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TLT

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STRATEGIC OIL ANALYSIS:

Best Practices for Developing and Managing a Successful Condition Monitoring Program.

Special 56-page issue!

Foreword from the Publisher

RELIABILITY MAINTENANCE is an often overworked term, but nonetheless the concept is one of increasing importance in our industrial world today. The philosophy was derived from the quality assurance concepts developed in the previous decades and codified in ISO 9000 and similar quality initiatives. This is a proactive and predictive, rather than a reactive, approach to maintenance and manufacturing. It has emerged as one of the basic building blocks for a successful company's business strategy. We call this business philosophy asset management. Proactive, predictive plant maintenance has now become an integral part of the asset management strategy of successful manufacturing companies.

In the U.S. alone, billions are lost each year to friction and wear. A portion of these losses affects plant maintenance. Indeed, so called reactive maintenance costs companies three times that of predictive maintenance. This is reason enough to develop an effective strategy to reduce maintenance costs. These costs directly affect the bottom line, and therefore, the net return on assets. Because good maintenance practices so directly affect the financial performance of a manufacturing operation, no manager can neglect this aspect of his management responsibilities. Thus, it is imperative that companies adopt a competitive maintenance strategy if they want to remain viable competitors in today's highly competitive markets.

STLE members are directly responsible for the successful operation of manufacturing equipment by utilizing the best possible lubrication and maintenance practices to reduce friction and wear.

STLE's mission is "to promote the advancement of the science of tribology and the practice of lubrication engineering in order to foster innovation, improve the performance of equipment and products, conserve resources and protect the environment."

A key element in meeting this mission is for the society to deliver credible technical information each month in TLT for industry professionals to expand their knowledge to help better serve their employers and customers. That's why STLE introduces this digital compilation of nine "best of" articles for those involved in oil analysis and machinery maintenance.

For the last several years, the technology and best practices of this rapidly growing field continue to evolve. To address industry's needs, STLE offers two certification programs—Certified Oil Monitoring Analyst™ I & II—for predictive maintenance professionals that demonstrates proficiency in sampling and analyzing oil properties. OMA I is for the individual taking the oil sample on the shop floor. OMA II is for the person responsible for running the proper tests, interpreting data and managing the lubrication program. STLE also offers basic and advanced-level condition monitoring courses, held each year during the society's annual meeting.

For more information on these resources, visit **www.stle.org**.

Whether you're a newcomer to the field or a senior plant manager, these articles will be of great reference to today's practitioners.

Dr. Robert M. Gresham
Director of Professional Development
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Dr. George Staniewski

PdM: YOUR CHOICES FOR AN EFFECTIVE OIL ANALYSIS PROGRAM

KEY CONCEPTS

- In the last 30 years, predictive maintenance has slowly replaced preventive maintenance as the preferred machine maintenance strategy.
- Commercial labs, in-house testing, mobile labs and at-line sensors are the four key oil analysis options and have their individual advantages and disadvantages.
- For most industrial operations, a condition monitoring program that integrates the four testing options is usually the best approach for protecting machinery and reducing costs.

For decades preventive maintenance (PM) has been the preferred maintenance strategy for manufacturers. Unfortunately, this approach is costly due to the need to halt the production process.

In the last 30 years, predictive maintenance (PdM) has been slowly replacing PM, particularly for critical equipment. Regrettably, most corporations did not achieve the expected level of economical benefit, as vibration monitoring was the only employed PdM monitoring technique. End-users slowly realized that their PdM programs could be more efficient if vibration analysis was supplemented by other PdM techniques such as oil analysis, infrared thermography and motor diagnostics.

The experience of successful industrial organizations suggests that an integrated lubrication program can significantly improve equipment reliability and availability, reduce operating costs and improve production and safety. Factors influencing the effectiveness of an integrated lubricant program include lubricant selection, the procurement process and quality assurance, the lubricant station database, storage and handling processes as well as condition monitoring and waste disposal.

An integrated lubrication program can significantly improve equipment reliability and availability, reduce operating costs and improve production and safety.

While this article concentrates on condition monitoring, please recognize that improvement in only one element of a lubrication program cannot generate a sufficient and sustainable effect on improving equipment reliability and cost control.

GENERAL REQUIREMENTS

An effective oil monitoring program requires a high degree of cleanliness of the lubricating oils to enable the detection of changes in the solid particle distribution (i.e., strong signal-to-noise ratio). Individuals responsible for the condition monitoring program should initiate a design review of seals, filters and air breathers for the equipment selected. In addition, the cleanliness of new oils should be reviewed as well as associated handling and storage processes to ensure initial oil cleanliness is below the generic cleanliness target for a particular piece of machinery.

Since condition monitoring can be time-consuming, only selected equipment can be included in this program. In most cases this includes critical safety-related machines, equipment that may cause environmental hazards, equipment with long replacement lead times and equipment that has a critical impact on production. You also might want to include equipment with a poor operational record and those for which spare parts are not readily available.

Another important step is identifying an appropriate oil sample location, as non-representative samples can make the testing and analysis meaningless. Equally important is *consistency* of sampling methodology. For forced oil circulation systems, the preferable sample port location is on the oil return line. The concentration of wear

A nuclear engineer analyzes four testing options and explains how to best balance machine maintenance and cost factors.

Dr. George Staniewski

particles in this line is greater than in other locations. Include a number of secondary sample ports for additional oil sample access if further investigation is necessary.

For splash oil-lubricated equipment, the preferable sampling port location is on the sump wall, usually with a stainless tube extension to the area of high turbulence. A similar option is a drain valve with a tube extension to allow sampling above the sump bottom. Ensure that the stagnant material in the tube is not captured for analysis.

The next steps are determining sampling frequency and the type of oil tests. Typically, sampling is based on the fastest rate of progression of the critical degradation mechanism. Some users, however, simplify this task by increasing the initial sampling frequency to generate a reliable baseline for all test methods. The purpose of a baseline database is to identify the present condition of equipment, determine the rate of change of lubricants and component deterioration and optimize target and alarm limits.

A typical oil sample volume is approximately 100 to 200 ml depending on oil type, its design function and the performed test.

An oil baseline should be taken at the beginning of the condition monitoring program, after equipment overhauls, oil changes, and/or after any major process changes. Baseline, as well as all samples, should be obtained during normal operating conditions.

Sampling methods should facilitate the procurement of a representative sample from equipment with minimum requirements for flushing the sample line. In addition, the sample should be kept to a minimum and the sampling procedure strictly adhered to.

A typical oil sample volume for most medium-size industrial equipment is approximately 100 to 200 ml depending on oil type, its design function and the performed test. Wherever possible, transparent plastic sample bottles (i.e., polyethylene terephthalate or PETE) should be used. However, end-users should also refer to ASTM D4057 standard.

The information on the oil sample bottle's label is critical. At a minimum, each sample should include:

1. Equipment ID/description
2. Sampling point
3. Lubricant type
4. Operating times or equivalent value, if possible
5. Sample date and the name of the person taking the sample.

Extensive knowledge and experience is required from individuals involved in the interpretation of oil test results. Failed components should be inspected by those who performed the oil analyses. Images (obtained through an optical microscope and recorded by a digital camera) should be compared with previously obtained oil test results to establish a comparison between test results and actual wear.

Components considered for visual inspection should have clear orientation marks before their removal. This is necessary in order to identify the direction of acting forces. Carefully select the cutting area to avoid any damage to the wear pattern.

Finally, it must be realized that condition monitoring is an expensive approach; therefore a cost/benefit analysis should be performed on anomalies. Lack of cost benefit or cost avoidance may result in scope reduction or elimination of the condition monitoring program.

Specific industry applications have different requirements and, therefore, a different form and scope of oil monitoring program. In general, they can be divided into four primary forms:

1. Commercial oil labs
2. In-house oil screening facilities
3. Mobile oil labs
4. Continuous monitoring using sensor technology.

Let's look at the pros and cons of each.

COMMERCIAL OIL LABS: ADVANTAGES

There are several advantages of an oil analysis program performed at commercial labs. First, this continues to be the most widely used approach for oil analysis. Initiated almost a century ago, its success generated a solid foundation for the concept of oil analysis by highly qualified experts.

Historically, the primary disadvantage that initially existed was inadequate oil testing capabilities, testing procedures and quality control systems. New and specialized instrumentation was yet to be developed, the information on the oil degradation mechanism was not well understood, and testing capabilities were significantly limited. The effect of lubricant on the lubricated components and particularly the testing of failed components were not always performed.

Most of today's commercial laboratories are well equipped with efficient, sophisticated and precision oil testing instruments. Commercial laboratories maintain control of oil standards and associated documentation such as the Certificate of Analysis and perform adequate periodic calibration of their testing instruments as well as frequent data validation activities. Most commercial

Predictive maintenance (PdM) is more effective when vibration analysis is supplemented by other techniques such as oil analysis, infrared thermography and motor diagnostics.

laboratories regularly participate in different quality programs driven by ISO standards (i.e., 9001, 17025) or specific industry requirements (i.e., Nuclear Utility Procurement Issues Committee).

The personnel involved in oil testing and particularly in the analysis of oil test results are well trained, provide unbiased opinion and possess information not only on the lubricant testing method and oil deterioration but also on generic equipment design. By performing frequent analysis for many different applications, they continuously enrich their interpretation skills and offer excellent input on both the lubricant and equipment conditions. Also, the work undertaken by commercial laboratories provided excellent input for our understanding of oil degradation mechanisms and provided justification for more formal research activities by oil suppliers and/or research institutions.

