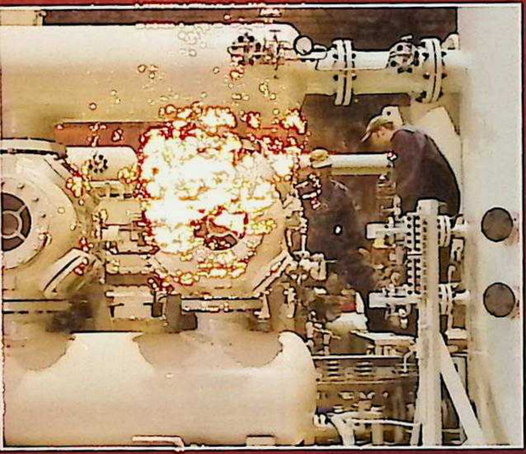
ROTATING MACHINERY FUNDAMENTALS AND ADVANCES

Condition Monitoring, Troubleshooting and Reliability in ROTATING MACHINERY



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Optimizing Lubrication and Lubricant Analysis

By Jim Fitch and Bennett Fitch

Introduction

Lubrication is an unmistakably integral part of machine reliability. Rotating machines are dependent on lubrication decisions made, such as which lubricant to use, how the lubricant needs to be applied to the tribological zones, and what is done during operations to monitor and control the integrity of these frictional zones.

At the same time, lubrication is too often not top of mind when considering the critical aspects of rotating machines, partly because there is a lack of general understanding of the crucial role the lubricant plays in reliability. But even for those who may understand this, it still is not intuitive to manage these factors carefully. Rather, there are incorrect assumptions that lubrication is straight forward; in other words, simply "just having oil or grease in the machine is largely all that is necessary" is a perspective of many. This, coupled with the fact that lubrication is messy and not as exciting as the many other maintenance tasks, often challenge workforce culture.

As a result, the industry suffers from stagnant practices and lethargic attitudes. Although, the dismal state of an old and generally unexciting field is a huge opportunity in disguise. For plant maintenance personnel that see this opportunity, improvements in lubrication not only help avoid unnecessary costs in repairs and downtime, but also have a huge impact in improving the maintenance culture and creating a foundation for sustainable growth. But what should be the focus for improvement and achieving lubrication excellence?

Lubrication Excellence is a term used to describe the holistic achievement of maintaining all lubrication practices from start to finish. One way

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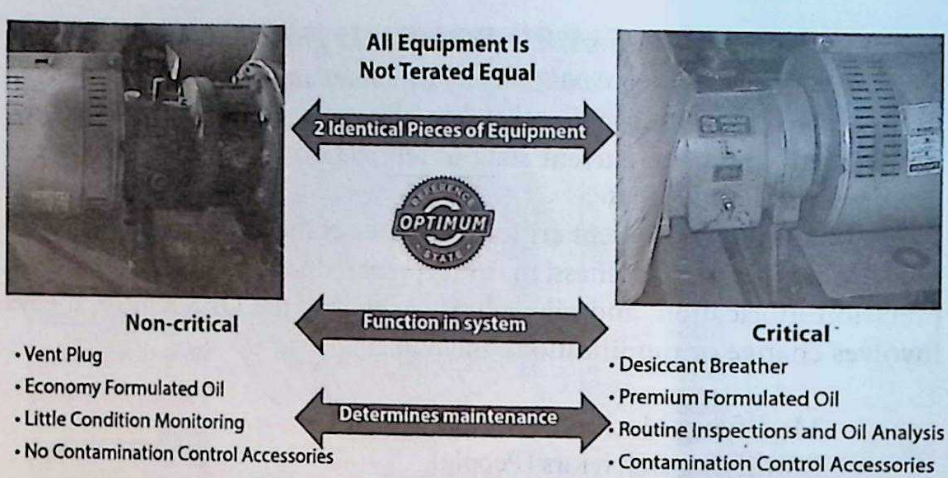


Figure 4.2 Example of optimum reference state on two identical centrifugal pumps.

Table 4.1 The optimum reference state avoids waste and excess.

Sub-optimum	ORS = Precision Lubrication	State of Excess
	Activity	
Price-selected base oils	Machine and application-specific base oil selection	Across-the-board synthetics
Bi-annual sampling	Setting sampling frequency based on criticality and failure probability	Continuous sampling
Factory filters only	Selecting filters based on criticality, machine sensitivity and surge ingression risk	Across-the-board 3-micron filters
Weekly oil-level checks	Engineered daily PM inspection checklists	Sensor-based real-time monitoring
Old-timer apprentice training	Professional skills training using subject-matter specialists and peer-reviewed curriculum	Degreed engineers and chemists only
Economy-based one-size-fits-all test slates	Application-specific oil analysis test slate selection with exception tests	Premium test slates for all machines

When making plant-wide lubrication decisions, such as selecting which machines are appropriate for oil analysis or how to consolidate lubricants to a manageable selection across the plant, the ORS applies here as well. From a macroscopic perspective of decision making, managing risk and costs can override (or complement) the decisions made for each machine. In fact, when the sum of all lubrication ORS attributes in the plant are considered from both micro- and macroscopic perspectives, this creates an engineering specification for Lubrication Excellence.

Fundamentally, there is a need for users to understand how their current lubrication practices may be sharply different than what might be considered the optimized state. This is further underscored by showing the value to the organization and to maintenance workers individually (financially and career development). And ultimately, it needs to be specified, through good engineering practices, in such a way that deployment can be sustainable with manageable risk and cost. The Ascend methodology structures, codifies, and prioritizes this comprehensively based on the ORS in all essential areas of lubrication-enabled reliability.

Lubrication Excellence and the Ascend Chart

The Ascend Methodology deploys six lifecycle stages of a lubricant that follow in chronological order starting at the top going clockwise represented by angular wedges on the Ascend Chart. Each stage plays an important part in lubrication excellence, machine reliability, and asset management.

- Lubricant selection (S)
- Lubricant reception and storage (R)
- Lubricant handling and application (H)
- Contamination control and lubricant reconditioning (C)
- Condition monitoring, lubricant analysis, and troubleshooting (A)
- Energy conservation, health, and the environment (E)

Following the lubricant life cycle allows users to correlate their day-to-day activities at each stage with fundamental business objectives and how each stage functions individually as a part of the whole in executing correct principles of lubrication.

Ascend punctuates the importance of selecting the right lubricant, with performance specific to the requirements of the machine and its operational context. But it doesn't stop there. It also needs to specify the correct condition, storage, and handling practices, application methods, and frequency. Precision lubrication also includes application of the correct amount, with the right tools, by a person with the right knowledge and skills. Lastly, there is a fundamental need for sustainable contamination control of lubricant in storage and use and, through lubricant analysis, a metric on the state of lubrication and overall machine health.

Lubrication activities across the lifecycle of the lubrication process are divided into 40 Factors (see Figure 4.3). Each of these factors is interrelated to one or more of the 12 areas of the lubrication plan as specified in clause 5.0 of the standard ICML 55.1[1] Asset Management Requirements for the Optimized Lubrication of Mechanical Physical Assets.

Figure 4.3 40 Ascend™ factors.

However, it should be noted that these 40 factors do not all share the same weight (priority) or urgency of implementation. Therefore, to emphasize and clarify these differences, the factors are arranged into three levels (see Figure 4.4):

- Platform (P)
- Management and Training (M)
- Performance Indicators (K)

The Ascend™ methodology uses Six Sigma's DMAIC (Define, Measure, Analyze, Improve, and Control) tool to assess the maturity of the lubrication program from an established starting point through the transformation plan. The Optimum Reference State is defined based on the requirements of the ICML 55.1 standard. ORS compliance is assessed through inspections, measurement, verification, and interviews.

Differences between required ORS performance and current performance are analyzed by the Ascend methodology to prioritize the implementation plan based on impact on business objectives and reliability. When an assessment is performed using the Ascend methodology, a maturity of each factor based on the degree of compliance (completeness) is defined along with a list of specific improvements aimed at complying with the ORS in each of the 40 factors of the lubrication process. It identifies the critical actions needed to ensure that the process is sustainably implemented with suitable controls.

Similarly, a maturity score can be identified for each of the six lifecycle stages and the three levels. Finally, a holistic indicator of maturity of the lubrication program, called the Ascend Compliance Level (ACL), is a sophisticated calculation based on a proprietary mathematical algorithm that includes a Balanced Score Card (BSC) of the lubrication process and the maturity of each of the factors. The active ACL value can be displayed in the center of the Ascend Chart and as a guiding key performance indicator for lubrication excellence.

Figure 4.4 Three levels of ascend™.

Bringing Awareness to Lubrication, Contamination, and Oil Analysis

The following sections in this chapter are not intended to be a comprehensive overview in lubrication, contamination, and oil analysis, as this would be too extensive and there many other published references, including ICML 55.1, that very adequately suffice. Rather, what is written here is aimed at uncovering key aspects in lubrication and contamination that are often less understood yet are crucial in establishing foundational knowledge on the impact it has on machine reliability.

Then, oil analysis is brought into focus to carefully identify what is necessary for end-users to get right in order to achieve the expected return on investment. While it has long been a common practice for monitoring the conditions in the lubricant, thus the machine's conditions, there is much that can unknowingly go wrong and jeopardize the integrity of the efforts. Furthermore, it is important to connect this to newer (and often simpler) techniques to monitoring lubricant conditions in improving lubrication and controlling contamination

What You Might Not Know About Lubrication

Machine Surface Interaction

It is crucial to understand how two metal surfaces within a machine interact with each other. Regardless of how smooth a surface may appear, each metal surface has high points, known as surface asperities, and low valleys. When the two surfaces move past each other, the asperities on each surface come into contact (collide), as illustrated in Figure 4.5.

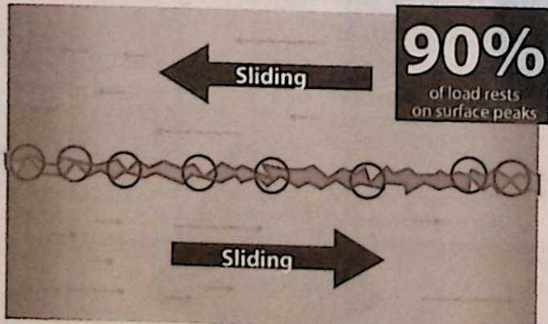


Figure 4.5 Circles represent asperity contact during sliding conditions.

The height and amount of the asperities dramatically affect the friction between the surfaces. It is the lubricant's job to keep asperities apart and prevent or mitigate destructive contact and mechanical friction. Metal-to-metal friction causes two surfaces in relative motion to generate heat, consume energy, and often weld together, causing adhesion (galling) and abrasion (cutting). In severe cases, the metal may completely weld together.

Reducing friction can be accomplished with:

- Proper lubricants and lubrication.
- Replacing sliding friction with rolling friction.
- Improved materials selection and surface finish – softer babbitt materials are often used to reduce friction during start-up and shutdown.

