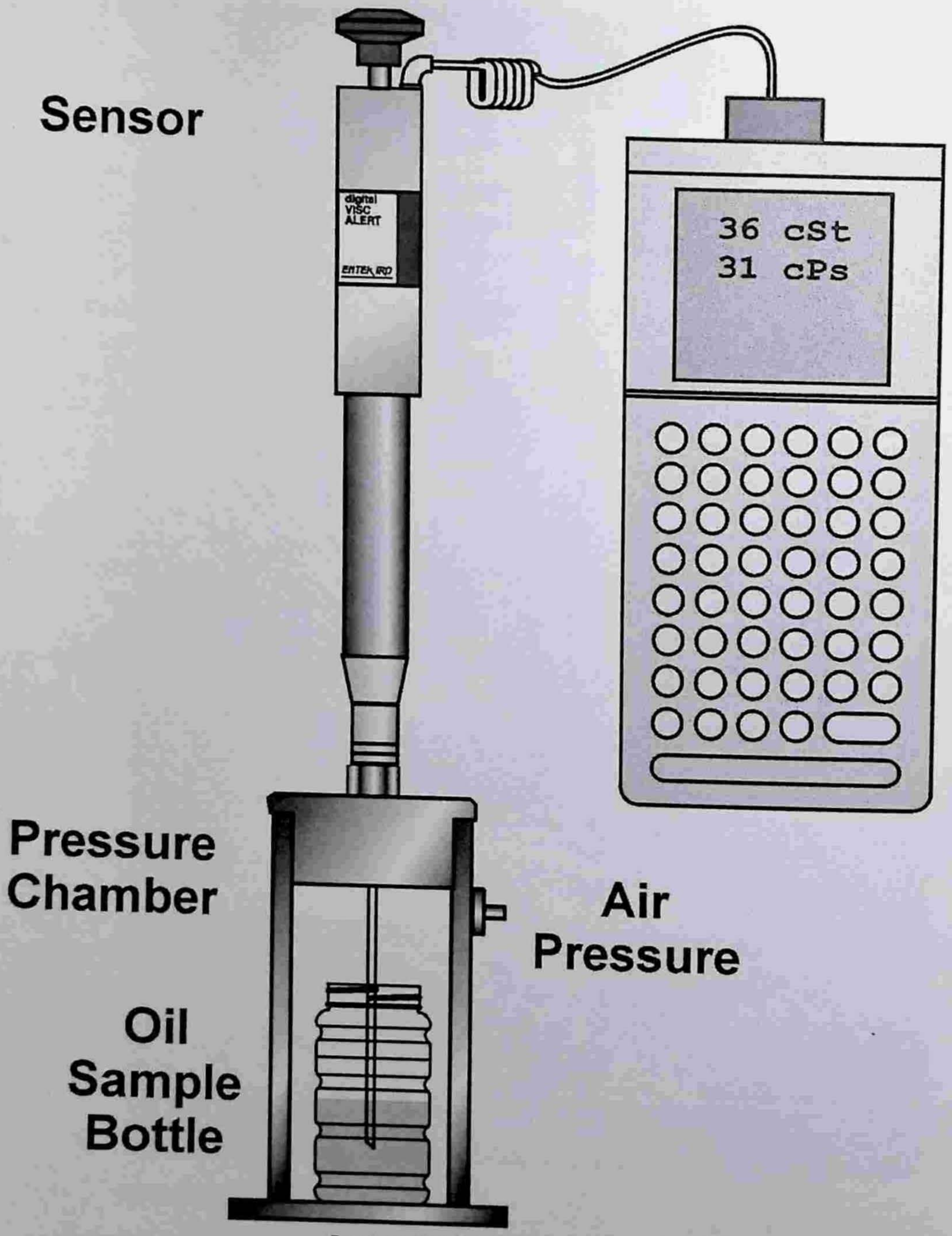
Courtesy Noria Corporation

FIGURE 11.8



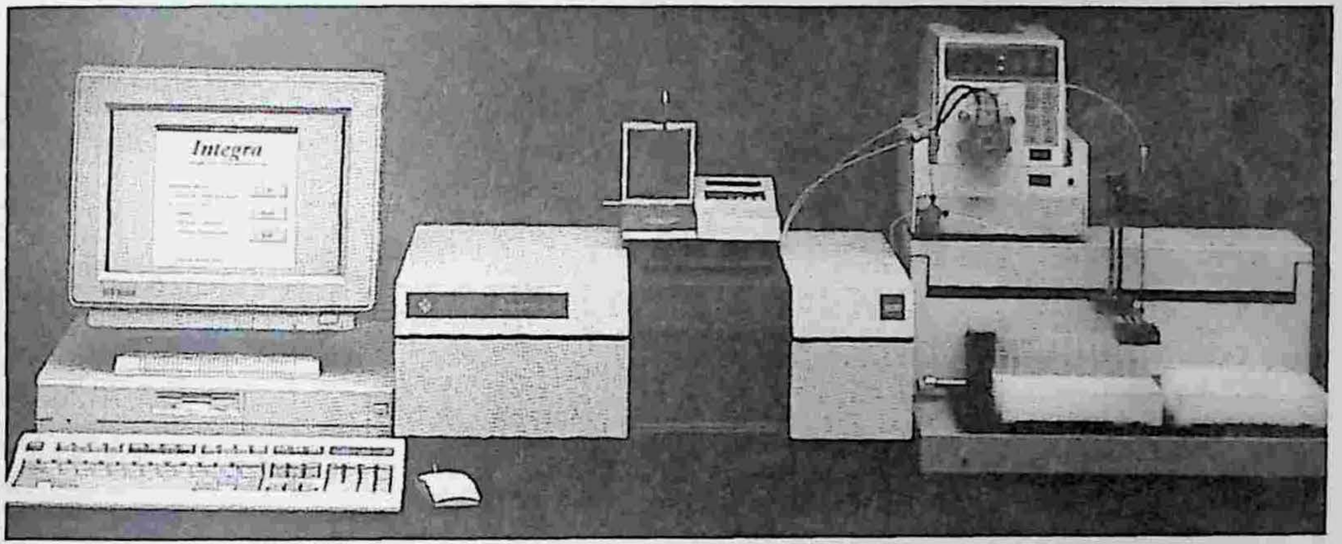
Courtesy Cannon Instruments

FIGURE 11.9



Courtesy Entek IRD

FIGURE 11.10



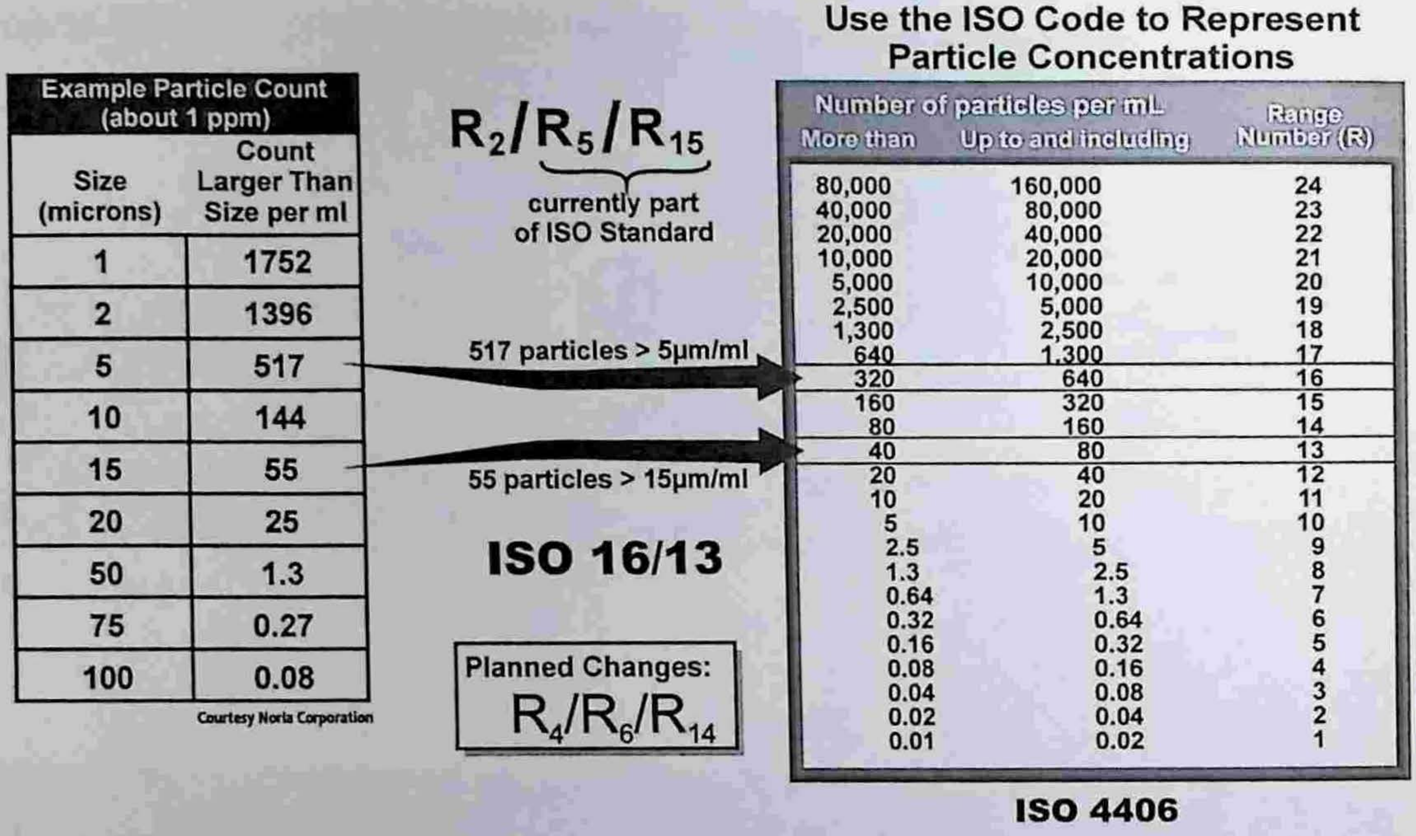
Courtesy Biorad

Figure 11.11

Additive	Monitoring Method	Effectiveness
ZDDP (antioxidant, antiwear, and corrosion inhibitor)	FTIR - (@ ≈950 wavenumbers) FTIR - oxidation (1750 wn) RBOT TAN (downward trend) TAN (upward trend) Voltametry Elemental Spectroscopy	Fair (early detection) Good (later detection) Excellent (early detection) Fair (early detection) Good (later detection) Excellent (early detection) 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 Elemental Spectoscopy	Excellent Excellent
Hindered Phenol (antioxidant)	FTIR	Fair