Another benefit of commercial laboratories is in their advanced computerized lab management system. Typically, the sample is effectively monitored from the time of arrival, through all phases of testing to report formation. Some laboratories allow their customers to have read-only access to their lab management system so that they also can monitor testing progress. Data transfer is done electronically and in some circumstances automatically imbedded into end-user database software. The end-user can not only inspect the current sample test results and developing trends but also be aware of the samples and testing status.

Commercial laboratories commonly deliver critical sample test results within 24-48 hours of sample receipt. More time-consuming tests are reported later, but this is due to test procedures rather than poor process efficiency. The benefit of an efficient and effective oil testing process allows commercial laboratories to offer end-users an affordable price for testing services. The cost per sample is most likely the lowest of any of the discussed options.

Some industries have very specialized requirements for testing. In these cases, specialized commercial laboratories are the best choice for such analysis. An example of such a requirement is the need for thermal aging and/or irradiation resistance of selected lubricants used at nuclear power plants in safety-related systems.

COMMERCIAL OIL LABS: DISADVANTAGES

There are, however, several disadvantages of commercial laboratories. One of the most important is a poor control over sampling methodology. End-users must use proper sampling bottles with an acceptable internal cleanliness level, employ proper sampling hardware and follow correct sampling procedures.

Typically, sampling is based on the fastest rate of progression of the critical degradation mechanism.

Additionally, end-users must obtain representative oil samples from appropriate locations, under normal operating conditions at designated intervals. This might require installing new sampling ports.

A further concern is shipping. This task depends on appropriate packaging and shipping procedures, which can be more challenging than it sounds—consider oil samples from marine ships, military armor vehicles or radiation-contaminated equipment from nuclear stations.

End-users also should communicate to the commercial laboratories all factors that could affect the oil analysis such as oil makeup, external filtration or performance of equipment maintenance. In general, commercial laboratories have poor access to the end-user's operation database. Both parties must implement an efficient two-way communication process. Without this feedback loop, some test results could be misinterpreted. Laboratories deal in high volume and cannot afford to learn about the sample history.

One of the important limitations of an effective oil analysis program is the in-service cleanliness of the lubricating oil or hydraulic fluid systems. End-users must maintain a relatively high cleanliness level in their lubrication and hydraulic systems to allow for early detection of wear particles.

Commercial laboratories commonly deliver critical sample test results within 24-48 hours of sample receipt. More time-consuming tests are reported later.

Also, most commercial labs do not always use ASTM test methods, as some are not cost-effective. Most of them implement some modifications of typical ASTM standards. In such situations, the repeatability and reproducibility of their data is an unknown. End-customers have no way of knowing how precise the data is, so the data provided from a commercial lab is likely to have the lowest quality of

End-users must use proper sampling bottles and techniques when working with a commercial lab.

any of the discussed options. The associated problem with oil test modification is the possibility of being unable to compare test results from one lab to another.

Another disadvantage of commercial laboratories is the potential for relatively poor in-house knowledge on lubricating oils and their deterioration mechanisms. Although there is always a possibility to get input from the commercial lab analyst, it is the end-user's responsibility to verify the recommended corrective actions and implement them as required. Lack of adequate understanding of the test results and their interpretation could cause a failure of the entire analysis program.

Finally, the need for revenue generation will entice most commercial laboratories to accept and process large numbers of samples. This may negatively impact their ability or willingness to specialize within a specific industry or application and, therefore, limit the interpretation skills of their analysts.

IN-HOUSE OIL SCREENING: ADVANTAGES

During the past two decades, for safety or regulatory requirements, some corporations were forced to perform initial oil testing in-house. Some users, however, implemented in-house oil testing to increase their monitoring capabilities of critical equipment. The same crews involved in the predictive maintenance program enlarged their monitoring scope by performing not only vibration analysis but also in-house oil screening tests, infrared thermography and ultrasound or motor diagnostics. This was implemented to achieve earlier detection of equipment deterioration and widen the margins for scheduling corrective actions.

One of the greatest benefits of this approach is that the personnel directly involved in the monitoring process have a good knowledge of the equipment and its performance. The predictive maintenance crew has the advantage of inspecting the removed failed components and correlating their monitoring parameters with actual component damage. There is also the opportunity to perform correlation analysis with different PdM indicators and optimize the predictive maintenance scope, an invaluable learning opportunity.

By performing in-house oil analysis, corporations may eliminate or significantly reduce the requirements for oil sample shipments and their associated costs. This could be of great benefit in cases of regulatory requirements for additional testing prior to shipment.

One of the benefits of in-house oil testing is the potential for immediate oil analysis in emergency conditions. Although the aforementioned monitoring approach improves the early detection of equipment deterioration, emergency situations will occasionally occur, and the rapid response of an in-house facility is critical for safety. The in-house screening facility also allows an organization to test equipment to declare that it is acceptable for service. This is almost as powerful as stating that a problem exists.

In-house oil testing also improves the quality control process of new lubricants through verification of critical properties against approved specifications. Such commercial grade dedication activities provide another baseline for the trending purposes. The in-house lab is likely to produce the highest quality data in terms of repeatability and reproducibility of the discussed options.

IN-HOUSE OIL SCREENING: DISADVANTAGES

In today's economy, justifying a large budget for an extensive in-house monitoring program is difficult. Only some industries can justify such a large budget and relatively high cost per oil sample based on the penalty of lost production or jeopardized public safety.

Some end-users tried to minimize the purchase of expensive instruments by substituting simple testing equipment. In most cases, the precision and detection limits of these apparatuses are significantly lower and do not allow for the detection of early lubricant deterioration.

Another potential disadvantage of in-house oil screening programs is the maintenance personnel's inadequate knowledge of a robust analysis program. Most end-users do not possess adequate knowledge of component degradation mechanisms and the parameters that allow for the monitoring of their progression. They may not have sufficient knowledge of the critical elements of an efficient in-house oil analysis program, the preferable scope and frequencies of oil sampling and the testing.

In addition, the testing is carried out by mechanics who require additional training and may not fully appreciate the need for data validation or periodic instrument calibration. In-house testing is generally understood as a screening tool that does not require extensive data verification. This is a concern as standard maintenance activities such as *in situ* filtration or oil replacement may be performed based on erroneous interpretation.

In-house oil screening requires a selection of appropriate database software capable of recording and trending all collected data, performing some statistical analysis and providing good access to the maintenance work management system and other predictive maintenance databases. Since maintenance labor is one of the main cost factors of in-house testing, both automated instruments as well as automated data transfer from test instrument into database are preferred. In most cases, neither oil database software nor all lab instrumentation has these capabilities.

Relatively few oil samples make it difficult to justify automated instrumentation, forcing in-house personnel to perform manual testing of each sample. This decreases testing efficiencies, increases the cost per oil sample and diminishes the interest of personnel involved in repetitive oil testing. As a result, frequent personnel rotation may be experienced, thereby increasing the cost of training and negatively impacting the quality of testing and the interpretation of results. The in-house lab produces a higher cost per sample than a commercial lab and has limited flexibility.

Another frequent problem associated with in-house oil screening programs is related to an inadequate lab management process. Usually, only

Many end-users begin in-house oil analysis programs to better monitor critical equipment.

personnel directly involved in oil analysis are aware of the status of the oil sampling process. This leaves management and equipment owners unable to independently monitor the progression of the sampling process.

In most cases, in-house testing concentrates only on the basic properties, which may necessitate periodic testing at external commercial laboratories. This increases the cost of the testing program, sometimes bringing into question the need for in-house testing.

Similar to any sample-based monitoring program, in-house oil screening programs require the installation of proper sampling ports and use of adequate hardware and procedures. Organizations with in-house oil screening programs are responsible for purchasing and storage of oil sampling supplies and any safety procedures related to solvent handling. Safety and fire protection hardware and procedures also must be implemented to satisfy all local and national requirements. Further modification to the equipment components also might be required to minimize contaminant ingression rate.

Mobile oil laboratories provide better access to operating data and knowledge of environmental impact and design limitations of the equipment.

Another potential problem is related to the limited number of qualified in-house staff capable of performing oil analysis and possessing extensive interpretation skills. These personnel are not always on-site due to training, sickness or vacation—furthering the potential for problems, particularly during emergency conditions.

MOBILE OIL LABS: ADVANTAGES

To address some of the disadvantages of oil analysis programs performed by commercial laboratories and in-house oil screening, some organizations introduced an oil program based on testing performed in mobile oil laboratories. This concept eliminates an in-house oil screening facility and also reduces shipment costs.

In general, this approach can significantly reduce the overall cost of the oil analysis program, particularly in comparison to a typical in-house oil screening concept. At the same time, mobile oil laboratories provide better access to operating data and knowledge of environmental impact and design limitations of the equipment. Depending upon the particular arrangement, the contractor also could perform oil sampling.

Most mobile oil labs possess automated testing instrumentation with high precision and detection limits that allow for early detection of equipment deterioration and efficient testing. The test results can be automatically downloaded to the local user's database with immediate interpretation and corrective actions. Theoretically there is a greater opportunity to inspect the failed components and adjust oil limits and program scope.

End-users are not responsible for calibration of the oil testing instruments and data validation process. Additionally, end-users are not responsible for upgrades to the oil testing instruments and storage of the clean oil-sample bottles.

This approach for oil sampling allows for a better understanding of particular equipment operating data, working conditions and performed maintenance. If required, analysts immediately can have access to additional design data or operational history. Finally, a good relationship between the mobile and maintenance crews can reduce or even eliminate the need for an on-site resident expert on lubrication.

MOBILE OIL LABS: DISADVANTAGES

The main disadvantage of this approach is a limited number of oil testing instruments in the mobile laboratory. Usually, only tests with a short completion time can be conducted. A long-term test requires a commercial laboratory.