The Lubricant Film

When thinking of lubrication, one should consider how the base oil creates a film to separate metal surfaces to minimize mechanical contact. For the base oil to provide separation, there must be a balance of three contributing factors: relative surface velocity, base oil viscosity, and applied load. These three factors are also influenced by other elements such as temperature, contamination, and surface topography. The film thickness that is achieved is called hydrodynamic lubrication.

In applications involving rolling contact, film thickness can still occur, even with greater localized pressure (unit load). In fact, these pressure points play an important role in achieving the film. The base oil's pressure-viscosity relationship results in the viscosity to increase temporarily and significantly. This is called elastohydrodynamic lubrication. It is best to keep machine surfaces separated and the film thickness provides the best opportunity to reduce friction and wear. But what happens if these film thickness conditions are not met, such as when there is insufficient surface velocity, inadequate viscosity, and/or excessive load?

When the hydrodynamic or elastohydrodynamic lubrication prerequisites are not met, the base oil will require support from boundary contact conditions. This support involves using wear and friction-control additives. The base oil and additives are mixed together to produce a lubricant, either oil or grease. This lubricant is then formulated to mitigate the anticipated boundary conditions. This process ensures the lubricant will have the correct amount of film strength and boundary lubrication properties.

Film Strength

Film strength is the lubricant's ability to lessen the effects of friction and control wear by means other than viscosity-induced film thickness. When the base oil viscosity is insufficient to overcome metal-to-metal surface contact, the base oil and additive chemistry work together to create a surface protection mechanism. Even when loads and temperatures are higher and relative surface velocities are lower, functional film strength can be achieved.

Unlubricated Surface Interactions

When observing frictional surfaces on a microscopic level, they are rough, form a topography of undulating peaks and valleys, even while they may look smooth or even polished to the unaided eye. This is similar to how spherical the Earth looks from space but in fact is brimming with mountains and valleys on the surface. Because the surface has these mountains and valleys, when unlubricated metal surfaces come into contact, the actual contact area is actually less than the apparent (perceived) contact area. The surfaces will only touch (bearing load) where the higher asperities reach the opposing surface. However, these asperities can elastically deform under pressure, making the contact area increase with an increased load.

Friction and Wear Generation

Many consider surface roughness the primary contributing factor of friction. However, when considering that the real contact area may be less than 1 percent of the apparent contact area, the actual roughness becomes much less relevant. The significant process contributing to friction is a result of the adhesive bonds occurring at the atomic level of asperity contact.

In conditions where there is inadequate lubricant film thickness, the asperity contact points can lead to cold welding, which leads to adhesive wear. The adhesion undergoes a work-hardening process, which strengthens it. Thus, the shear point happens layers below the asperity contact point where the metal has not been strengthened. As the metal shears, the asperity tip is either transferred to the other surface or broken off, becoming an abrasive particle.

Mitigating Surface Interactions

Friction and wear-control additives are formulated in small quantities within the base oil and have polar properties that foster metal surface attraction. These attractions are encouraged to chemically react with the surface. When machine surfaces interact with higher pressures and temperatures, the additives mitigate the typical effects of wear by creating initial flexible molecular layers on the machine surface. These friction-control layers become sacrificial and directly reduce shear strength during contact, as illustrated in Figure 4.6.

The initial layers can mitigate friction by allowing the lubricant's weaker molecular bonds to release with less force compared to that of the strong bonds that result from the metal-to-metal asperity boundary conditions. The formation of low-shear-strength films is also influenced by the base stock type and the metallurgy of the mechanical surfaces.

There are three types of lubricant additives that help reduce this friction and control wear formation:

- Friction modifiers
- Anti-wear additives
- Extreme-pressure additives

Physics and Chemistry

The interactions of asperities at the actual contact pressure points are the main concern when poorly lubricated machine surfaces come into sliding

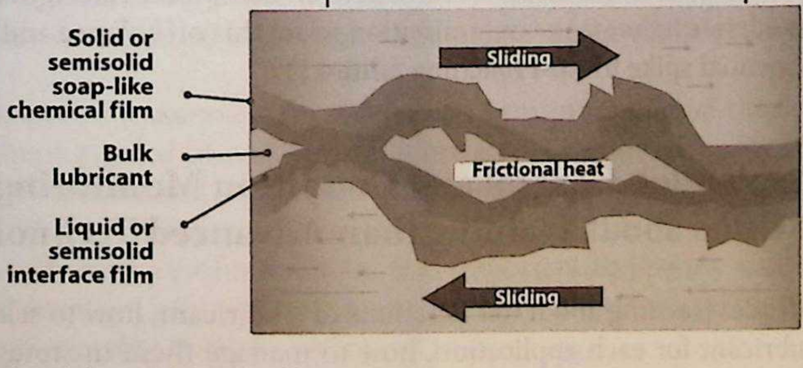


Figure 4.6 Sliding and frictional heat.

contact. At this molecular scale of the machine surfaces, boundary conditions are subject to numerous principles of physics and chemistry.

The role of oxidation, corrosion, chemisorption, and other chemical reactions on the machine surfaces must be carefully balanced when additive compounds are selected for film strength protection [7]. These friction and wear-control additive films reduce the shear strength at the contact points. The low-shear-strength films are sacrificial during physical interactions and protect the surface from the effects of adhesive, abrasive, and fatigue wear.

While the base oil's viscosity is always preferred to protect the machine surfaces with hydrodynamic and elastohydrodynamic lubrication, boundary conditions will still exist. Therefore, to protect against boundary conditions, a properly formulated lubricant with friction and wear-control additives should be used to provide a film strength that is proportional to the exhibiting mechanical interactions.

Contamination: The Antagonist to Lubrication

Contamination is often a silent lurking danger and can alter or destroy critical mechanical zones of your machinery. All lubricants have some level of solid contamination. Even with new lubricants, complete cleanliness is unattainable. The key is to ensure that there are more contaminants being filtered out than contaminants being ingested or generated within. Problems arise when too many contaminants are allowed to exist in the workings of a machine.

Since contaminants can silently accumulate and generate within machines, this cyclical act proliferates to a point where the filter cannot maintain a healthy balance in contamination levels. So, while oil analysis may show that contaminant levels remain at an acceptable rate, it may only take a moderate increase in contamination to set this off balance and create an exponential spike toward machine failure [1].

Contamination Control and Condition Monitoring is More Often about Training than Advanced Technology

This includes learning about the functions of a lubricant, how to select the right lubricant for each application, how to manage them in storage and properly apply them to machines, and of course, it is all about monitoring lubricant and machine conditions through inspections and oil analysis. There are two specific areas of lubrication that must be communicated by bringing awareness to those who work with and around plant equipment. The first one is the importance of contamination control, which is discussed here. The second is inspections, which will be discussed later in this chapter.

Contamination Control

Contamination is defined as "any foreign or unwanted substance that can have a negative effect on system operation, life or reliability." This is more than just solid particulates from the environment, it includes other factors such as water, air, glycol, soot, and fuel. Even the wrong lubricant being mixed into the current lubricant is considered a form of contamination referred to as cross-contamination.

Contamination control for lubrication includes the "planning, organizing, managing, and implementing all activities required to determine, achieve and maintain a specified contamination level." Notice that neither the word "eliminate" nor "remove" is used in this definition.

Don't Leave It to Instinct

A lot of what is important with contamination control is not intuitive. For example, take the physical size of solid contaminants that could damage a rolling or sliding contacting component. Oil films are usually 5-20 microns for sliding contact (turbine bearings, gears, pistons), all the way down to less than one micron for rolling contact (rolling element bearing, gears, cams). Typical airborne particulates that ingress into machines are usually much smaller than 40 microns, which is the visibility limit of the unaided eye.

This makes it common for there to be a misperception of the degree of cleanliness needed in and around lubricated machines. It is not intuitive for us to understand the importance of these virtually invisible contaminants with everyday practices. This is just one example of what must be learned through careful training. It is important to provide a discussion and explanation why contamination control is important, rather than just telling them what to do and what not to do.

Creating a Balance Between Exclusion and Removal

It is often incorrectly assumed that contamination control is just about filtration. While it is a big part of contamination control, filtration is only necessary because contamination is first allowed to get into the oil and the machine. The actions that must be taken to control contamination include both exclusion (seals, breathers, clean new oil, etc.) and removal (filtration). In fact, it will always be much cheaper (at least one-tenth the cost) to exclude a gram of dirt from getting into a machine than it is to remove it through filtration.

Nevertheless, neither exclusion nor removal is perfect; they must be considered together as a contamination control solution and where appropriate based on the Optimum Reference State. Contamination control requires a balance of a two-part approach, just like our bodily caloric control, where we strive to burn more calories than we consume. For machines, we can monitor contamination levels, such as with oil analysis, to verify that this is staying in balance. If more contaminants are accumulating in the oil than are being removed, it is only a matter of time that the contamination will induce a failure. Component contaminant sensitivity, contamination likelihood, criticality, safety risks, and downtime are examples of variables that go into justifying the ORS contamination control requirements. It is important that those who make decisions about breathers, seals, filtration, and other everyday oil sump management have learned about contamination control and optimizing these decision variables to ensure enough is being done to keep this in balance.

Scenario Analysis: Many maintenance teams don't realize the benefits of contamination control. For decades, countless industry studies by OEMs and end-user groups have identified that contamination is the number one cause of wear on rolling element bearings, gears, and the majority of lubricated components. Additionally, it is well established that the cost of controlling contamination through optimized best practices will be considerably less than the cost savings from mechanical wear-related failures decreasing over that period.

Then why is this not often realized? This is where bringing awareness is necessary and must influence the maintenance culture. As mechanical wear occurs from moderate levels of contamination, it propagates a gradual Failure Development Period (FDP) that appears largely uneventful to the untrained person. As the wear gets worse, eventually predictive maintenance (PdM) may trigger a corrective action through vibration analysis, inspections, or other means. If this becomes a common occurrence, then a preventative maintenance (PM) task may get scheduled to replace these components on a fixed interval that is significantly less than the intended design life and unfortunately, this is very common.

These PdM catches and scheduled PMs are rewarded, but these habits form an unhealthy maintenance culture focused on reacting to failure rather than establishing proactive measures to recognize the root cause (contamination) and improve proactive maintenance (via contamination control).

When a root cause failure analysis is performed, it is usually difficult to pinpoint one single cause. Rather, the root cause is viewed as a collection of decisions and practices that impact contamination. Good practices include everyday activities or decisions such as:

- Managing new oils and keeping them clean and dry before use
- Transferring new oils in clean, sealable-and-refillable containers or filter carts
- Managing machines' headspaces by using quality desiccant breathers
- Monitoring contamination levels with particle counting on critical machines
- Establishing filtration needs effectively, either through continuous stationary filtration or through periodic filtration with a filter cart
- And many more daily activities like careful machine washdowns, keeping machine areas tidy and clean, walk-by inspections, etc.