Courtesy Noria Corporation

Figure 11.12



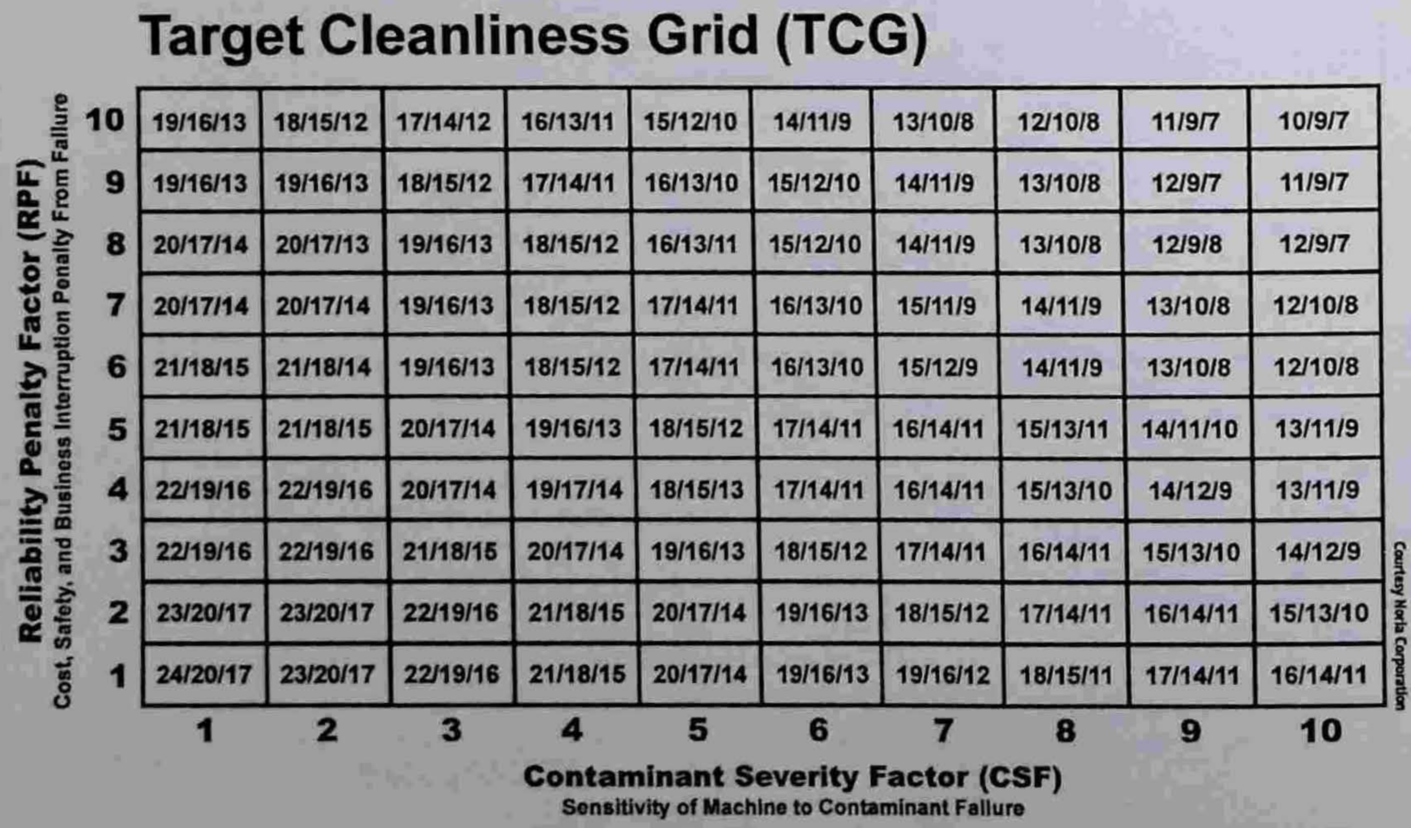
Use the ISO Code to Represent Particle Concentrations