Also, mobile laboratories present difficult working conditions for personnel performing tests and analyzing data. This may result in frequent staff rotation. In addition, the congested space, an inability to control temperature and humidity as well as the potential for vibration impacting instruments during frequent mobile lab movement might affect test results.

Since the oil testing and sampling could be conducted by the contractor, there could be inadequate in-house knowledge and experience on lubrication practices. Lack of a resident lubrication expert may influence the quality of the integrated lubrication and advance PdM programs.

Again, installation of appropriate sampling ports and additional improvements to the equipment hardware to minimize contamination ingression are necessary.

SENSOR TECHNOLOGY: ADVANTAGES

Sensors detecting simple oil parameters and other associated properties have been implemented successfully for several years in industrial applications. The most important advantage of sensor technology is its ability to provide continuous monitoring and data collection during the entire operation cycle. This is an invaluable asset, particularly for equipment in remote or inaccessible locations. Applications such as wind power turbine gearboxes, equipment located in nuclear reactors or in mobile equipment are good examples of systems benefiting from sensor technology.

Sensors are rugged enough to withstand normal industrial environments and can be installed directly in hydraulic systems and lubricated components, providing real-time data collection and retrieval. Typically, sensors monitor such properties as cleanliness, wear debris, water content, dynamic viscosity, presence of some additives, dielectric properties, oxidation and acid/base numbers. Recent developments in multiparameter-based sensors, providing multiple outputs on several properties, further enrich the sensor technology potential.

The introduction of more sophisticated sensors capable of monitoring critical properties of lubricants and contaminants allows end-users to make decisions based on real-time conditions reported continuously. Sensor technology also allows for the implementation of expert systems providing consistent and more accurate interpretation of oil and equipment conditions. Oil results can be immediately correlated with other predictive indicators and performance parameters to enhance the interpretation capabilities. Current developments in telecommunications can allow for continuous monitoring anywhere in the world via the Internet. This provides a comprehensive integrated automatic assessment of stationary and mobile equipment conditions worldwide.

Sensor technology provides an additional advantage to the traditional monitoring programs by helping to identify the optimum time for additional testing. Lubricant samples will be taken only as required, when a definitive need for additional input has been identified.

SENSOR TECHNOLOGY: DISADVANTAGES

One concern is the poor involvement of equipment manufacturers in including sensors in their equipment. Most manufacturers do include a number of sensors for monitoring performance characteristics of equipment or systems; however there is resistance on their part to install oil monitoring sensors. End-users are taking the initiative by retrofitting oil sensors to their equipment and enhancing their monitoring program. This process is more expensive as it includes design approval for the proposed modification and loss of production time.

Another challenge facing sensor technology is the need to improve data collection and storage. Software must be capable of monitoring large volumes of data, including proper data selection, recording, retrieving and reporting. Although there are databases that can handle such demanding requirements, further innovation is needed in this area.

The most important disadvantage of the sensor approach is the limited number of properties that can be measured. This often requires further testing, using standard test methods, conducted in a laboratory environment. However, the one advantage in this scenario is that additional testing would only be conducted as required. It is important to note that sensor technology would not exclude the need for the previously discussed testing options including commercial lab, in-house screening program or mobile laboratories.

Since additional testing in laboratory environments could be needed, the end-user might need to install appropriate sampling ports, maintain sampling containers and packaging and improve equipment hardware to minimize contamination ingression.

One further challenge facing sensor technology is the need for periodic calibration. Also, sensors will eventually have to be replaced in a manner that allows for continuous data collection.

The most important advantage of sensor technology is its ability to provide continuous monitoring and data collection during the entire operation cycle.

CONCLUSION

None of the discussed options alone can satisfy the requirements of an all-encompassing and sustainable monitoring program. In most cases, end-users implement a combination of options to achieve their cost-control objectives.

A significant interest in the installation of in-line monitoring sensors is likely. Sensor technology will be associated with expert systems for helping end-users to interpret lubricant and equipment conditions.

In the near future, end-users will more readily implement the integrated lubrication programs due to recognition of the benefit and impact on improvements to equipment reliability and production cost-control. TLT

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Jeanna Van Rensselar / Contributing Editor

Leveraging the power of oil analysis

'It's the little details that are vital. Little things make big things happen.'

–John Wooden

KEY CONCEPTS

- Selecting the right mix of equipment and tests is the first and most critical step in a successful oil analysis program.
- Failure to follow through on details, such as reading the entire report or poor sampling methods, is the primary cause of poor ROI.
- A good relationship and solid communication with the testing lab is essential.

And so it is with oil analysis where the time and attention to detail makes the difference between mediocre return on investment and spectacular return that saves critical equipment, prolongs the life of expensive machinery and eliminates the surprises that lead to shutdowns.

All photos courtesy of TestOil

On the surface, the whole process seems straightforward: select the equipment, take the sample, send it to the lab and wait for results. In the real world:

- Equipment selection is random and based on what one person thinks should be tested.
- Samples are taken from the locations with the easiest access and not from where they best represent the oil in use.
- Samples sit around for several days before anyone sends them to the lab.
- The lab doesn't process the sample in a timely fashion.
- The lab report is formatted in a way that assumes customers have a background in statistics.
- The lab report doesn't really matter anyway because either no one reads it thoroughly or it doesn't get read at all.
- No one follows through on obvious action items.

David Kirkwood, business development manager for TestOil in Strongsville, Ohio, explains, "Many organizations throughout the world have implemented oil analysis programs to help manage equipment reliability. Some have experienced substantial savings, cost reductions and increased productivity. A successful oil analysis program requires a dedicated commitment to understanding the equipment, the lubricant, the operating environment and the relationship between the test results and actions to be performed."

Paying attention to detail means doing everything just a little better at every stage of the oil analysis process.

BETTER EQUIPMENT SELECTION

Smart, strategic equipment selection is one of those details where customers should take advantage of their lab's expertise. STLE-member Alessandro Paccagnini, CLS/MLT I, laboratory manager at Mecoil Diagnosi Meccaniche Srl, Firenze (Florence), Italy, says, "When we help customers choose the equipment to be monitored using oil analysis, the first criterion is always equipment criticality within the production process. How costly would an unscheduled equipment failure be? The second criterion is equipment repair cost. Then it comes to operating conditions severity and actual equipment fault history, for example using FMECA."[1]

Equipment critical to plant operations is generally the most important (especially if there is no backup to replace it), followed closely by the most expensive equipment. The Criticality Index ranks equipment based on how important it is to operations. It places each piece of equipment into one of three categories:

To measure viscosity, a predetermined volume of lubricant is introduced into the viscometer tube. Gravity causes the sample to flow through the tube. The amount of time the sample takes to flow through the calibrated portion of the tube is recorded. The time is multiplied by the tube's calibration factor to give the result.

- **Critical:** The rest of the working environment can't function without it and there is no backup.
- **Essential:** This equipment is key but not critical to the operating environment—usually the case if a backup exists.
- **General purpose:** This encompasses everything else.

BETTER TEST SELECTION

Nearly all fluid analysis labs are experts at recommending tests to their customers. The problem is that some customers don't trust their labs—thinking that labs are recommending expensive tests they really don't need. So they schedule tests without consulting with their analysis provider. Customers can be assured that they are selecting the right tests and the right frequency by insisting that their labs take the time to explain *why* they recommend specific tests.

Basic oil analysis tests fall into one of three categories:

1. **Lubricant condition**—whether or not it is ready for a change.
2. **Contaminants**—whether there are machine-degrading contaminants present and, if so, what and to what extent.

CONSIDERATIONS FOR CHOOSING A LAB

Following are a few considerations for selecting an oil analysis lab:

- What are the costs per test and what is/is not included?
- How easy is it to read and interpret reports? (Ask to see a sample report.)
- What guarantees does the lab offer?
- What are the lab's hours of operation?
- How much technical support is available?
- How quickly can the sample get to the lab?
- What are report delivery and format options? Can users sort data?
- What is the turnaround time for sample results?
- What kind of customer training programs does the lab offer?
- Does the lab have proper ISO accreditation?
- Do tests conform to ASTM standards?
- Are lab employees' skills kept up to date and/or are they regularly certified?

3. **Machine wear**—in the form of particles that indicate the level and rate of machine deterioration.

Following are four specific tests that are performed on most samples in most labs.

Viscosity. Viscosity is a measure of a fluid's resistance to flow (thickness), which is affected by a number of factors, including temperature (which is why the report states the viscosity at a specific temperature). Viscosity is measured at standard temperatures of 40 C and 100 C because industrial oils are graded according to their viscosity in centistokes at 40 C, while mobile (mostly multigrade) oils are graded according to their viscosity in centistokes at 100 C. The viscosity index (VI) measures how much viscosity changes with temperature.

Water (rust, oxidation). Water is one of the more common (and preventable) contaminants, but its potentially devastating effects include rust, increased wear rate, the formation of acids from chemical reactions between additives and base oils, biological formations (i.e., mold and algae) and loss of additive functionality and the additives themselves.

Particle count. Particle count measures the size of the particles and the content relative to the entire sample. The test quantifies all solid particulate within a sample that is 4 microns and larger. Most normal wear particles are too small to be counted by this method.

Spectroscopy. Spectroscopy measures the concentration of a variety of elements in the oil. These elements include wear metals, contaminants and oil additives.

Some elements fall into multiple categories. In order to pinpoint the source of the elements, all of the results need to be reviewed. It is generally limited to measuring particles in the 0-5 micron range (at most 8-12 microns).

Beyond this, test selection and test frequency need to be strategized with the lab—taking into account such factors as results that need further investigation, criticality, age, operating conditions, function and protocol specific to that type of machinery.