The actions and decisions that influence contamination control are part of a collective effort involving nearly everyone working around the machines including maintenance, operators, lube techs, reliability engineers, supervisors, etc. Similarly, when these teams go through contamination control trainings as a team, everyone builds a collective awareness and a better understanding of what each of their roles entail. The benefit of contamination control training multiplies as the importance is bought-in together, especially when the training takes place in person as one group.

Ultimately, contamination control is everyone's responsibility. When contamination control is analyzed as part of the overall lifecycle of a lubricant in the Ascend Methodology, it tends to dominate the next step requirements that follow. This is especially true through metrics that identify the impact of contamination on lubrication. It becomes comparatively important to selecting the right lubricant or monitoring the conditions, such as through oil analysis. Lubrication awareness training sets the tone from the top down that lubrication is not a trivial part of maintenance but instead requires carefully made decisions, quality daily actions, and, most importantly, it impacts the bottom line.

Why Perform Oil Analysis [3]

Oil analysis is performed to understand the condition of the oil in an effort to bring awareness to the condition of the machine from which the oil sample was taken. It is a practice that has been around for a long time, yet it is a challenge to get right for many and its viability is too often disregarded. Why? Laboratory-based oil analysis is often monitoring data that can be difficult to comprehend because it is not as straight forward as many other condition monitoring technologies such as vibration, thermography, or even the more recent addition of motion amplification. All of these technologies are viable and can provide value when performed correctly.

However, oil analysis finds itself in a category that arguably provides the most value as a condition monitoring strategy when performed correctly. This is because it can do an excellent job of detecting problems ahead of machine failure by looking for changes in fluid properties or contamination levels in addition to machine faults in the form of wear debris. It targets issues largely in the proactive maintenance domain and closer to the root cause. This is why it is so important to figure out. These three aspects of oil analysis are often clearly defined as categories of oil analysis.

Fluid Properties Analysis

This type of oil analysis focuses on identifying the oil's current physical and chemical state as well as on defining its remaining useful life (RUL). It answers questions such as:

- Does the sample match the specified oil identification?
- Is it the correct oil to use?
- Are the right additives active?
- Have additives depleted?
- Has the viscosity shifted from the expected viscosity? If so, why?
- What is the oil's RUL?

Contamination Analysis

By detecting the presence of destructive contaminants and narrowing down their probable sources (internal or external), oil analysis can help answer questions such as:

- Is the oil clean?
- What types of contaminants are in the oil?
- Where are contaminants originating?
- Are there signs of other types of lubricants?
- Is there any sign of internal leakage?

Wear Debris Analysis

This form of oil analysis is about determining the presence and identification of particles produced as a result of mechanical wear, corrosion, or other machine surface degradation. It answers questions relating to wear including:

- Is the machine degrading abnormally?
- Is wear debris produced?
- From which internal component is the wear likely originating?
- What is the wear mode and cause?
- How severe or threatening is the wear condition?

Achieving Oil Analysis Success by Looking Holistically [5]

To get the answers to the questions mentioned above, a number of practices must be well established in the oil analysis program (see Figure 4.7), such as: How often should oil samples be taken? Which machines should be sampled? What test should be performed? In fact, there are several crucial factors that must be carefully considered when building out an oil analysis program. If one of these factors are overlooked, then the entire oil analysis program may not live up to its return on investment. The next few sections review some of these crucial factors, grouped into three categories:

- Obtaining a Representative Oil Sample
- Ensuring Reliable Testing
- Determining the Optimum Course of Action

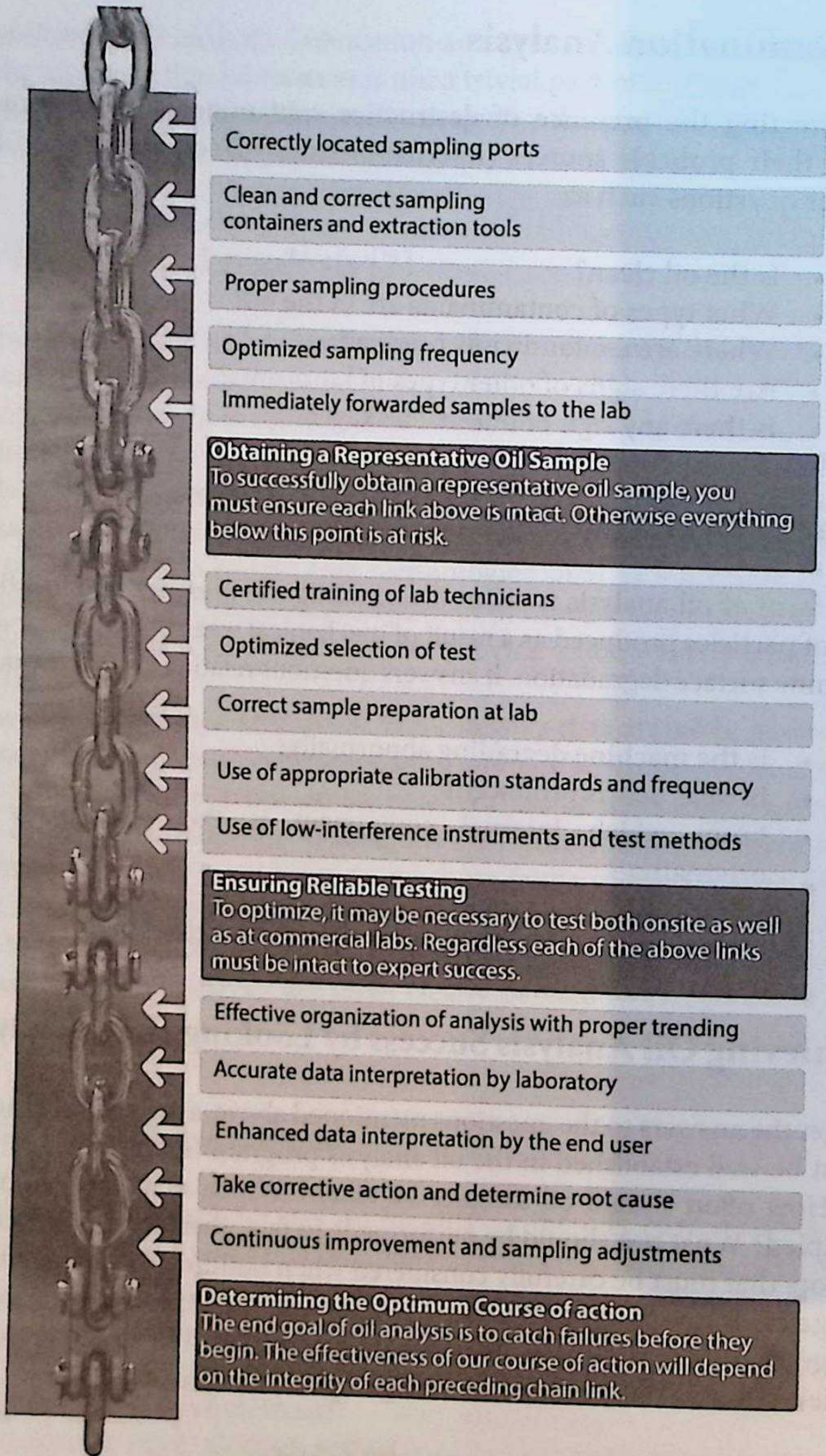


Figure 4.7 Holistic approach steps.

The first and third category are weighed greatly on the end-user to get right. Therefore, these will be focused on more below. Following this, we will discuss how oil analysis should be considered beyond just what is laboratory-based. After all, any time an analysis of the oil is performed this is considered oil analysis and often times, what is perceived as more basic and unsophisticated, such as a visual inspection, is exactly the opposite. These visual inspections should occur even while taking a sample. Although, let's start with what it takes to obtain a representative oil sample and why that is important.

Obtaining a Representative Oil Sample

Select the Right Machines for Oil Analysis

Each sample obtained for oil analysis can be costly, so sampling every machine in a facility is not feasible. The best method is to determine the Overall Machine Criticality (OMC). The Overall Machine Criticality is a risk-profile assessment that can be calculated to a single numerical value. The lower the OMC, the lower the risk. The OMC is the multiplied product of two factors: the Machine Criticality Factor (MCF) and the Failure Occurrence Factor (FOF).

A risk-profile assessment directly justifies which machines need oil analysis (or other condition monitoring techniques) in order to help lower the risk. For example, let's consider a machine with an MCF of 5 which may be associated with high repair costs if a failure were to occur and has moderately highly impact on production. With the implementation of better oil analysis practices (aided by carefully collected representative oil samples), this can effectively reduce the machine criticality factor to a 2.5 with early detection achieved through oil analysis. (See Figure 4.8 below.)

Machines across a facility should be viewed in a similar manner to choose which machines would benefit from early detection. Other factors, such as accessibility or a similar risk-profile assessment on the lubricant to calculate the Overall Lubricant Criticality (OLC) should be considered.

Clean and Correct Sampling Containers and Extraction Tools [2]

One of the main objectives of oil sampling is minimizing data disturbance. Using the right sampling tools and ensuring their cleanliness will be vital.

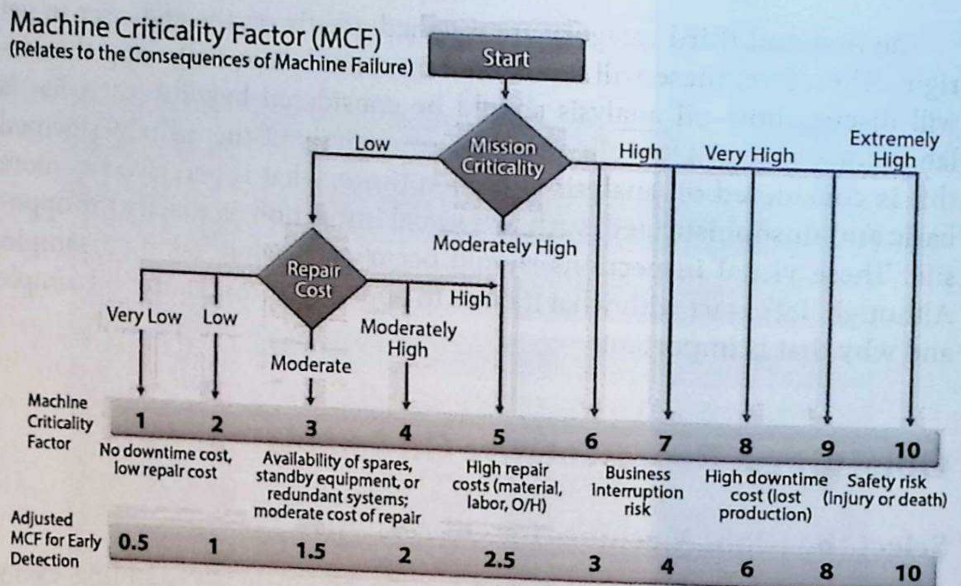


Figure 4.8 Machine Criticality Factor (MCF) (Relates to the consequences of machine failure).

Oil sampling bottles should be certified as one of the three cleanliness levels: clean, super clean, or ultraclean (per ISO 3722[1]).