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

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

Figure 11.13



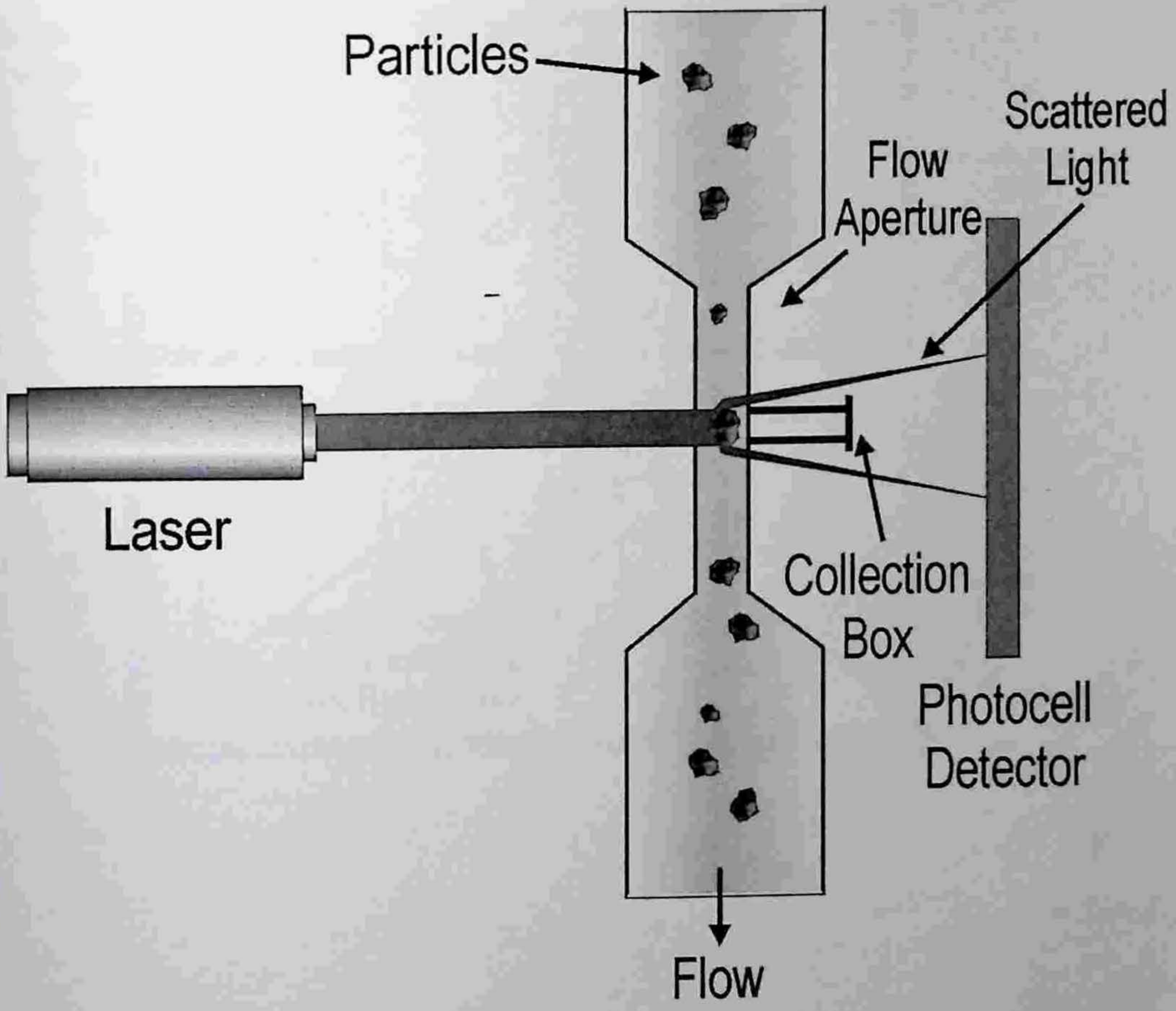
Target Cleanliness Grid (TCG)

Reliability Penalty Factor (RPF) Cost, Safety, and Business Interruption Penalty From Failure	1	2	3	4	5	6	7	8	9	10
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