In the case of TestOil, anytime from the initial analysis that a machine condition is flagged as abnormal, an analytical ferrography is automatically performed. Kirkwood explains, "We feel that it is impossible to determine what is occurring inside the equipment and impeding its health without visually inspecting the wear particles present in an oil sample. Measurements, compounds, color microscopic photos and summaries from the analyst are provided as a part of this additional test."

BETTER SAMPLING PROCEDURES

Better sampling procedures are the result of better training, and many analysis labs offer training to customers either for

One of TestOil's lab technicians demonstrates the particle count test, which measures the amount of particulates in a fluid sample. Using the pore blockage method, the sample is passed through a calibrated screen. As particles collect on the screen, the amount of flow decreases. This decrease in flow is measured and the particle count result is obtained.

an additional fee or as a value-added service. If a customer has enough participants to fill a class, some analysis providers will teach lubrication fundaments and practices onsite. Other excellent sources of training are seminars, trade shows and conferences.

Ultimately, establishing sampling protocol is the customer's responsibility, but the lab can help by identifying logical equipment, specific tests and their frequency. In addition, the lab will provide the best procedures for taking and then accurately and completely labeling the sample. Label information should include anything out of the ordinary (such as topping off with a dissimilar fluid) that has occurred since the last sample.

Experts say that not choosing the right equipment and not sampling correctly are the two most common causes of fluid analysis program failure. Most samples are taken at a drain port, but since drain ports (and the drop-tube and vacuum pump method) are prone to producing contaminated samples, this location is not ideal. A better option is a dedicated simple-to-install sample valve that's free of contamination sources.

"The most common errors people make when collecting a sample are related to poor sample location, faulty collection methods and sample contamination," Kirkwood says. "A sampling location should be identified to allow for trouble-free, repetitive and representative sampling of the health of the equipment and the health of the lubricant. This location should allow the equipment to be tested under its typical operating condition while maintaining a safe sampling method for the technician.

"Lastly, it is important to ensure that the sample does not become contaminated during the sampling process," Kirkwood adds. "All of the sophisticated oil analysis tools, techniques and diagnostic processes are meaningless if the oil sample fails to effectively represent the actual condition of the oil in service."

The customer should send samples to the lab the same day they are collected. In fact, it's best to overnight or hand-deliver samples. Waiting longer affects the integrity of the sample and prevents prompt action on critical issues that the lab uncovers. Even labs that don't offer online access to reports should have the results to customers no more than 48 hours after they receive the samples.

"The two most common errors are picking a sample point that is not representative of the system, for example from bottom drain of reservoir, and not adequately flushing the sample point to pull *live* oil," says STLE-member Evan Zabawski, CLS, senior reliability specialist at Fluid Life in Edmonton, Alberta, Canada. "Improper sample location and/or flushing will skew the results to generally show higher wear and contamination. For example, sampling from drain tends to pull much of what has normally settled out of the oil that is not usually causing problems."

Zabawski further states some general rules of thumb for sample point selection:

1. For systems with lubricant piping: on or after an elbow to ensure turbulent flow homogenizes the fluid.
2. On return lines or after the return line header to assess the wear of the components.
3. When return lines are not available: after the pump and before the filter.
4. For filtered systems: on the inlet side of the filter represents a live area with turbulent flow.
5. For systems without piping, pump or filtration (e.g., gearboxes) that must be sampled through a drain port: use a sample port equipped with a pitot tube (bent if necessary) to reach a live area.

INTEGRATING WITH OTHER CONDITION MONITORING TECHNIQUES

For critical and expensive machinery, it makes sense to supplement oil analysis with the following complementary condition monitoring technologies:

- **Vibration Analysis.** Oil analysis and vibration analysis complement each other well; vibration analysis monitors and controls balance, looseness and alignment, while oil analysis monitors and controls lubricant quality and contamination.
- **Thermography.** This detects issues that oil analysis can't such as the degree of deposit buildup in tanks and the condition of couplings, rollers and high-speed bearings.
- **Ultrasound.** This complements vibration analysis well. Trending values will point to potential bearing defects caused by contact conditions such as rubbing and friction.

Newer test technologies include embedded sensors, motor current analysis and stress wave analysis.

"Vibration analysis, thermography, ultrasonics are all great additional tools, but we must not forget our five senses," says Evan Zabawski, CLS, senior reliability specialist at Fluid Life. "People who are familiar with an asset can tell if it feels too hot or is making more noise than usual, etc., and that can be an earlier indicator. When pulling a sample, noticing cloudiness, foam or separation reveals immediate information that doesn't need to wait for lab results to understand there is a problem."

BETTER REPORTS

Kirkwood explains, "A common issue that end-users have with reports is understanding and interpreting the reports they receive from their labs. Some reports are just difficult to read and interpreting the data becomes guesswork. Also, oftentimes the tests run are not appropriate for the oil in the equipment or aren't adequate to allow a complete assessment of the lube or machine."

Most labs make reports as easy to read as possible—but someone still needs to read them. Today, nearly all labs provide digital reports that are instantly available online. In addition, many labs now offer proprietary Web-based tools that let customers easily interpret and customize the information contained in their oil analysis reports. In addition to information on the oil's condition, digital reports allow users to review and compare past reports (trend analysis, the key to predictive maintenance) and create easy to interpret trend graphics.

STLE-member Eric Arnold, CLS/OMA/MLT II/MLA III, a field engineer at Castrol Heavy Duty Lubricants, explains, "The predictive component of condition monitoring is the ultimate goal. Individual oil samples give a snapshot of the condition at a given point in time. Trend analysis of consecutive samples of the same component over time gives indications of what's to come. On a larger scale, comparison of multiple 'similar' components also can highlight trends of commonalities between units, which can be of greater value to a predictive program."

The Karl Fischer test measures the amount of water contained in a sample. A portion of the sample is measured and introduced into the Karl Fischer titrator. Any water present in the sample will react with the Karl Fischer reagents. The amount of reagent needed to react with the water present is measured and used to calculate the amount of water present. Results are given in parts per million (ppm) or percent.

"Our reports are neat, clean and easy to read," Kirkwood says. "We also have the capability to display any corrective actions taken by the customer from previous samples. Looking at our report gives the customer a very clear and concise history of the problems and actions taken on that machine."

Arnold says, "Computer software has been the largest contributor here—the ability to analyze and distribute large amounts of data easily and quickly. There is also improved accuracy of oil sample input data like the use of oil sample labels generated online." In addition to Castrol's proprietary Labcheck software, Arnold says that other game-changers include mobile devices, more powerful computers and more capable data analysis software.

Zabawski says that trending based on comparison to other similar assets and previous samples is very powerful. ASTM D7669 and D7720 both offer useful guidelines for performing such analysis.[2] Fluid Life reports employ intuitive color-coded reporting of the data to highlight anomalies, coupled with dynamic inclusion of graphs using proprietary statistical comparison to other samples from similar make, model, oil and industry matches and statistical trending to identify both upward and downward deviations from historical results.

CUTTING-EDGE REPORT METHODOLOGIES

Most oil analysis providers have developed reporting methods that take advantage of the latest Web-based tools. Two of these providers are TestOil and Castrol.

TestOil developed DataSight,® a Web-based data-reporting application that allows its customers to track all aspects of their oil analysis program. Using DataSight, customers can analyze data and plot trend graphs, generate monthly management reports and more. TestOil also has devised a unique email-based notification system that communicates with customers as their samples flow through the lab. Customers are notified when the samples are received and again when the testing is completed. There are direct links built into the email that take the user directly into their DataSight account where they can begin analyzing the results and taking action.

Each TestOil report includes a color-coded assessment of both lubricant and machine condition prominently displayed in the top corner of the report and an area highlighting and clearly defining the specific anomalies the analysts found with the sample, along with recommendations and suggestions of potential actions to take. Each TestOil report also includes five columns of data representing the information it obtains from running a reference oil and a column showing the most current findings followed by data from the customer's last three samples. In addition, TestOil provides trend graphs on five of the most critical parameters.

The company also includes a second page of analytical ferrography analysis whenever there is a machine anomaly.

Castrol's *Labcheck* is a used oil analysis program that provides ongoing analysis of used oil samples and a full range of information that supports operations and maintenance decisions.

All information in the report is available for tracking and monitoring performance. Following the fourth routine sample, results are trended and available graphically for easier reference; trending specific parameters provides a better overview of system and/or machine performance. Technical recommendations are given whenever analysis results are outside the agreed limits. Customers have their choice of reporting methods—from traffic light warnings to straightforward data only and also their choice of download formats. Reports can be retrieved online as soon as the analysis is complete, and all reports (current and historical) are stored in a single, easily accessible location.

TestOil's DataSight® program management tool is a proprietary Web-based data-reporting application. As with similar Web-based reporting systems, it allows TestOil's customers to track all aspects of their oil analysis program online.

BETTER REPORT REVIEW

Most oil analysis reports have the same basic information. That information is usually qualified by observations, flags of problem areas and a summary. Oil analysts advise customers to read the entire report, rather than just the summary and flagged areas. There is always the possibility that the lab may have missed an outlier or sent a report by mistake that was created for another customer.

Also, some customers don't read reports promptly (or at all). This becomes obvious after a critical piece of equipment breaks down and management discovers the report predicting the failure was never read.

"End-users typically do not understand what the numbers represent, nor do they necessarily know what levels are normal and acceptable," Zabawski says, "I liken it to having your blood tested for iron the very first time and the doctor simply telling you it is 125. You would ask 125 what? What's the usual range, what's high, what's low?"

The majority of today's oil analysis reports are straightforward and easy to read and interpret. In addition, some labs offer formal training in report interpretation. Most labs are available for clarifications and recommendations during normal business hours.