For extraction tools, nothing in the fluid's pathway from the machine to the bottle should further contaminate the sample and disturb the data. In addition to the bottle, this takes into consideration the sample valve, the sample tube, and vacuum devices. It only takes a small amount of contamination to trigger premature cautionary or critical alarms (false positives).

Correctly Located Sampling Ports

Along with using the right sample valves, the precise location where an oil sample is extracted must be carefully chosen so the analysis results will be representative of the oil in the machine's wear protection zones. Two samples taken from the same machine but in different locations will likely have different results for tests such as particle counts, elemental analysis, and Fourier transform infrared (FTIR) spectroscopy.

Therefore, it is best to take a sample in a live (active) zone of the machine, which typically requires a sample valve with a pilot tube for splash/bath lubricated machines, as seen in the Figure 4.9 below. In a wet sump circulating system, the best location is usually after the pump and before the filter and for dry sump circulating systems, this would be on the return line

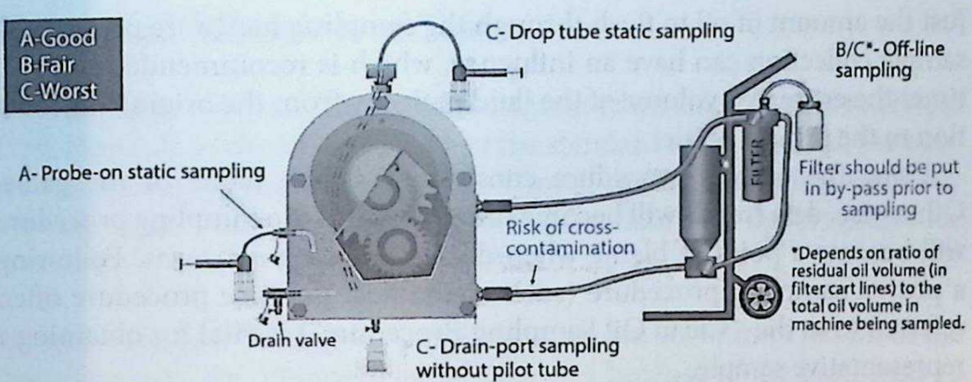


Figure 4.9 Sample locations for splash/bath lubricated machines.

before a filter and before the oil returns to the reservoir. Once chosen, the sample location should remain consistent to ensure the trends of data can be reliable.

Proper Sampling Frequency

The sampling frequency should be frequent enough to detect dangerous spikes in unfavorable results but not so often that time and money are wasted. Typically, this may range anywhere from two weeks to three months for routine oil sampling in the context of the Optimum Reference State for each machine and plant-wide reliability objectives. Periodic adjustments to these frequencies should be addressed based on the trends of the data and known maintenance practices, such as sampling more frequently in the early stages after installation or as machines are actively experiencing possible failure modes.

Proper and Consistent Sampling Procedures

During the sampling process, an oil sample can be altered in a variety of manners, many of which are not apparent. As discussed with sampling hardware cleanliness being imperative to avoid false positive, the procedure to take the sample can have significant influence.

Scenario Analysis: Imagine two lube techs independently take a sample from the same machine on the same day using the same type of tools and same location. It may surprise you the difference in data that may result.

Just the amount of oil to flush through the sampling hardware prior to the sample collection can have an influence, which is recommended to be 10 times the estimated volume of the fluid pathway from the originating location to the sample bottle.

Using the correct procedure consistency is the name of the game. Otherwise, data trends will become unreliable and the sampling procedure will become a point of blame when data is showing concerns. Following a proven sampling procedure (such as the best practice procedure often referred to as the "Clean Oil Sampling Procedure") is vital for obtaining a representative sample.

Forward Samples Immediately to the Laboratory

This one is simple but often overlooked: Do not wait any longer than necessary to send your samples off to the laboratory after collection and assess the state of your machines.

Scenario Analysis: This is from a real example where a crusher gearbox at a copper mine failed, losing ~$10,000 every hour that the machine was down. Oil samples were taken days before the failure but left on a desk to finish collecting samples from other machines before shipping off. The sample was eventually tested and sure enough the indications of a concern were clearly seen in the changes in fluid properties and rise in wear debris data. The mine learned the hard way how important it is to get quick results.

Ensuring Reliable Testing

Certified Training of Laboratory Technicians

Many people assume that their laboratory will have a staff of properly trained and certified technicians who know how to operate all the lab's instruments, but this may not always be true. A quality-control program should be in place with written procedures for consistently providing the best instruments for your oil analysis. The tests performed on your oil samples deserve uniformity. Without it, accurately comparing one sample result to another will be impossible.

Optimized Selection of Tests

A typical laboratory will have an assortment of oil analysis tests to choose from. Don't allow the lab to select just the standard test slate for all the samples. Unless the appropriate tests are chosen for each sample point, early warning signals may be missed. More often than not, opportunities for maintenance cost savings are overlooked.

Scenario Analysis: Testing for particle counts are sometimes left off of the "basic package" by commercial laboratories because of the hard costs to the lab associated to this, although this is one of the most important tests. The vigilant practice of monitoring particles in oil effectively tracks the number one cause of wear (particles) and effect of wear (wear particles) using a single technology.

Test slate optimization requires a selection of cost-effective tests for routine analysis and exception tests that are triggered based on the results of the routine tests. For example, analytical ferrography is a more expensive test but is critically important to have triggered anytime particle counts and ferrous density reach critical alarms. This methodology should be used with all test packages for each machine type and criticality [13]. For more information on the most common oil analysis tests, review the section on this topic.

Onsite Oil Analysis

An excellent way to enhance any oil analysis program, regardless of whether a commercial (offsite) laboratory has been selected, is to incorporate onsite oil analysis. Certain types of tests are standard and should be conducted on every sample, such as particle counts and moisture content. But, there is often a need to get same-day data. If this is the case, consider investing in onsite lab equipment to handle some of the oil analysis needs or at least some "field tests" that can provide a cost effective and time sensitive validation of data. This may include viscosity comparators, blotter spot tests (for analyzing insolubles and other contaminants), or the crackle test (a pass/fail test for water). Visual inspections as an important part of oil analysis will be discussed later [4].

Determining the Optimum Course of Action

Effective Organization of Analysis with Proper Trending

Although laboratories generally attempt to display oil analysis results in a user-friendly manner, they usually are not straightforward. Comprehending how results are organized will be necessary for proper interpretation. The organization of oil analysis results is initially the laboratory's responsibility, although the data can be transferred into other software to allow for more user preferences. The more effective the organization is for interpretation, the less likely a preventable machine failure will be missed. This is elaborated further in the following sections on Interpreting an Oil Analysis Report and Following the Trends.

Accurate Data Interpretation by the Laboratory

End-users often do not have enough time to interpret oil analysis results and must rely on the laboratory for interpretation. Oil analysis results typically come with a summary paragraph that suggests actions the end-user should take. Laboratory personnel interprets the data to the best of their ability, but without a representative sample taken and crucial details about the machine provided, a diagnosis or prognosis can be inaccurate. Some of these important details include:

- The machine's environmental conditions (extreme temperatures, high humidity, high vibration, etc.)
- The originating component (steam turbine, pump, etc.), make, model, and oil type currently in use
- The permanent component ID and exact sample port location
- Proper sampling procedures to confirm a consistently representative sample
- Occurrences of oil changes or makeup oil added, as well as the quantity of makeup oil since the last oil change
- Whether filter carts have been in use between oil samples
- Total operating time on the sampled component since it was purchased or overhauled
- Total runtime on the oil since the last change
- Any other unusual or noteworthy activity involving the machine that could influence changes to the lubricant

Enhanced Data Interpretation by the End-User

Following the laboratory's interpretation, the end-user must make the final decision. No one knows the machine's history and application better than those who see the machine daily. The oil analysis program can greatly benefit from the involvement of these personnel if they are also trained to interpret an oil analysis report. For those individuals, here are a few things to look for when reviewing an oil analysis report

1. Read and check the data on the oil type and machine type for accuracy.
2. Verify that reference data is shown for new oil conditions and that trend data is at an understood frequency (preferably consistent).
3. Check the measured viscosity.
4. Verify elemental wear data and compare to reference and trended data. Use a wear debris atlas to match elements to their possible source.
5. Check the elemental additive data and compare to reference and trended data. Use a wear debris atlas to match elements to their possible source.
6. Verify elemental contamination data along with particle counts and compare with reference and trended data. Use a wear debris atlas to match elements to their possible source.
7. Check moisture/water levels and compare to reference and trended data.
8. Verify the acid number and base number and compare to reference and trended data.
9. Check other analyzed data such as FTIR oxidation levels, flash point, demulsibility, analytical ferrography, etc.
10. Compare any groups of data that are trending toward unacceptable levels and make justifications based on these trends.
11. Compare written results and recommendations with known information on the oil and machine, such as recent changes in environmental or operational conditions or recent oil changes/filtration.
12. Review alarm limits and make adjustments based on the new information.

Take Corrective Action and Determine the Root Cause

Every crucial factor mentioned that goes into building a successful oil analysis program is all providing the confidence to the end user of what step to take next. This confidence must be achieved, otherwise all the efforts to obtain a representative oil sample and use a capable laboratory are pointless. You should not expect a return on the time and money spent unless action is taken as a result of the oil analysis. Be sure to always follow up on the results and be intentional with a conclusion on what the corrective action should be, if any. Remember, it takes just one catch, such as the discovery of elevated wear debris levels on a critical machine to justify the cost of the oil analysis program. Always focus on eliminating the root cause with a proactive maintenance strategy.

Continuous Improvement and Key Performance Indicator (KPI)

Whenever oil analysis is effective in providing proactive maintenance, machine failures are significantly reduced. As time passes, it may eventually be forgotten that the oil analysis is the reason for failures, especially for new personnel. Maintaining this awareness through proper training and key performance indicators (KPIs) will be the key to the sustainability of successful oil analysis.

Oil analysis performance indicators are essential for realizing the overall health of a plant over time. While oil analysis KPIs may be beneficial for your machines, they can also prove to be valuable indicators of the progress made in improving your plant's overall health as well as establishing the viability of oil analysis.

Oil Analysis Tests [8]

For a standard piece of equipment undergoing a recommended oil analysis, the test slate would consist of "routine" tests. If more testing is needed to answer advanced questions, these would be considered "exception" tests.

Routine tests vary based on the originating component and environmental conditions but should almost always include tests for viscosity, elemental (spectrometric) analysis, moisture levels, particle counts, Fourier transform infrared (FTIR) spectroscopy, and acid number. Other tests that are based on the originating equipment include analytical ferrography, ferrous density, demulsibility, and base number testing.

Viscosity [14]

Viscosity is a lubricant's most important characteristic. Monitoring the oil's viscosity is critical because any changes can lead to a host of other problems such as oxidation, glycol ingression, or thermal stressors. Several methods are used to measure viscosity, which is reported in terms of kinematic or absolute viscosity.