Contaminant Severity Factor (CSF)
Sensitivity of Machine to Contaminant Failure

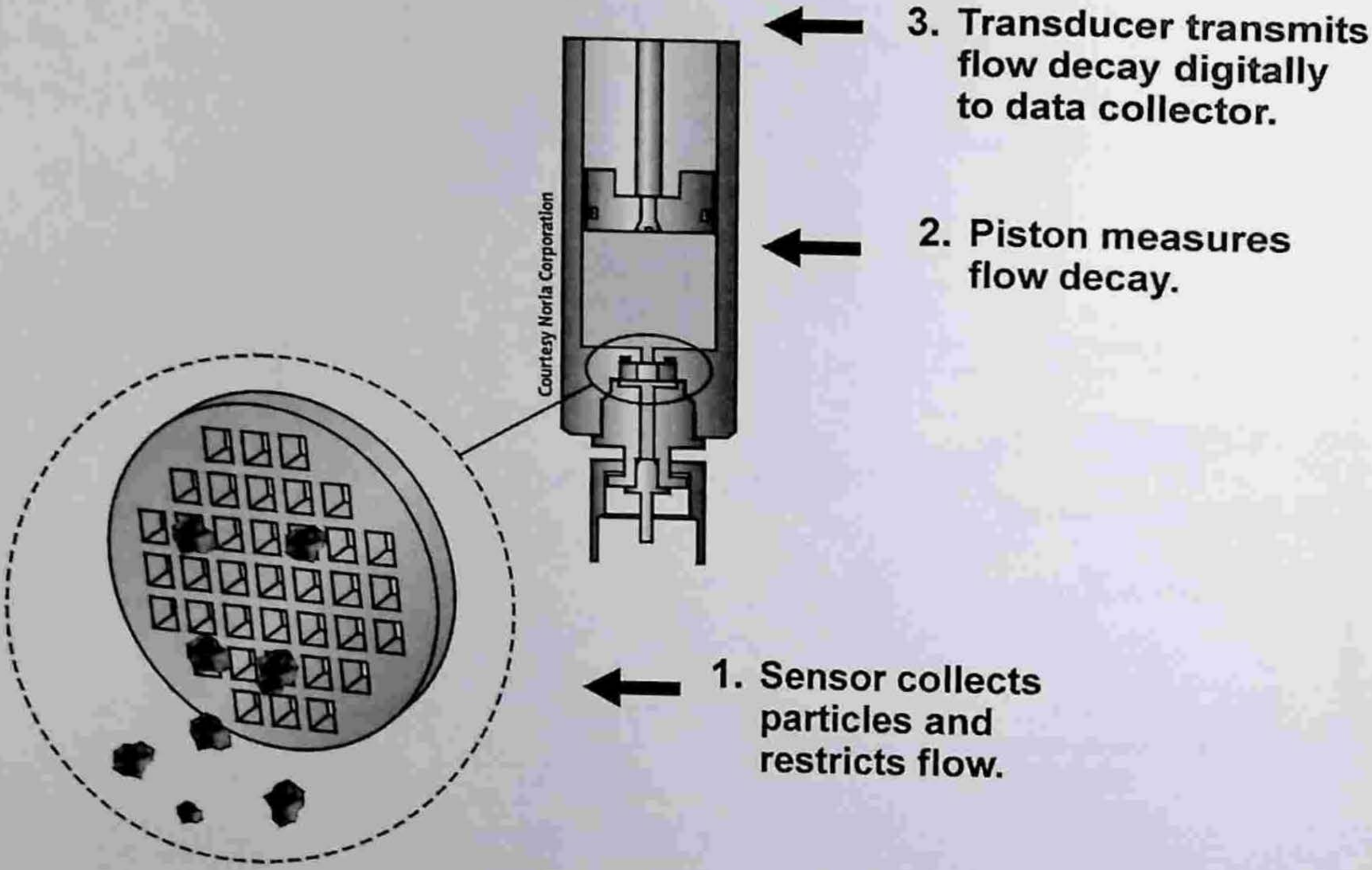
Courtesy Noria Corporation

Figure 11.14



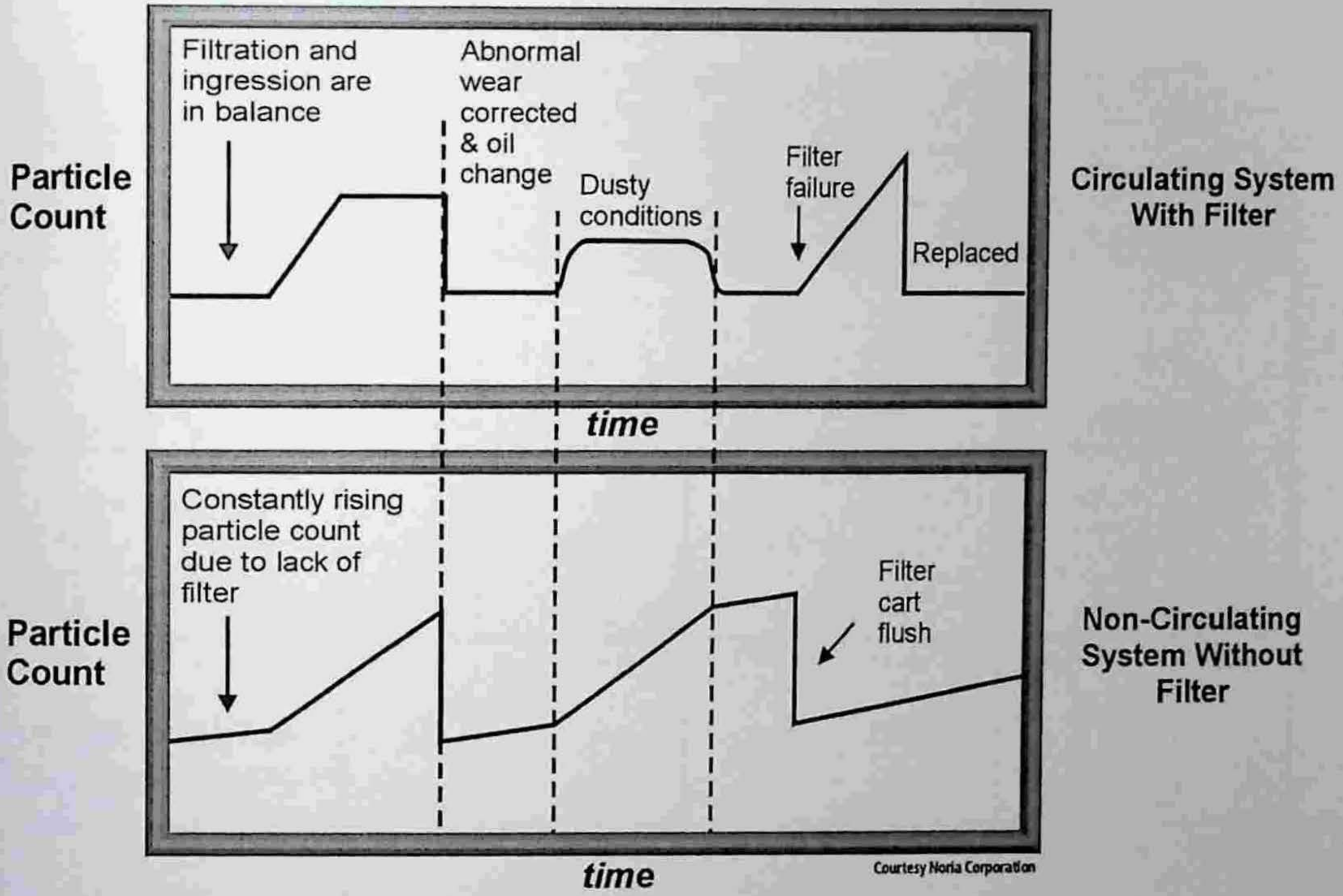
Courtesy Noria Corporation

Figure 11.15



Courtesy Noria Corporation

Figure 11.16



Courtesy Noria Corporation

Figure 11.17

Temperature			Water Concentration					
			100 ppm		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