But the responsibility for follow through rests squarely with the customer. STLE-member Michael Mayers, laboratory operations manager for Analysts, Inc. in Stafford, Texas, says, "In today's plant/shop environment, maintenance professionals are expected to do more with less. This applies to their use of oil analysis. Maintenance professionals have to review and react to oil sample reports, but often they fail to take it to the next step to identify patterns in the data to better predict failures in the future or recognize trends in equipment performance."

Zabawski adds, "Many customers don't read every report or all the information on the reports they do read. Their intimate knowledge of the equipment offers them a unique advantage over the laboratory interpretation. It is very much in their best interest to perform a secondary assessment of the data."

BETTER ROI

When companies commit to fluid analysis programs and abandon them in a few months because they aren't seeing the return on investment, the fault is often their own. "An oil sampling program where a customer is simply taking oil samples and not reviewing or learning from the data is of little value," Arnold says. "Used oil analysis is a process that when used correctly can yield tremendous results in terms of efficiency, uptime, reduced maintenance expense, etc. Much of this depends on what the customer's objectives are with the program at the onset. Used oil analysis programs should be measured against these objectives over time to ensure that value is being delivered."

Arnold adds that the oil analyst's experience and expertise are crucial for success. "Our greatest asset for providing value is our field engineering team, specifically their understanding of the customers and their equipment/industries combined with their expertise in used oil analysis," he says.

Following is an excerpt from an oil analysis business case that WearCheck lays out in its report, "Maximizing the Value of Your Oil Analysis Program."[3]

> *In a typical oil analysis program, roughly 80 percent of sample results are normal, 15 percent are abnormal, and 5 percent are critical. The largest return on investment from your oil analysis program comes from averting machinery failure in the critical 5 percent of instances. To realize these returns, it is incumbent on the reliability and maintenance departments to ensure that appropriate maintenance activities are carried out based on the oil analysis recommendations. A good oil analysis program demonstrates an obvious return on investment in the following ways: it optimizes drain intervals; it supports service/warranty claims; it minimizes unscheduled downtime; it extends equipment life; it improves equipment reliability; it reduces maintenance costs.*

"Ultimately, the success of a program comes down to the dedication and drive of those in charge of running the program and the communication they have with their lab," Kirkwood says. "A lab has to be much more than a source to get data. They have to be responsive to the customer's needs and answer questions immediately. They need to give customers the confidence that they are working as a partner to help solve pressing machine issues, that they have someone to talk to who can help interpret a report that they might not understand." TLT

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PREDICTIVE AND PREVENTATIVE MAINTENANCE

Predictive and preventive maintenance are not the same. Preventive maintenance is scheduled based on a predetermined protocol, while predictive maintenance is scheduled based on the condition of the equipment trended over time. While the two types of maintenance are different, they have the following three goals in common:

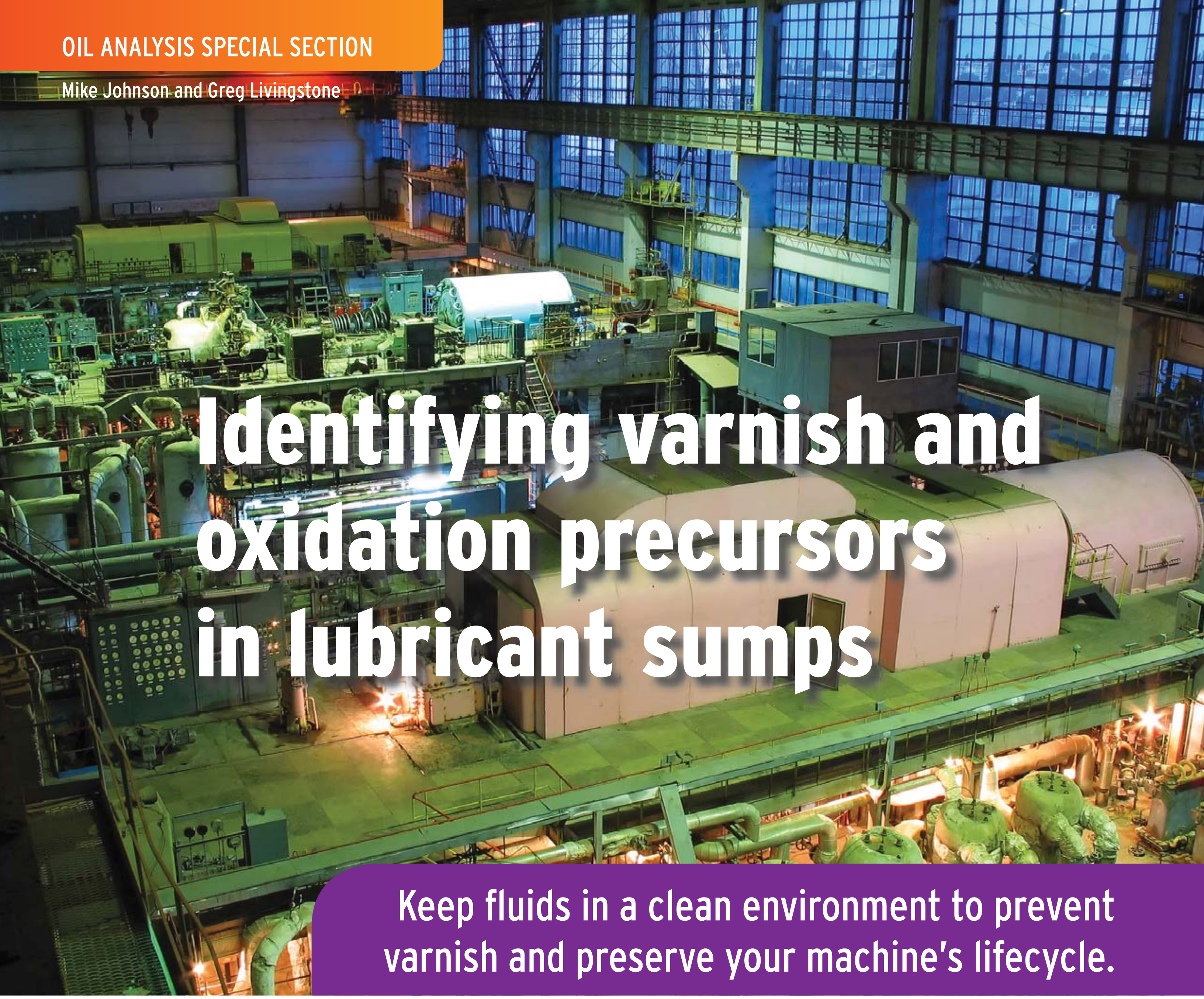
1. To maintain the equipment in the best operating condition.
2. To reduce unscheduled downtime as much as possible.
3. To perform all work on a regular schedule.

'The program's success comes down to the dedication of those in charge of running the program and the communication they have with their lab.'

REFERENCES

1. Failure Mode, Effects, and Criticality Analysis, performed at either the functional or part level, is used to chart the probability of failure modes against the severity of their consequences.
2. ASTM Standard D7669 (2011), "Standard Guide for Practical Lubricant Condition Data Trend Analysis," ASTM International, West Conshohocken, Pa., DOI: 10.1520/D7669-11, **www.astm.org**. ASTM Standard D7720 (2011), "Standard Guide for Statistically Evaluating Measure and Alarm Limits when Using Oil Analysis to Monitor Equipment and Oil for Fitness and Contamination," ASTM International, West Conshohocken, Pa., DOI: 10.1520/D7720-11, **www.astm.org**. An example of such a report is attached, see second page for example of the statistical analysis and trending.
3. From: **http://www.wearcheck.com/literature/brochures/WC-OA-PROGRAM-SETUP.pdf.**

Mike Johnson and Greg Livingstone



Identifying varnish and oxidation precursors in lubricant sumps

Keep fluids in a clean environment to prevent varnish and preserve your machine's lifecycle.

> **KEY CONCEPTS**
>
> - Varnish in lubricant and circulation systems can harm your machines and reduce productivity in a variety of ways.
> - Controlling varnish formation starts with maintaining contaminants and sump conditions.
> - The risk and presence of varnish can be measured either directly or indirectly.

One of the primary failure modes for lubricants and hydraulic fluids serving in thermo-oxidative (high-temperature, high-degradation) environments is the production of deposits commonly referred to as varnish. The impact that varnish deposits have on the lubrication system is application specific and, in most cases, can be harmful to your machines and reduce productivity.

In the case of hydraulic plastic-injection molding machines, varnish can cause erratic valve movements that lead to scrap rate increases and yield decreases. In a paper machine, deposits such as those seen in Figure 1 can compromise the precision of the press-roll control, impacting paper finish and quality which then impacts the paper's market value.

The highest-profile varnish problems, however, are found in large-frame gas turbines used in the power generation industry. Even a small amount of varnish may impact the availability and reliability of a power plant, and the

Figure 1 | **Deposits in a sensitive paper machine can impact the quality of the finished paper product.**

cost of a varnish-induced event is very high. If a peaking turbine is not able to start due to a sticky servo value when the grid demands power (often called a fail-to-start condition), the plant incurs significant costs. If the turbine is firing at full load and is tripped due to an alarm caused by a sticking valve, the costs can easily exceed $100,000.

Varnish can even negatively impact the many low-criticality support systems that represent 80 percent of a plant site's machine complement. For instance, a thin layer of varnish on plain and element bearings, as shown in Figure 2, can act as an insulator, preventing the lubricant from adequately cooling the bearing surface, which can trigger alarms. Varnish deposits on gears and element bearings attract dirt and debris like flypaper, increasing the rate of abrasive and fatigue wear to the gear teeth, races and elements. In some lubricant systems, varnish first develops in the reservoir. If it doesn't spread to other critically lubricated components within the system, it poses little reliability risk to the machine but can increase the rate of degradation of the oil each time the sump is changed.