Too high or too low viscosity readings may be due to the presence of an incorrect lubricant, mechanical shearing of the oil, and/or the viscosity index improver, oil oxidation, antifreeze contamination, or an influence from fuel, refrigerant, or solvent contamination.

Limits for changes in the viscosity depend on the type of lubricant being analyzed but most often have a marginal limit of approximately 10 percent and a critical limit of approximately 20 percent higher or lower than the intended viscosity.

Acid Number and Base Number

Acid number and base number tests are similar but are used to interpret different lubricant and contaminant-related questions. In an oil analysis test, the acid number is the concentration of acid in the oil, while the base number is the reserve of alkalinity in the oil. Results are expressed in terms of the volume of potassium hydroxide in milligrams required to neutralize the acids in one gram of oil. Acid number testing is performed on non-crankcase oils, while base number testing is for over-based crankcase oils.

An acid number that is too high or too low may be the result of oil oxidation, the presence of an incorrect lubricant, or additive depletion. A base number that is too low can indicate high engine blow-by conditions such as soot, the presence of an incorrect lubricant, internal leakage contamination (glycol), or oil oxidation from extended oil drain intervals and/or extreme heat.

FTIR

FTIR is a quick and sophisticated method for determining several oil parameters including contamination, oil degradation products like oxides, nitrates, and sulfates, as well as the presence of additives such as zinc dialkyldithiophosphate (ZDDP) and phenols.

The FTIR instrument recognizes each of these characteristics by monitoring the shift in infrared absorbance at either a specific or a range of wavenumbers. Many of the observed parameters may not be conclusive, so these results are often coupled with other tests and used as supporting evidence.

Elemental Analysis

Elemental analysis works on the principles of atomic emission spectroscopy (AES), also called wear metal analysis. This technology detects the concentration of wear metals, contaminants, and additive elements within the oil. The two most common types of atomic emission spectroscopy are rotating disc electrodes (RDE) and inductively coupled plasma (ICP).

Both methods have limitations in analyzing particle sizes, with RDE limited to particles less than 8 to 10 microns and ICP limited to particles less than 3 micron, but they are still useful for providing trend data [6]. Table 4.2 shows possible sources for common elements.

The best way to monitor this type of data is to first determine what is expected to be in the oil. An effective oil analysis report will provide reference data for the new oil so any amounts of additive elements can be easily distinguished from those of contaminants. Because many types of elements should be expected at some level, it is better to analyze trends rather than focus on any specific measurement of elemental analysis data.

Particle Counting

Particle counting measures the size and quantity of particles in the oil. Many techniques can be used to assess this data, which is reported based on ISO 4406:21. This standard designates a range number that correlates to the particle counts of particles greater than 4, 6, and 14 microns. Table 4.3 provides an illustration of how different particle counts are assigned specific ISO codes.

Table 4.2 Possible sources for common elements.

ELEMENT	POSSIBLE SOURCES
Aluminum	Pistons, bearings, pumps, thrust washers
Antimony	Bearings, grease
Barium	Rust and oxidation inhibitor additives, grease
Boron	Anti-corrosion additives in coolant, dust, water
Calcium	Detergent/dispersant additives
Chromium	Piston rings in internal combustion engines
Copper	Bearings, brass/bronze alloys, bushings, thrust washers
Iron	Shafts, rolling-element bearings, cylinders, gears, piston rings
Lead	Bearings, fuel additives, anti-wear additives
Lithium	Grease, additives
Magnesium	Transmissions, detergent additives
Molybdenum	Piston rings, electric motors, extreme-pressure additives
Nickel	Bearings, valve train, turbine blades
Phosphorus	Anti-wear additives, extreme-pressure gear additives
Potassium	Coolant additives
Silver	Bearing cages (plating), gear teeth, shafts
Silicon	Dust/dirt, defoamant additives
Sodium	Detergent or coolant additives
Tin	Journal bearings, bearing cages, solder
Titanium	Bearing hub, compressor blades
Zinc	Neoprene seals, grease, anti-wear additives

Moisture Analysis

Moisture content within an oil sample is often measured with the Karl Fischer titration test. This test reports results in parts per million (ppm), although data is often shown in percentages. It can find water in all three forms – dissolved, emulsified, and free. The crackle test and hot-plate test are non-instrument moisture tests for screening before the Karl Fischer method is used. Possible reasons for a moisture reading being too high or too low would include water ingression from open hatches or breathers, internal condensation during temperature swings, or seal leaks.

Table 4.3 Assigning particles ISO codes.

EXAMPLE PARTICLE COUNT	
SIZE IN MICRONS (C)	COUNT LARGER THAN SIZE PER ML
4	1,752
6	517
10	144
14	55
20	25
50	1.3
75	0.27
100	0.08

Renard Series Table

$R_4/R_6/R_{14}$
ISO 18/16/13

1,752 particles > 4 μm/ml

517 particles > 6 μm/ml

55 particles > 14 μm/ml

NUMBER OF PARTICLES PER ML		
MORE THAN	UP TO AND INCLUDING	RANGE NUMBER (R)
5,000,000	10,000,000	30
2,500,000	5,000,000	29
1,300,000	2,500,000	28
640,000	1,300,000	27
320,000	640,000	26
160,000	320,000	25
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

4 μm	6 μm	14 μm	ISO CODE
1,301	321	41	18/16/13
2,500	640	80	18/16/13
2,501	641	81	19/17/14
5,000	1,300	160	19/17/14

one more particle

4 times as many particles

If only two range numbers are used: ISO */16/13 or ISO 16/13

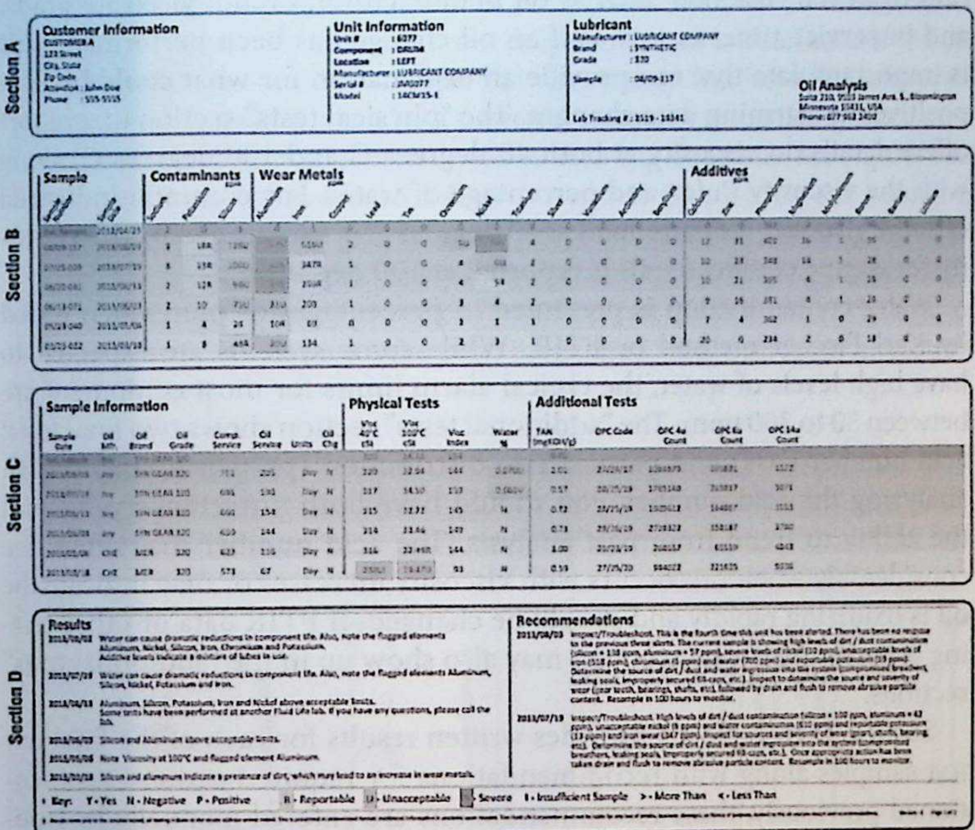
Interpreting Oil Analysis Reports

The first thing to check on an oil analysis report is the information about the customer, originating piece of equipment, and lubricant (see Section A in Table 4.4: Example Oil Analysis Report). Including these details is the customer's responsibility. Without this information, the effectiveness of the report will be diminished.

Knowing which piece of equipment the oil was sampled from affects the ability to identify potential sources of the measured parameters, especially wear particles. For example, the originating piece of equipment can help associate reported wear particles with certain internal components. The lubricant information can provide a baseline for several parameters such as the expected viscosity grade, active additives, and acid and base number levels.

Section B in Table 4.4 shows the elemental analysis findings. This data can help identify contamination, wear metals, and additives present within the oil and these parameters are reported in parts per million (ppm). Still, this does not mean a contamination particle, for example, can only be indicated by sodium, potassium, or silicon spikes.

Table 4.4 Example oil analysis report[1].



In the example above, the rise in silicon and aluminum could indicate dust or dirt contamination as the root cause. One likely explanation for these spikes is that as dirt, or silicon, enters the oil from an external source, followed by three-body abrasion occurring within the machine causing wear debris including aluminum, iron, and nickel to increase.

With a better understanding of the metallurgy within the system's components, any spikes in wear metals can be better associated, allowing a proper conclusion for which internal components are experiencing wear. Keep in mind that this trend analysis benefits from representative samples taken at an appropriate and uninterrupted frequency.

With elemental data related to contaminants and wear metals, alarms are set for upward trends in the data. For elemental data about additives, alarms are set for downward trends. Having a baseline of new lubricant reference data is critical in assessing which additives are expected and at what levels. These baselines are then established to help determine any significant reduction in specific additives.

Section C in Table 4.4 presents previously identified sample information from the customer such as oil manufacturer, brand, viscosity grade, and in-service time, as well as if an oil change has been performed. This is important data that can provide an explanation for what could be false positives in alarming data changes. The "physical tests" section of a report offers details on viscosity at both 40 degrees C and 100 degrees C, along with the viscosity index and percentage of water. For common industrial oils, the viscosity measurement at 40 degrees C is usually given. The viscosity for engine crankcase oils is reported at 100 degrees C.

Water contamination is presented in percentages or ppm when tested by Karl Fischer method or FTIR. While some systems are expected to have high levels of water, the typical alarm limits for most equipment are between 50 to 300 ppm. The "additional tests" section shows two final tests: acid number (AN) and particle size distribution (particle count). When analyzing the acid number, you should have both a reference value and the ability to trend from past analysis. The acid number may often rise considerably when this occurs with viscosity increases or may indicate the oil is oxidizing rapidly and should be changed. If FTIR data or other testing is performed, water content may also show up in the "additional tests" sections.