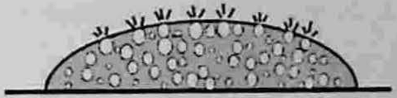
Courtesy Noria Corporation

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

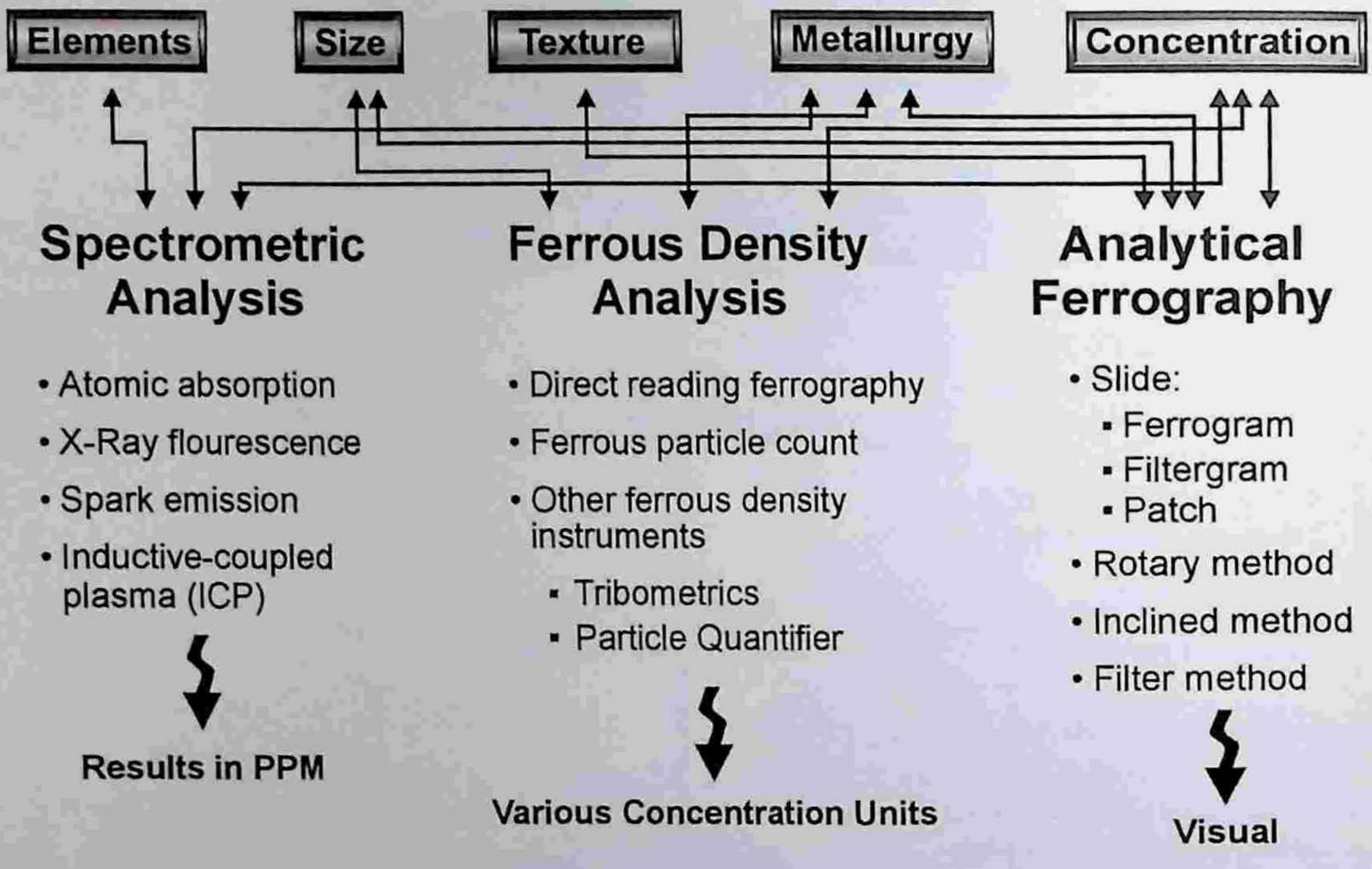
Figure 11.18

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 11.19



Elements **Size** **Texture** **Metallurgy** **Concentration**

Spectrometric Analysis

- Atomic absorption
- X-Ray flourescence
- Spark emission
- Inductive-coupled plasma (ICP)

Results in PPM

Ferrous Density Analysis

- Direct reading ferrography
- Ferrous particle count
- Other ferrous density instruments
  - Tribometrics
  - Particle Quantifier

Various Concentration Units

Analytical Ferrography

- Slide:
  - Ferrogram
  - Filtergram
  - Patch
- Rotary method
- Inclined method
- Filter method