For these and many other reasons, it is particularly important for the reliability engineer to be aware of the risk and have a method in place to accurately measure the presence of the precursors to oxidation byproducts that lead to formation of both soluble and insoluble contaminants, which can produce visible varnish and other oxidation byproducts. This article examines what varnish is, what causes it and how to measure the precursors of the condition.

VARNISH CONTAMINATION

Varnish is typically defined as a thin deposit in a lubrication system that is difficult to remove and comprised primarily of organic residue. It is created by chemical reactions within the lubricant that fall under the general heading of oxidation. Lubricants that are formulated for use in thermally stressful environments contain additives called antioxidants whose purpose is to slow down chemical reactions that produce the organic residue.

These antioxidant molecules are more reactive species than the base oil and, therefore, sacrificially degrade in an effort to protect the base oil. It is not surprising when doing chemical analysis of varnish deposits in a system to find that their main composition is degraded antioxidants, which have reacted with base oil components. Antioxidants are divided into primary and secondary classes.

Primary antioxidants such as amines and phenols will, upon depletion, form organic byproducts whose solubility depends upon temperature and pressure. The temperature at which these contaminants dissolve in oil is usually between 40 C and 55 C.

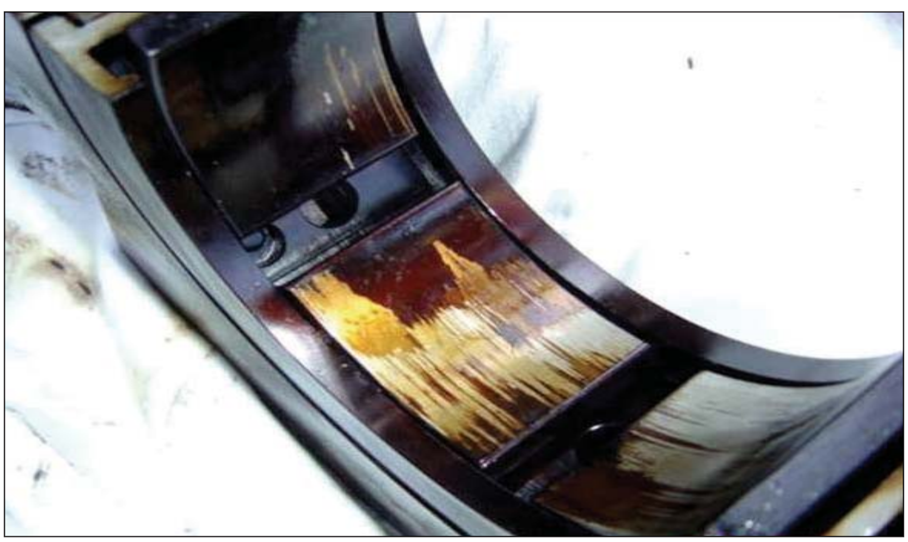


Figure 2 | **Deposits on tilt bearing pads in a steam turbine.**

There may be a wide range of contaminant chemistries present in one oil system, depending upon the temperature and mode of degradation. Each degradation product may have different solubility characteristics and may precipitate out of the fluid at different rates.

The fluid in Figures 3 and 4 contains an example of a varnish product that is insoluble at low temperature (*see Figure 3*), but becomes part of solution at a moderate temperature (*see Figure 4*). In most cases, the degradation products come out of solution at room temperature over 72 to 96 hours. However, it may take a week or more for the contaminants to precipitate out. Clearly, testing for these organic varnish precursors is more challenging than their inorganic cousins.

Many hydraulic formulations utilize secondary antioxidants such as zinc dialkyl dithiophosphate (ZnDDP). Upon depletion, ZnDDP forms sulfates and phosphates, which are often insoluble in the oil. In many respects, insoluble degradation products are easier to measure as these products do not transition in and out of solution.

Figure 3 | **At room temperature, this degraded oil is cloudy due to a high amount of soft contaminants.** *(Courtesy of Ansaldo Thomassen, The Netherlands)*

Figure 4 | **At 50 C, the oil instantly becomes clear and bright as the degradation products solubilize.** *(Courtesy of Ansaldo Thomassen, The Netherlands)*

The highest-profile varnish problems are found in large-frame gas turbines in the power generation industry.

CAUSES

In short review, there are various stresses in a lubricating system that causes the fluid to break down. Oxidation is the primary reason for lubricant failure in most systems. Oxidation's destructive rate on the lubricant is accelerated by temperature and various metallic components and gaseous catalysts. Depending upon the environment of the system, several other degradation regimes may be present such as:

- UV radiation
- Radiological contamination
- Reactions with incompatible chemistries
    a. Water may cause hydrolysis
    b. Wear metals accelerate reactions
    c. Additive or Base oil incompatibilities
    d. Compressor gases.

There are also thermal events that can occur in the oil and cause the fluid to break down, resulting in varnish creation. Electrostatic spark discharge is a phenomenon whereby static electricity is accumulated as rapidly flowing, nonconductive lubricants are passed through very small spaces until the energy is released in the form of a spark. This mode of degradation has been shown to be a primary cause of fluid degradation in some systems.

Additionally, hot spots in the system also can cause coking and thermally attack the hydrocarbon backbone of the lubricant. Micro-dieseling is also a common cause of thermal degradation in hydraulic and some lubricating systems. The implosion of air bubbles as they migrate from low-pressure zones to high-pressure zones creates carbonaceous byproducts. As system pressures increase, the potential for micro-dieseling also increases.

SOFT CONTAMINANTS

Performing oil analysis tests to determine the presence of varnish in a system is challenging for a few reasons. The sample of oil that is obtained for analysis may not be indicative of the condition of the lubricating system. If the lubricant in a heavily varnished system is changed without performing a flush to remove the deposits, the new oil may initially indicate a low varnish potential, even though there are deposits throughout the system.

Often in peaking or cycling gas turbines, the varnish potential will increase during times of the year of high demand and decrease when the unit is offline for several weeks. This is due to the degradation products coming out of solution in the oil and forming deposits throughout the lubricant system.

The lubricant degradation products (soft contaminants) responsible for causing varnish deposits can be challenging to measure. They are very small and often estimated at less than 0.1 μm in size, although they can easily agglomerate together. Soft contaminants are soluble and easily transition in and out of solution, depending upon temperature and pressure. Current testing methodologies only measure soft contaminants when they are in suspension, so sample handling prior to testing impacts results. While the soft contaminants are in solution, they don't typically impact the bulk chemistry of the fluid. This makes soft contaminants difficult to measure.

Most routine analytical tests are not successful in measuring the onset of varnish or the varnish potential of a lubricant. Fortunately, there have been several testing advancements in recent years that provide much more effective identification of underlying issues.

The first step in determining the potential to produce varnish is to understand its overall health and remaining vitality. This is influenced by a variety of things, as mentioned above, but the fluid's antioxidant system health and strength (concentration) is paramount. The best way of determining the antioxidant's remaining health, and consequently the fluid's remaining useful life, can be done both directly and indirectly.

Direct methods are preferable, as the test results are not influenced by other components in the fluid. A technique called Linear Sweep Voltammetry (aka RULER) measurement identifies the antioxidant type and measures the quantity of additive present. The results are typically reported as a percentage of new oil and separated by antioxidant family.

An example can be seen in Table 1. This example indicates that the used oil contains 23 percent phenols and 56 percent amines (red line) of the original sample (blue line). Another effective method for measuring a fluid's antioxidants is Fourier Transform Infrared (FTIR) analysis. This method is excellent at monitoring phenolic chemistries, though the amines are often masked by other additive components in the formulation, making them more challenging to detect.

Indirect antioxidant measurement is measuring the effect of the health and concentration of the antioxidants in the subject fluid versus the same fluid in its original state. There are a few accelerated oxidation tests that are commonly used to indirectly measure antioxidants such as Rotating Pressure Vessel Oxidation Test (RPVOT) and Pressurized Differential Scanning Calorimetry (PDSC). Because these tests are influenced by other lubricant components, their results may not directly relate to the health of the antioxidant system. For example, copper passivators can neutralize the catalytic effect of the copper coil used in RPVOT testing, increasing the time it takes for the fluid to fail. The stability of the original basestock also provides influence.

There are other physical and chemical property measurements that may be useful in assessing the overall health of the fluid such as the fluid's ability to handle contamination. In addition, how a fluid reacts with air or water also indicates something about the health of the fluid. When additive health is lost and/or the fluid has been cross-contaminated with incompatible chemistries (from other lubricants, water treatment chemicals or process chemicals), one of the first performance criteria that fails is demulsi-

The first step in determining the potential to produce varnish is to understand its overall health and remaining vitality.

Table 1 | Example of analytical results from the RULER, which indicate the antioxidant health of the lubricant.