Section D in Table 4.4 provides written results for each of the final few test samples along with recommendations for required actions. As mentioned previously, these recommendations are entered manually by laboratory personnel and based on information provided by the customer and the data collected in the lab. If there is an explanation for the data that stems from something not explicitly stated by the customer, this is where the end user must further the interpretation of the data to consider factors associated to the machine's history of environmental and operating conditions. Understanding the information given here is critical. Remember, there is always an explanation for each exceeded limit and the root cause should be the focus of an investigation.

Following the Data Trends

Monitoring cautionary and critical limits for oil analysis results is essential and irreplaceable as groundwork in an oil analysis program. Nevertheless, the data fluctuations observed, even if they are within the established limits, can still prove to be valuable. In these conditions, trending oil analysis data is where hidden value can be realized.

Simply obtaining a snapshot of data from an oil sample is essentially worthless without something with which to compare it. Therefore, trending data in oil analysis reports is beneficial. It not only allows you to determine if the current oil properties are unfavorable, but also if they will become unfavorable soon. Quality trending provides a powerful means of recognizing when an oil property is moving in an unhealthy or threatening direction (see Figure 4.10).

The most effective way to follow a trend is by plotting the results on a property-versus-time graph. The "property" can be anything from the remaining additives within the oil to the base oil's changing properties or the number and types of particles. Trending can quickly reveal the rate-of-change over time (slope on the plot) associated with a series of monotonic

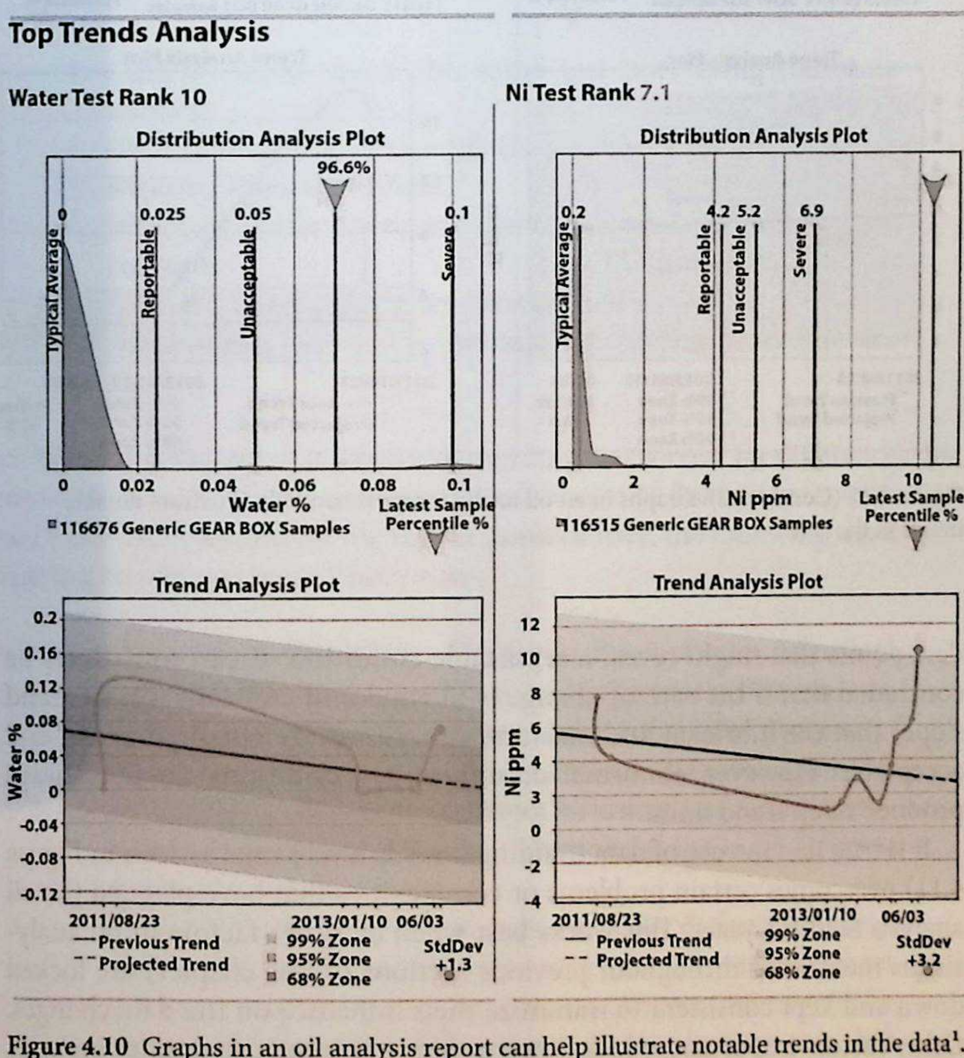


Figure 4.10 Graphs in an oil analysis report can help illustrate notable trends in the data[1].

(Continued)

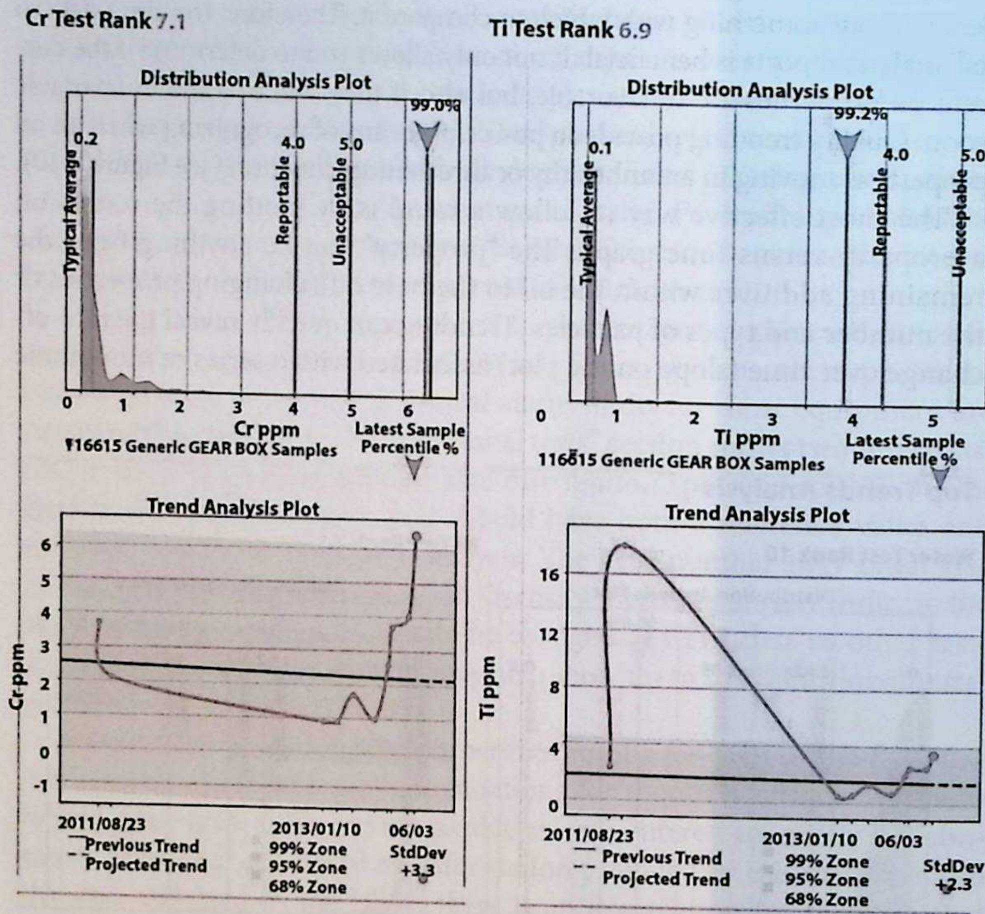


Figure 4.10 (Continued) Graphs in an oil analysis report can help illustrate notable trends in the data[1].

data points that might reveal a reportable condition. It can sometimes be concluded that if the rate-of-change is normal and constant (linear trend slope) that the lubricant and machine conditions are equally normal and acceptable. However, abnormal or unhealthy conditions do not always produce steep trend lines.

It is true that the use of data trending (versus level limits as seen in Figure 4.11) overcomes certain problems or complexities that have plagued the oil analysis field for years. This works best when all other factors in oil analysis (as mentioned throughout previous sections of this chapter) are locked down and kept consistent to minimize their influence on the data changes. Other factors important to lock down to improve trend capabilities include:

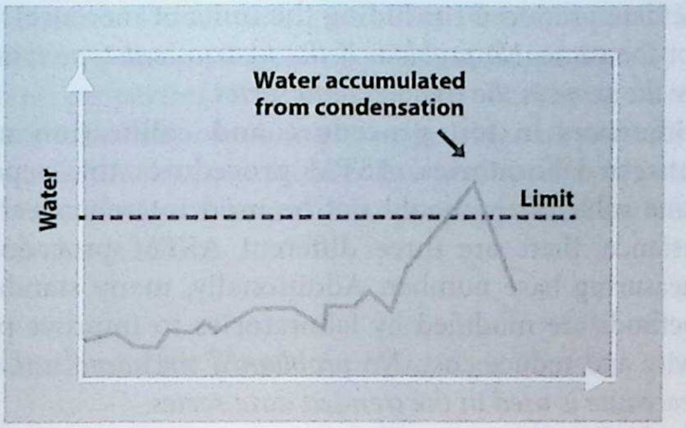


Figure 4.11 Moisture trend approaching a level limit.

1. Samples taken from the same test port using the same method
2. Oil and machine service life (in hours) are known
3. Makeup rates are known
4. When machine operating conditions and environment are constant
5. Oil type and formulation remain fixed
6. Exact same laboratory test instrument and procedure are used

When this regiment is followed, trending can correct for differences that are often outside of the control of the laboratory. For instance, when you use trend analysis and follow the six points above, the following trend-corrupting conditions would not occur.

- **Data reproducibility discrepancies between identical instruments.** There is often data disagreement between two instruments of the same type used for the same procedure. This trend corruption might be noticed if you send samples randomly to different laboratories using the same instruments. *No problem if the instrument used is always the same in the trended data series.*
- **Differences in instrument types used by different laboratories.** There are many diverse instrument types that target the same exact property. For instance, ferrous density can be measured by several different proprietary instruments, but

the data produced (including the units of measure) is often not the same. *No problem if the instrument type and brand are the same in the trended data series.*

- **Differences in test procedure and calibration method between laboratories.** ASTM procedures that report the same value often should not be used interchangeably. For instance, there are three different ASTM procedures for measuring base number. Additionally, many standardized methods are modified by laboratories to improve productivity and reduce cost. *No problem if the same suitable test procedure is used in the trended data series.*
- **Machine wear rate and operating environment differences.** Identical machine types often produce sharply different wear rates, preventing the data between machines from having any mutual statistical significance in setting alarms. Some machines are "high readers" while others are "low readers" compared to statistical averages. Nominal readers, however, follow statistical averages for a machine group. *No problem if the trended data is compared only to historical data from the same machine in the same operating environment.*

Trend analysis requires diligence with the entire oil analysis program. When successful, it is an intrinsic part of data interpretation of the lubricant. When combined with other alarming tactics, it can recognize such things as bad samples, an oil filter going into bypass, additive depletion, a new forcing function (abnormal wear), and wrong oil in use. While computer software is extremely helpful, it is hard to improve upon the ability to detect discernable oil analysis trends by simply plotting the data graphically and using our eyes.