Visual

Courtesy Noria Corporation

Figure 11.20

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

Figure 11.21

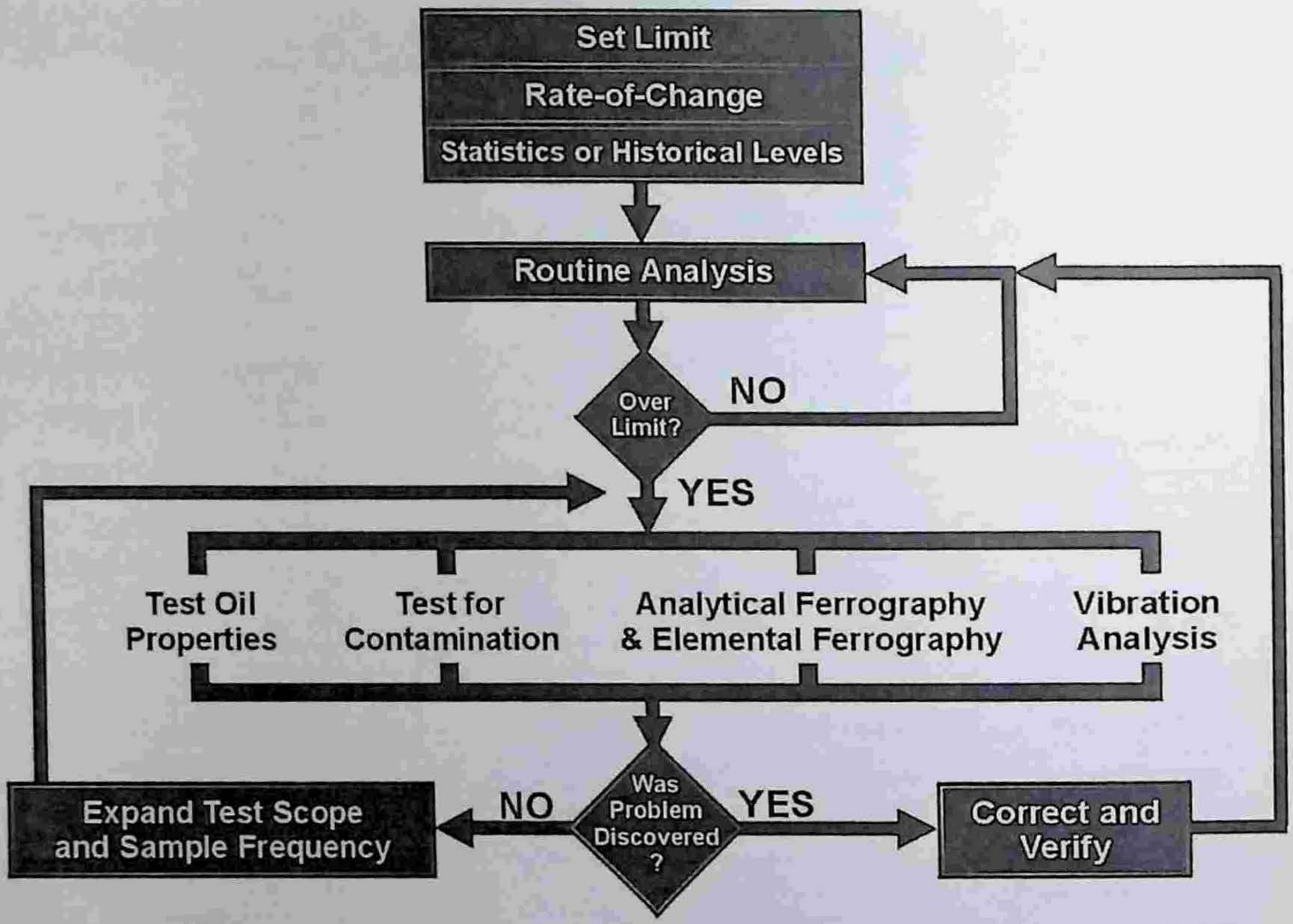

Set Limit
Rate-of-Change
Statistics or Historical Levels
Routine Analysis
Over Limit?
NO
YES
Test Oil Properties
Test for Contamination
Analytical Ferrography & Elemental Ferrography
Vibration Analysis
Was Problem Discovered ?
NO
YES
Expand Test Scope and Sample Frequency
Correct and Verify