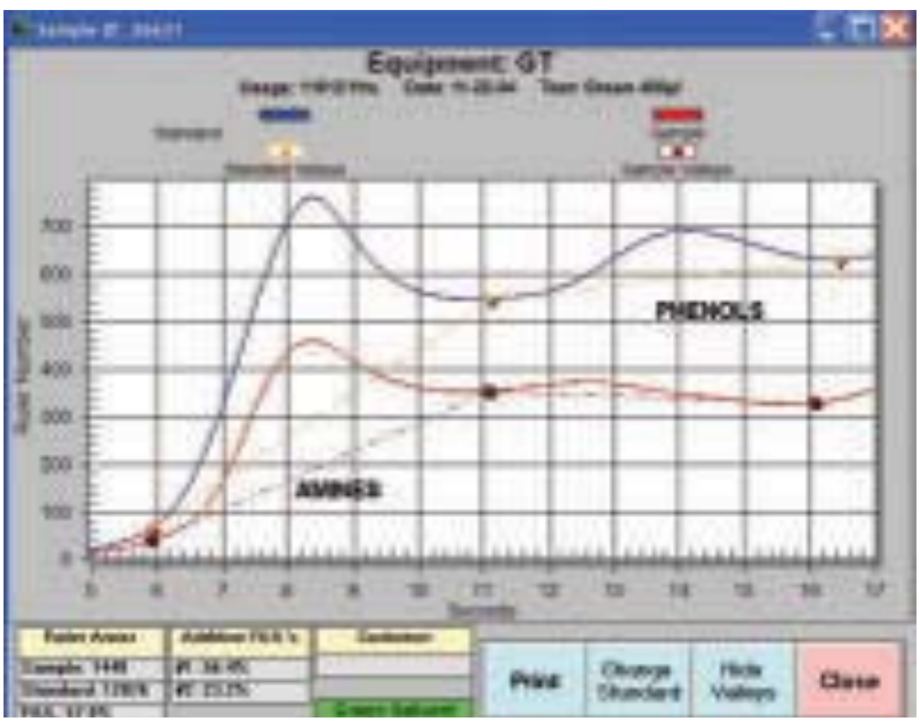


Figure 5 | Portable Kit for Membrane Patch Analysis.

bility (ASTM D1401). Foam (ASTM D892) and air release (ASTM D3427) characteristics also change for similar reasons.

When compared to performance of the new fluid, each of these characteristics can indicate that some type of damaging change has occurred in the fluid. Since chemical incompatibility can be a cause of degradation products and varnish, these are important characteristics to know about the lubricant.

Profiling the amount of contamination in the fluid by particle counting, water and spectrographic analysis is also of value. However, one common measure, TAN (Total Acid Number), which has been a widely used fluid degradation test for decades, provides less value in many fluids today since degradation products may occur long before a change in TAN.

Once the overall health of the fluid is determined, measuring the amount of soft contaminants is the next step in determining a fluid's propensity to produce deposits. The Membrane Patch Colorimetry test, as shown in Figure 5, is the most widely used test for this purpose. The MPC method is quite simple as 50 milliliters of oil are mixed with 50 milliliters of solvent (usually petroleum ether) and filtered through a 0.45 mm nitrocellulose patch. The color of the patch is determined by spectrophotometer, and the results are reported in CIE LAB DE value, representing the total amount of color on the patch. In general, the darker the color stain on the patch, the higher the fluid's varnish potential.

This technique requires that the sample remain idle for up to a week at room temperature, prior to analyzing to ensure the soft contaminants have come out of solution. There is good correlation between the readings and actual field varnish issues, but interpretation is sometimes challenging.

Different degradation products may generate different color bodies. In rare cases, a fluid's degradation products may be white, which renders the MPC test incapable of adequately predicting the fluid's varnish potential. Conversely, sometimes there are very low or virtually no deposits in the oil, and the patch still produces a stain.

Anytime one is taking measurements for the purpose of machine health diagnosis, it is advisable to have additional corroborating test data. In this instance, the gravimetric patch augments the MPC test effectively. Most importantly, one needs to understand what the analytical test is measuring and how those results may or may not relate to the specific application in question.

SUMMARY

Varnish is commonly considered to be a thin deposit in a system composed of organic material from the decomposition of the lubricant. It can also be of a soluble variety, which is difficult to identify and remove. As such, maintaining fluid in a clean, dry and cool environment and without chemical contamination is key to avoiding varnish and preserving machine and fluid lifecycles. Fluid analysis to identify the presence of either varnish or the precursor conditions that lead to varnish can be done both directly and indirectly. Varnish presence may be directly measured through photometric techniques such as the Membrane Patch Colorimetry, which is useful for this purpose.

The precursors of varnish complications are conducted by measuring for fluid heath properties for antioxidant presence both directly and indirectly. These techniques each have strengths but should be corroborated with other methods where possible. TLT

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Stacy Heston

Managing a lubricant changeover

KEY CONCEPTS

- If improperly managed, changing suppliers can wreak havoc on a stable lubrication and oil analysis program.
- When switching lubricants, be aware that there is a difference between *comparable* products and *compatible* products.
- The oil analysis laboratory should be notified about the status of the conversion for each individual component.

Start small, control product compatibility and establish a timeline with proper documentation.

FROM TIME TO TIME, COMPANIES WILL MAKE EXECUTIVE DECISIONS to change lubricant suppliers. These changeovers can wreak havoc on a stable lubrication and oil analysis program. It is important to have a plan of action in place with a focus on steps and considerations from an operations perspective, as well as the inclusion of the oil analysis laboratory. This would include considerations of the component sump size, criticality and component inclusion in an oil analysis program.

When establishing the specific product to change over to, each component's lubricant requirement should be evaluated to determine if the proposed lubricant meets each component's needs. A one-to-one lubricant conversion is not advisable, as one manufacturer's product might currently meet all needs and required specifications while the comparable and compatible manufacturer's product does not. The current component grouping for lubricant application may be met by the current product, but the proposed products may require a shift in the component

Figure 1 | **Component Lubricants**

Current Lubricant A	Current Lubricant B	Current Lubricant C
Component 1	Component 10	Component 20
Component 2	Component 11	Component 21
Component 3	Component 12	Component 22
Component 4	Component 13	Component 23
Component 5	Component 14	Component 24

Proposed lubricants are demonstrated through color-coding. This evaluation should follow industry standards for the determination of lubricant requirements, which includes looking at operating speeds, temperatures, contamination, vibration, load, etc.

grouping to ensure adequate lubricant properties.

With the introduction of new lubricants on site, it is vital to understand the difference between *comparable* products and *compatible* products and identify which type these new products will be. Changeover to products that are compatible requires less management with regard to mixing but can affect oil analysis results unless the changeover is communicated to the oil analysis laboratory. For lubricants that are comparable and not compatible, the management of the changeover must be more vigilant to ensure the new and old lubricants are not mixed and that changeover occurs at an optimum time.

Comparable products are likened to one another and share similar characteristics, allowing use in components of similar make, model and application. Compatible products do not necessarily need to be comparable because compatibility relates more to the lubricant chemistry. Compatible lubricants can exist or occur together without conflict of the base oil and additive package. Knowing the compatibility of the new lubricants with existing lubricants will affect the specific tasks and procedures utilized for changing the lubricant in a component. It also will affect the steps required for managing the overall changeover, the inventory levels and packaging requirements.

Once the lubricant requirements are established, the proposed lubricant changes should be documented, and the current and proposed lubricant should be reviewed for compatibility. Additional information—such as component manufacturer and model, sump size and current and proposed lubricant cost per gallon—also should be compiled.

As stated earlier, converting to a non-compatible product requires additional steps to avoid component and lubricant failure. In Figure 2, components 10, 11 and 20-24 have a proposed lubricant that is not compatible with the current lubricant. Before the new lubricant can be introduced for these components, a full oil drain and flush of the component needs to be completed to ensure no residue remains. Depending on the lubricant base oil and additive packages, incompatible residue can have detrimental effects to the new lubricating properties. In some cases, there can be additive film interference where the residual additive film remains in place and is slowly overtaken by the new additive film. In extreme cases, where ester and mineral base oils are converted, the residue can react to such an extent that the oil forms a gel in the sump. Lubricant compatibility should be verified and acknowledged by the new lubricant supplier.

For small sumps, converting incompatible lubricants is a simple and inexpensive task. During the next scheduled oil change, a sump is easily drained, flushed and topped up with the new oil. Once this conversion is complete, CMMS information, lubricant identification tags and other documentation should be updated to reflect

Component	Current Lubricant	Proposed Lubricant	Sump Size (gallons)	Compatible (Y/N)
1	A	Red	1	Y
2	A	Blue	1	Y
3	A	Blue	10	Y
4	A	Blue	10	Y
5	A	Blue	10	Y
10	B	Red	1	N
11	B	Blue	25	N
12	B	Green	10	Y
13	B	Green	5	Y
14	B	Green	5	Y
20	C	Red	50	N
21	C	Red	50	N
22	C	Green	500	N
23	C	Green	500	N
24	C	Green	500	N

Figure 2 | **Current and Proposed Lubricants** that the component is now using the new lubricant. Documentation should not be updated until the conversion is complete.

With larger sumps, such as components 22, 23 or 24, the cost of converting the sump is higher. If a supplier agreement has been made at the corporate or plant level, does it allow for using a different supplier for specialized applications, or is the agreement rigid enough to require the use of a supplier equivalent? If the supplier agreement allows for the use of non-supplier lubricants, maintaining the current lubricant is most likely the best course of action, assuming the current lubricant meets the required lubricant specifications.

If the current lubricant is not up to par, conversion to the proposed lubricant is necessary. There are a few different approaches that can be utilized to convert the lubricant, and the chosen approach is dependent on how the plant operates and what the overall goal is. The first approach, and possibly most costly, is to simply set a date to drain, flush and top up with the new oil. This approach is beneficial if there is a stringent timeline for converting all assets to the new lubricants. Manpower availability also should be looked at to ensure properly trained lubrication technicians are available to perform the conversion within the specified timelines.

A second approach for converting large sumps looks to maximize the usage of the current oil through the monitoring of the lubricant properties. If the timeline for conversion for the larger quantity components allows for the lubricant's remaining useful life to be consumed, the state of the lubricant properties (oxidation, neutralization number, viscosity, etc.) should be used to determine when the oil is ready to be converted. This approach could extend a conversion timeline to multiple years if other lubrication maintenance tasks are performed.