It is imperative that oil samples are carefully collected and that all variables are minimized or at least addressed. Factors that can influence the results include:

- Sample location consistency
- Service life of the machine and oil
- Makeup oil rates
- Changes in environmental or operating conditions
- Oil formulation changes
- Testing procedure consistency

The key to success with trending is to learn from the past. This includes others' past failures, not just those of your machines. Start by identifying when certain oil properties have typically been healthy and use this as the standard. Also, take note of when a change in an oil property has previously led to a machine issue or failure. You must develop the awareness to recognize when a change in a particular property could eventually lead to a problem with the machine.

Looking Back at the Past

The world's population growth offers a good example of the types of trends that can exist within machinery. The earth's population has been growing for thousands of years, but it wasn't until around 1800 that it reached 1 billion people. While this was a major milestone, it only took approximately 120 more years to double to 2 billion. Less than 100 years later, the population is rapidly approaching 8 billion people. Many factors have influenced this recent trend, such as the Industrial Revolution and advanced medicine. Figure 4.12 shows how this rise in population would appear on a graph.

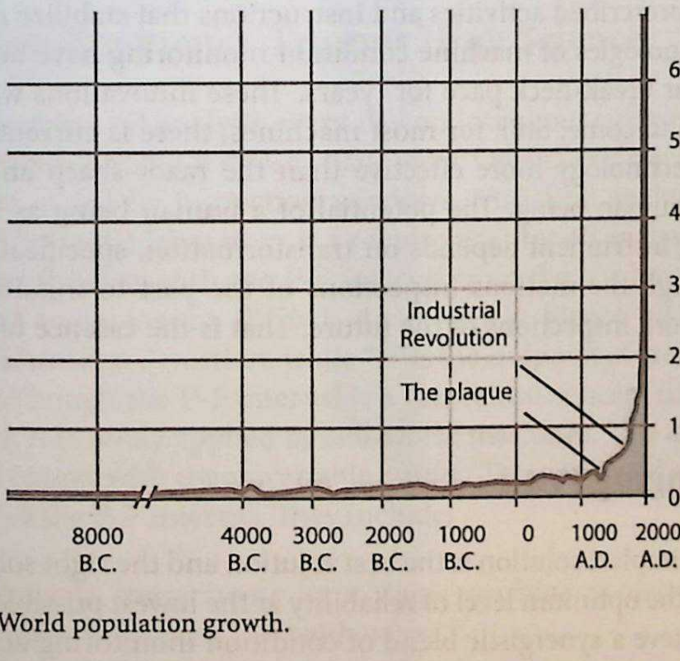


Figure 4.12 World population growth.

This trend can be compared to the growth of particle contamination in machinery. Particles produce particles. In fact, one particle can generate as many as 20 new particles within a machine. Of course, this will depend on many variables such as particle ingression rates, the filtration rate, and the likelihood of wear generation. Regardless, when particles are the instigator of new particles being created, the contamination can quickly escalate.

Inspection 2.0: Advances in Early Fault Detection Strategy [15]

Arguably one of the most important oil analysis functions doesn't require anything done at the laboratory. What it requires instead are skillful inspections that are rapid, comprehensive, and frequent. In its most basic form, they have been around forever. However, Inspection 2.0 is a radical reinvention of the whole concept of machine inspection. It has little to do with conventional practices of doing daily machine rounds.

With Inspection 2.0 you don't just "look" at a bearing, seal, coupling, or pump. Instead, you "examine" these components with a keen and probing eye. Inspection 2.0 is intense and purposeful. It seeks to penetrate and extract information from what's been referred to as machine sign language. Inspection 2.0 requires polished linguistic skills to translate this sign language into prescribed activities and instructions that stabilize reliability.

The technologies of machine condition monitoring have been advancing at a near break-neck pace for years. These innovations will continue for decades to come. Still, for most machines, there is currently no fault-detecting technology more effective than the razor-sharp and relentless focus of a human being. The potential of a human being as a condition monitoring instrument depends on transformation, specifically from the going-through-the-motions inspections of the past to mission-intensive detective work inspections of the future. That is the essence of Inspection 2.0.

Low-Hanging Fruit

Often, the simplest solution is the best solution and the right solution. How do you get the optimum level of reliability at the lowest possible cost? How do you achieve a synergistic blend of condition monitoring activities that unifies Inspection 2.0 with the range of other options being advanced and currently available?

Inspection presents some benefits and advantages that are difficult, if not impossible, to duplicate with other condition monitoring options. These include:

- Inexpensive, simple, lasting deployment
- Operator-driven (total productive maintenance emphasis)
- More emphasis on examination skills, less on technology [11]
- The power of frequency and the one-minute daily inspection
- Root-cause-oriented to avoid developing fault bubbles; more proactive, less reactive
- Early fault detection; more predictive, fewer misses and "just-in-time" saves

We all seek more for less and no one likes the pain and frustration that often come with exceedingly complex solutions to simple problems. KISS (keep it simple stupid!) solutions should always be your priority. Their application is at the core of Inspection 2.0. No array of sensors and computer intelligence can outperform a human inspector at a large number of condition monitoring tasks.

Inspection Frequency Trumps High Science

Why not perform oil analysis every day on just about every machine? Yes it sounds expensive, but it doesn't have to be. Oil analysis can be done with your senses, aided by inspection windows. Visual oil analysis is real oil analysis. Who said a laboratory is a requirement for oil analysis anyway?

Many are familiar with the P-F interval from the teachings of reliability-centered maintenance (RCM). As shown in Figure 4.13, "P" is the point-of-failure first detection, while "F" is the endpoint of functional inoperability. Although the P-F interval is a theoretical concept that has useful application, it is rarely applied in real-world machines. This is because the real world comes with many variable events. These events distort the predictability of the P-F interval. They include:

- Multiple components on a single machine or drive train, each with its own P-F tendencies
- Multiple failure modes for any single component
- Variable duty cycle (speeds, loads, shock, temperature, etc.)

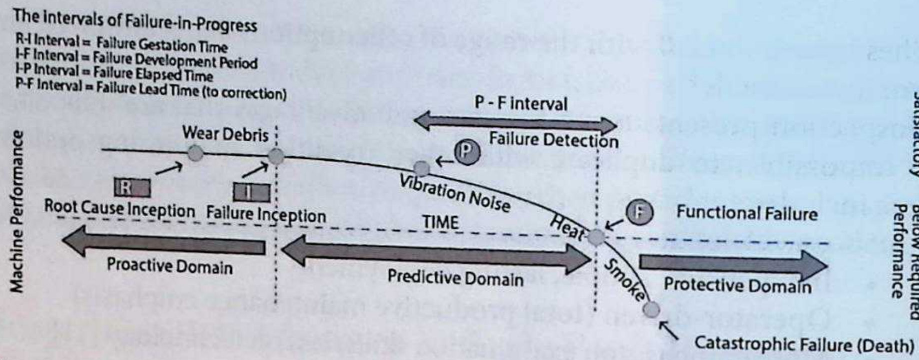


Figure 4.13 Condition monitoring and time domains of machine failure.

- Remaining useful life (RUL) varies with age. For any given fault mode, the P-F interval shrinks as the machine ages.
- Failure detection methodology and effectiveness vary (ability to detect faults early)

The best countermeasure for uncertain P-F intervals is frequency. For certain machines, real-time monitoring using imbedded sensors is justified, especially high-speed, high-risk machines. However, for nearly all other machines, the simple solution for early detection is daily inspection aided by inspection windows and tools.

Even the world's best oil analysis laboratories can't see faults in the "non-sample." Inspection 2.0 asks you to deploy your senses intensely every time you walk by the machine. The "oil sample" is examined carefully in the sight glass, but it never leaves the machine.

The power of frequency is illustrated in Figure 4.14. In this example, the failure development period (from inception to functional failure) is one month. If your condition monitoring interval is quarterly or bi-monthly, you won't catch the fault prior to functional failure (this is a condition monitoring "miss"). If you use a monthly monitoring interval, you catch

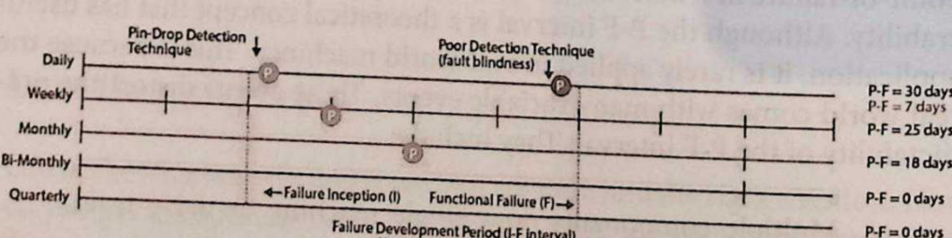


Figure 4.14 Failure detectability technique and inspection periodicity influence the P-F interval.

the fault with an 18-day P-F interval (lead time to corrective measure). Note: the longer the P-F interval, the better.

If your condition monitoring interval is weekly, your P-F interval jumps to 25 days (better). However, if you can inspect this machine daily using detection-sensitive Inspection 2.0 methods, your P-F interval is 30 days, which is better than weekly testing with the best condition monitoring technology (vibration, oil analysis, thermography, etc.). By comparison, a poor daily inspection technique yields a P-F interval of just seven days.

Beware of Short P-F and Sudden-Death Failures [9]

As mentioned, the P-F interval is almost impossible to predict for a variety of machine-specific reasons. In fact, the interval can vary from seconds to decades. Maintenance departments like long reaction times to schedule needed corrections. Still, Murphy's Law always looms to ruin an otherwise perfectly good day.

The best strategy to mitigate sudden-death failures is to focus on the early detection of root-cause fault bubbles. This is a fundamental proactive maintenance strategy (see the left side of Figure 4.13). Fault bubbles are escalating conditions that threaten the onset of an active failure event. As much focus should be spent on preventing the inception of failure as on detecting a failure in progress. Every failure mode has one or more root causes. Ensure good root-cause alignment with your inspection strategy.

Following are a few examples of short P-F and sudden-death failure modes and fault bubbles. What intervention strategy focused on root causes would you apply to detect and neutralize these threatening conditions?

- Oil filter rupture
- Wrong oil or severely degraded oil
- Fish-bowl conditions (disturbed and mobilized bottom sediment)
- Severe shaft misalignment
- Stiction/silt lock of hydraulic valve (motion impediment)
- Grease "cake lock" starvation of automatic lubrication system
- Impaired oil supply of a splash-lubed gearbox
- Heavy fuel dilution of a diesel generator
- Heavy chemical contamination of a compressor oil
- Gross seawater contamination of a shipboard hydraulic fluid
- Shock loading of a large thrust bearing

Inspection Windows and Zones

Inspection 2.0 is searching, i.e., detective work. It puts the machine under the microscope day by day. To do this, the machine's exoskeleton must be penetrated. You have to find ways to see through steel plate and cast iron. You must also "ready" machines for world-class inspection. New products, including modernized sight glasses, are being developed to bring vision to critical zones within the machine.