Figure 11.22

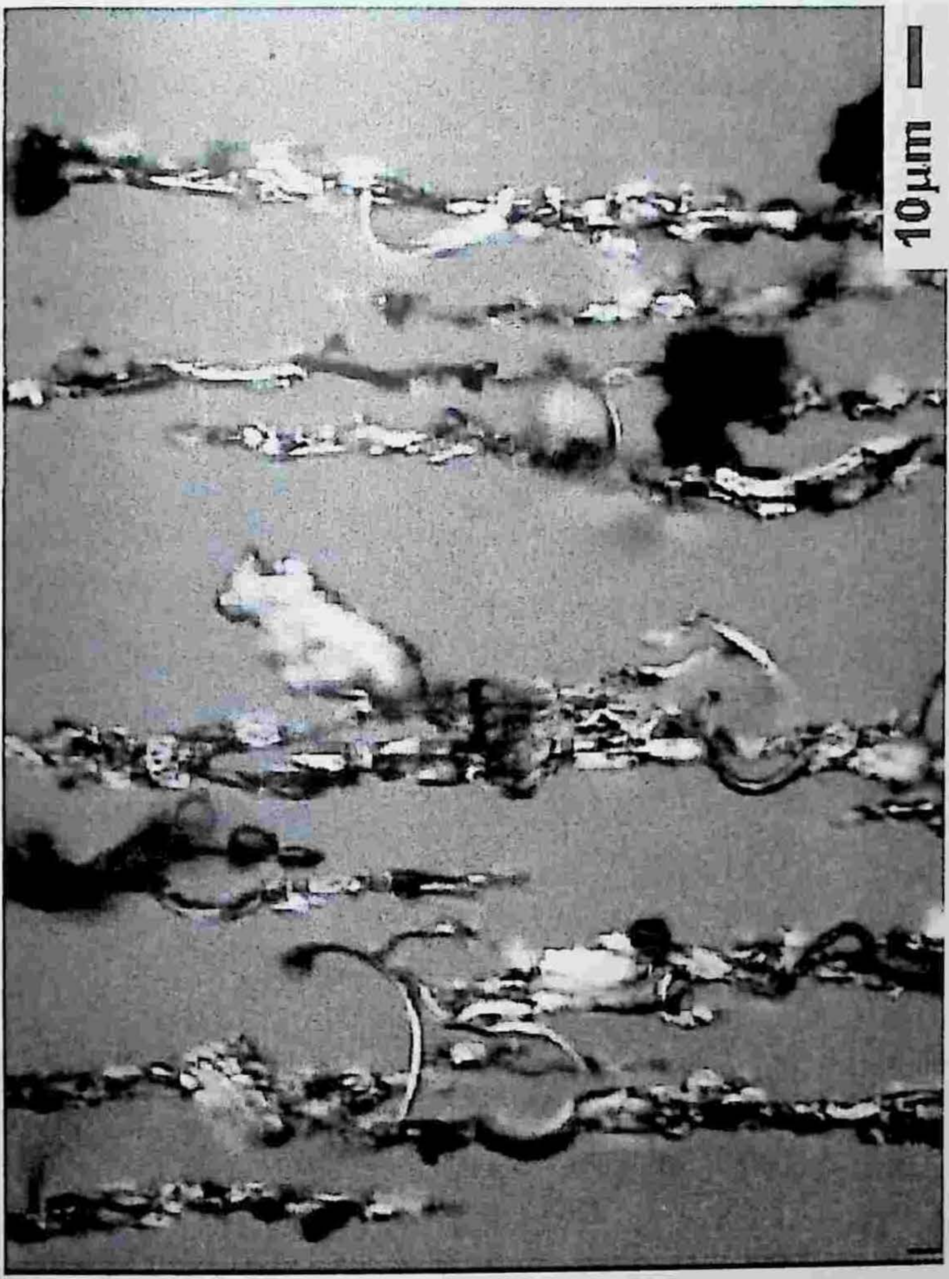


Figure 11.23

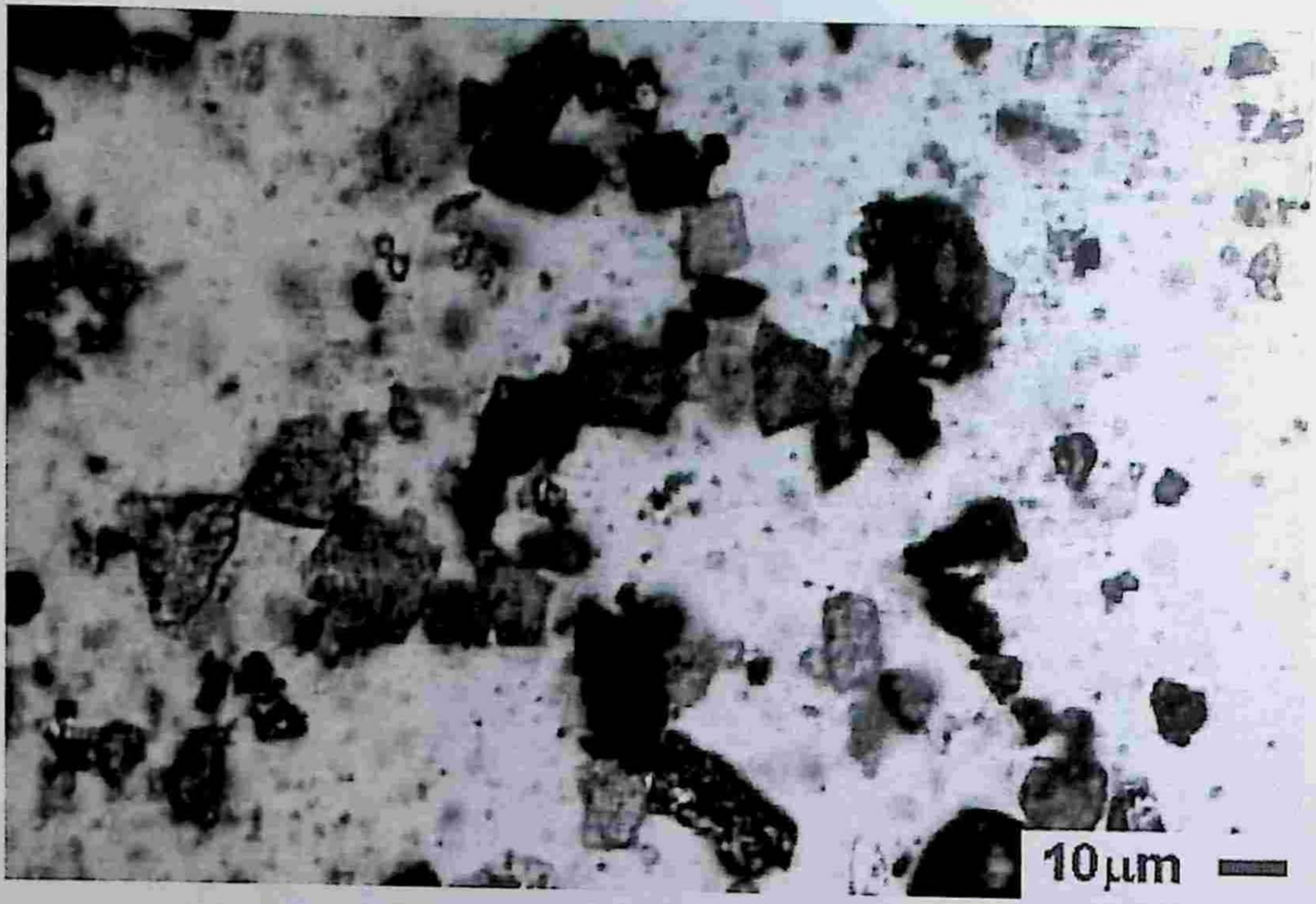


Figure 11.24