Figure 4.15 shows the use of windows for convenient zone inspections and a list of example root causes and faults that can be visually detected using these windows. The third zone, the bottom sediment and water (BS&W), is one of the best examples of where a modernized sight glass, in this case a BS&W bowl (Figure 4.16) can provide value for fault detection for common oil reservoirs and sumps. Each zone has a story to tell about the oil and machine.

If the BS&W bowl is properly positioned, anything that is heavier than the oil will accumulate there for quick inspection with a good light. This includes sediment, water, sludge, wear debris, coolant, dead additives, and dirt. If your BS&W bowl is clear, bright, and without sediment, there are many things that could be going wrong with your oil and machine that are not going wrong simply because this sight glass passes inspection.

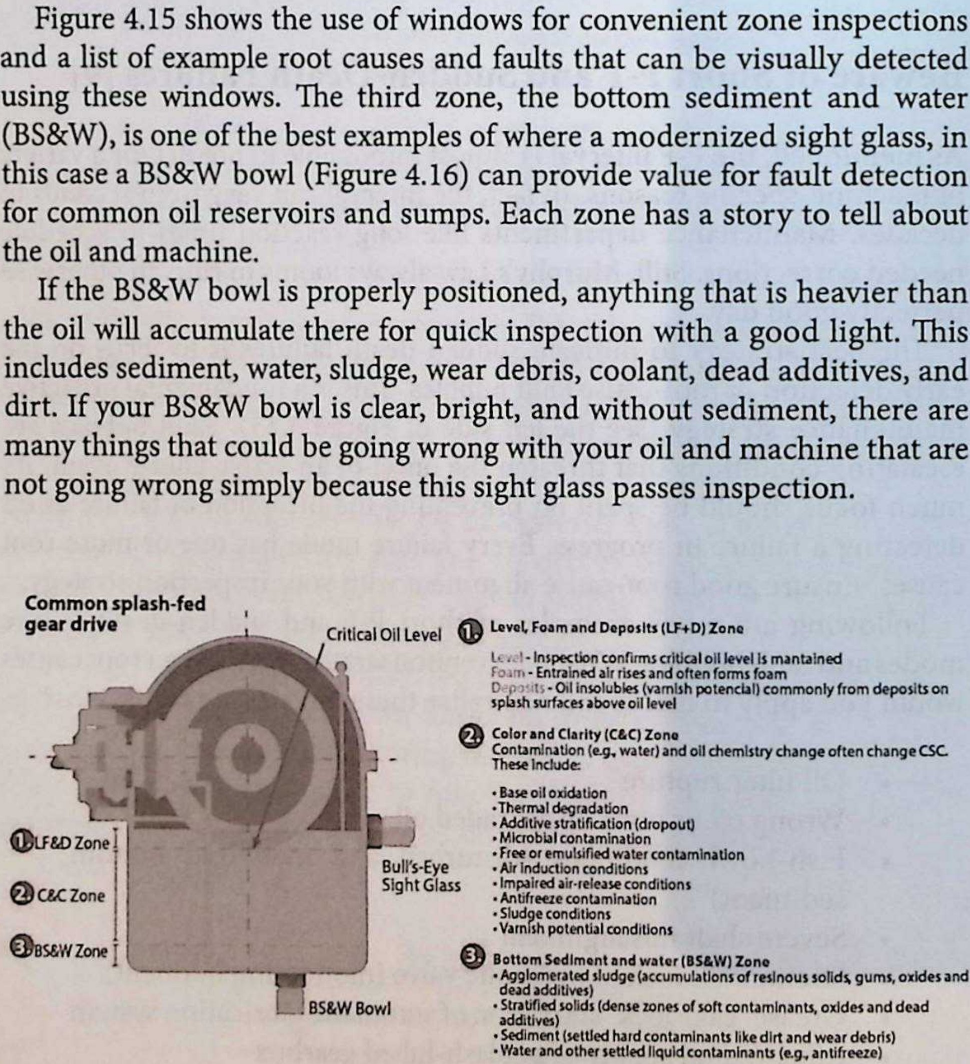


Figure 4.15 Zone inspections for early problem detection.

Figure 4.16 Modern bottom sediment and water (BS&W) Bowl Sight Glass.

Inspection 2.0 is a Nurturing Strategy

Applied tribology is a behavioral science. This means that in most plants the practice of tribology and lubrication is people-intensive. Lubricants are what we buy and lubrication is what we do. The main reason machines fail prematurely is the result of what people do or don't do.

Inspection is a subset of tribology (and lubrication) and likewise is very much a behavioral science. People have to passionately want to find faults and reportable conditions. The people I'm referring to are operators, technicians, lube techs, millwrights, mechanics, etc. It's no longer just "looking" during the inspection route and then checking the box on the report. Instead, it's about intense examining, probing, digging, and searching. The people factor will make or break any good reliability and maintenance undertaking and is perhaps truer with inspection.

People respond to work tasks and challenges differently. Much of it has to do with the leadership and maintenance culture. A positive, nurturing maintenance culture is a critical plant asset. Consider that when people do good work, they feel good about themselves and their job. When people do bad work, they feel bad about themselves and their job. The simple solution is to enable people to do good work that is recognized and celebrated.

Culture drives behavior. Behavior influences quality of work. Quality work is fundamental to plant reliability and the cost of reliability. Of course, this most definitely includes inspection activities. The following list delineates the minimum requirements for building a strong inspection culture:

- Training and inspection skill competencies (optimizing inspection skills readiness)
- Celebrating inspection "saves"
- Inspection KPIs and other performance metrics
- Installing penetrating inspection windows (optimizing machine inspection readiness)
- Availability and use of inspection aids and tools (optimizing tool inspection readiness)
- Promptly responding to inspection-generating alerts and red flags

Side-by-Side Comparison

What differentiates Inspection 2.0 from conventional inspection practices? It's mostly about execution. Think about how to make it 10 times more effective with very little extra cost. Table 4.5 details several of the main differentiators that distinguish and empower Inspection 2.0 to this higher level of performance. This is an exceptional low-hanging-fruit opportunity in machine reliability as well as a foundational element for lubrication excellence.

Final Tips to Help Error-Proof Your Lubrication Program [4]

Developing and managing a Lubrication Program can quickly become overwhelming without the right guidance. The Ascend methodology is one effective way to organize this and provide a guiding North Star on what the best practice is. This has been the methodology used for the hundreds of lubrication assessments performed as part of Noria's Lubrication Program Development. The results of a comprehensive questionnaire across all 40 factors provides a holistic analysis on a plant's current lubrication practices and stages of improvement

Table 4.5 Main differentiators between convention inspections and inspection 2.0.

Distinction	Conventional inspection	Inspection 2.0
Emphasis on daily inspections	Sometimes	Always
Emphasis on inspection location	Rarely	Always
Installed inspection windows	Rarely	Always
Inspection alignment to failure mode ranking	Sometimes	Always
Inspection designed to preempt fault bubbles	Rarely	Always
Emphasis on early "weak-signal" detection	Rarely	Always
Use of advanced inspection aids and tools	Rarely	Always
Inspectors who are highly skilled and motivated	Sometimes	Always

during reassessments. Using a tool like this to monitor progress and establish a firm understanding on what the current state is, is a great way to error-proof the lubrication program from the very beginning.

The Optimum Reference State (ORS) is another important way to help make the right decisions in machinery lubrication and oil analysis and keep them aligned to overall plant reliability objectives. Without the right tools, established practices, and team training, it can be common for lubrication programs to struggle. Often, it comes down to a lack of ownership or champion who maintains the focus, keeps key performance indicators (KPIs) tracked, and aligns them with maintenance and reliability goals.

As a final thought, the following is a list of a few tips to help error-proof your lubrication program:

- *Spread the Ownership but Maintain One Champion:* Everyone needs to be incentivized by the success of a lubrication program. It's easy for the executives to want this, as they gain from the profitability, but ownership must be realized and rewarded by the individuals making the daily efforts in lubrication activities. Overall, there should be one champion who has complete focus on the program's quality control and ensures nothing is falling behind.

- *Train Everyone Together and Frequently*: Training is a vital part of any lubrication program, but when it's done together as a team, there is a bit of comradery created that rallies everyone to make the needed efforts together. Buy-in is effective. Especially with Inspection 2.0, there is the value of learning from each other's experience and how to search for the subtle clues of lubricant issues or machine faults.
- *Prioritize and Follow up Routinely*: Every task must be prioritized because sometimes not everything can get done. Follow up is one of the ways to have a tracking metric. What gets measured gets done.
- *Keep Procedures Easy to See and Understand*: It is considered a best practice to keep procedures easily accessible and posted nearby and on the machines. Posting every routine procedure directly on the equipment provides clear instruction every time.
- *Track Compliance and Be Intentional*: Visually post your progress and lubrication activities with metrics on walls that are seen constantly. This shows everyone why these activities are done and why they must continue.
- *Consider Ergonomics with Machine Inspections*: The best inspections are those that are recognized by the untrained eye. For example, this would include using sight glasses that are installed next to a common walking path with the maximum and minimum levels clearly marked. Even better would be to post the contact information of the person to inform if these levels are breached.
- *Keep It Simple (KISS Principle)*: If your lubrication tasks are prepared to be easy to use and understand, they will be completed more often and more effectively.

Noria Corporation

This chapter is comprised of the knowledge and experiences of Noria Corporation's Jim Fitch and Bennett Fitch. Founded in 1998, Noria's single focus is helping user organizations improve machine reliability through the deployment of best practices in lubrication and oil analysis. For over 20 years, their world-class approach has changed how organizations manage and monitor lubricants to maintain optimum reliability and safety. The experts at Noria have become trusted advisors to many of the world's leading organizations.

Table 4.6 Acronym list.

ACL	**Ascend compliance level**
AES	Atomic Emission Spectroscopy
AN	Acid Number
BSC	Balanced Score Card
BS&W	Bottom Sediment and Water
DMAIC	Define, Measure, Analyze, Improve, Control
FDP	Failure Development Period
FOF	Failure Occurrence Factor
FTIR	Fourier Transform Infrared
ICLM	International Council for Machinery Lubrication
ICP	Inductively Coupled Plasma
ISO	International Organization for Standards
KPI	Key Performance Indicator
MCF	Machine Criticality Factor
OEM	Original Equipment Manufacturer
OLC	Overall Lubricant Criticality
OMC	Overall Machine Criticality
ORS	Optimum Reference State
PdM	Predictive Maintenance
PM	Preventative Maintenance
PPM	Parts Per Million
RCM	Reliability-Centered Maintenance
RDE	Rotating Disc Electrodes
RUL	Remaining Useful Life
ZDDP	Zinc Dialkyldithiophosphate

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