For components being converted to a comparable and compatible lubricant, a full oil drain, flush and top up may not be required. These components would be topped up on a normal inspection interval with the new lubricant until an oil change occurs. For smaller components with set oil drain intervals, there will be a time that the two lubricants must coexist until the drain occurs. For larger sumps subject to oil analysis, a set oil drain does not exist. The two lubricants would presumably have to coexist for a longer period until such time the oil analysis results dictate the need for an oil change.

Introducing one new lubricant at a time focuses attention on a core group of components and minimizes confusion.

EFFECTS ON OIL ANALYSIS

Mixing the lubricants in a sampled component can wreak havoc on an oil analysis program. It is critical that the addition of the new lubricant to a component be documented within the CMMS, work order, lubricant listings, etc. In addition, the oil analysis laboratory should be notified about the status of the conversion for each individual component (full change to new product, mixed). Typically this information can be provided on the sample label.

When an oil laboratory receives a sample, the workers there do not know what is taking place at the site level. They know as much as what is on the sample label and in the laboratory information management system. Once test results are complete, the documentation on lubrication will affect any subsequent recommendations. If a full lubricant changeover is completed without notifying the laboratory, inaccurate recommendations will result due to a shift in the lubricant characteristics (*see Figure 3*).

These lubricants share similar operational characteristics as described on their product data sheets and might or might not be compatible. However, it is important to note the differences between the two. These results are indicative of some of the viscosity grade, additive package and neutralization number and are generally constant results for a lubricant. A shift in these results would be reason to flag an oil analysis result and recommend corrective action without knowledge of a lubricant changeover. If Lubricant A were to be topped off with Lubricant B, the results would start to show an increase in phosphorus and zinc with specific results dependent on the ratio of Lubricant A to B.

THE NEW INVENTORY

Once the approach to lubricant changeover has been established, the issue of inventory needs to be addressed. The proposed lubricant list by components needs to be finalized and updated to reflect any changeover issues that have been addressed such as continued use of current lubricant. With the finalized lubricant assignments in place, the new inventory levels need to be determined. Rule of thumb varies from 5-10 percent of total machine charge as a starting point to the use of current consumption rates. However, consumption rates may not be readily available if there is a significant shift in the number of lubricants required, as well as the ratio of lubricant usage.

As the current lubricants are phased out, the new lubricants will be phased in and each lubricant will require its own storage space or tank. If bulk storage is in use, it is recommended that the current and new lubricants not be mixed. This might require temporary use of drum storage or other packaging types until the bulk lubricant has been completely consumed. At that time, the bulk storage tanks should be flushed using the same procedure as any component to ensure that residual lubricant does not remain.

For instances where prepackaged quantities (five-gallon pails, quarts, etc.) are in use, the additional purchase of current lubricants should cease, and the possibility of returning unused lubricants should be investigated. In some cases, suppliers might offer to buy back lubricants but could require the payment of a restock fee. Regardless, any outstanding stock of current lubricants should be consumed.

DEVISING A TIMELINE

As with any lubrication program, a key goal is minimizing the number of lubricants on site. Therefore, during a lubricant changeover, a short timeline is a key goal. When determining a timeline, the total number of lubricated components should be considered and a breakdown by lubricant performed. Introducing one new lubricant at a time focuses attention on a core group of components, minimizes confusion brought on by major implementations and reduces the total number of lubricants handled on site.

The key to lubricant changeover is to start small: Which lubricant change affects the least number of components? A successful changeover of a small number of components that are not included in the oil analysis program allows for the development of changeover management and increases the confidence level of all personnel affected by this type of implementation. Once one lubricant has been successfully introduced and changeover started, additional lubricants can be brought on as necessary.

A timeline for changeover should not exceed the one-year mark unless the components are of a large sump volume or part of the oil analysis program. The changeover should begin with a specific component type, size and lubricant requirement. Once complete, the next component type or size should be converted until the new lubricant is implemented; then repeat this implementation with the next grouping until the new lubricant product has been implemented for all affected components. After the completion of one lubricant, the next lubricant for changeover should be selected.

Characteristic	Lubricant A	Lubricant B
Viscosity @ 40 C	333.3	305.7
Magnesium	0	0
Calcium	0	103
Phosphorus	180	390
Zinc	1	519
TAN	0.54	0.92

Figure 3 | **Comparing Lubricant Characteristics**

It is not necessary to convert only one lubricant at a time if a lubricant program is well structured and managed. However, an implementation plan needs to be clearly established and documented to act as the road map.

Changing oil is a time-consuming task. With variation in component sump sizing, variation in the time requirement per oil drain also should be accounted for. During the first round of changeovers, as mentioned in the previous paragraphs, the relationship between the sump volume and time required to complete the drain, flush and top up should be documented so time projections are established for future changeovers.

For example, if a 10-gallon component requires 60 minutes, then it is extrapolated to be six minutes per gallon. A 50-gallon sump might require five hours to complete a changeover. Calculating an average time for multiple components yields a more accurate time per gallon result. Having a labor time associated with each component and subsequent asset or lubricant type aids in scheduling and timeline development.

CONCLUSION

To summarize, the required steps start with a review of lubricant requirements for each component. Avoid converting lubricants based on the lubricant in use. Lubricant suppliers should verify compatibility of proposed lubricants with current lubricants, and steps should be taken to avoid mixing incompatible products. For small-volume components, the set oil drain interval should be followed for conversion. For large-volume components, oil analysis should be utilized to determine when to convert the oil in order to maximize the oil life.

As analyzed components are converted, the oil laboratory should be notified to ensure data interpretation reflects acknowledgement of these changes. Inventory level modification should be implemented to reflect a decrease in current lubricants and increase in proposed lubricant while maintaining a first-in, first-out rotation. Timeline and scheduling should be managed within parameters prescribed by site management while following general guidelines to avoid possible cross contamination and documentation errors. TLT

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Jeanna Van Rensselar / Contributing Editor

VIBRATION ANALYSIS:

The other half of the equation

KEY CONCEPTS

- The premise behind vibration analysis is that specific mechanical defects produce characteristic vibrations at different frequencies.
- Vibration analysis is an excellent complement to oil analysis in some applications.
- The need for integrated monitoring depends on the applicability of the procedures and the importance of the equipment.

This proven condition monitoring method is an excellent complement to oil analysis in many applications.

It's intuitive—if something is obviously wobbling and vibrating that's not supposed to, it's not good. This applies to $300 washing machines and $25 million oil rigs.

Every aspect of highly engineered equipment is perfectly balanced and meant to stay that way for a long time. The slightest new vibration is an early warning that something is out of sync and is likely to get worse. While factory workers have known this for two centuries, until the advent of sophisticated vibration analysis, by the time you could see or hear something vibrating it was too late.

Today, most enlightened organizations have a proactive maintenance program in place—monitoring the condition of the equipment well before failure. Oil analysis is one of two major analysis methods, vibration analysis is the other.

In addition to wasting energy and, in the extreme, wearing on the nerves of everyone who has to listen to it for 40-plus hours a week, unusual machine vibration usually indicates impending failure (most vibrations in rotating machinery are caused by either imbalances in the rotating parts, poorly meshing gear teeth or uneven friction).

As oil analysts know, most carefully monitored machines don't suddenly fail. Well before failure there are anomalies or ominous trends in oil analysis reports. For vibration analysts, those warnings are an increase in the level of vibration at a particular location.

In the same way that oil analysis picks up the presence of particles too small to see with the naked eye, vibration analysis picks up increases in vibration levels that are too slight for the ear to detect or the hand to feel. By monitoring, measuring and analyzing those vibrations, users can often pinpoint the exact cause of the problem and correct it before real damage occurs.

Vibration analysis and oil analysis are rarely performed together, but experts say there are definite benefits to doing so in some applications—like gearboxes, reciprocating combustion engines and hydraulic systems where they create a very accurate and complete picture of equipment health.

Like oil analysis, vibration analysis allows users to evaluate equipment condition and (it is hoped) avoid failure. The sooner the problem is detected and fixed, the less expensive it is to repair.

VIBRATION ANALYSIS

The idea behind vibration analysis is that each piece of equipment has its own unique vibration signature. Once that signature is established, any variation is cause for concern. Mechanical defects produce characteristic vibrations at different frequencies. Specific vibrations relate to specific machine fault conditions. For example, when bearings and components reach the end of their lifecycles, they begin to vibrate more dramatically and distinctly. By using signal-processing technology to analyze the time and frequency spectrums, monitoring equipment can identify the defect and natural frequencies of targeted structural components.

Rotating structures are prime candidates for vibration analysis with their constant but arbitrary velocity in elements such as rotor shafts and propeller blades (wind turbines and helicopters). Most rotating machine failures are rooted in imbalances. The center of mass is not in sync with the center of rotation, which is especially rough on the bearings that are critical to the smooth operation and longevity of equipment.

The idea behind vibration analysis is that each piece of equipment has its own unique vibration signature.

Vibration analysis is also excellent for diagnosing the condition of complex machinery such as multistage gearboxes, turbine/generators and AC and DC motors. On the other hand, there are a number of machines that can't be adequately analyzed with vibration monitoring alone, these include diesel engines, piston type hydraulic pumps and reciprocating air compressors.

Bill Marscher is president and technical director of Mechanical Solutions, Inc., in Whippany, N.J., and also a past president of STLE and an STLE Fellow. He says, "Because they want to get very early warning of impending reliability problems—and vibration analysis typically does this best—the refinery/petrochemical, power generation and water/wastewater industries often rely more on vibration analysis than they do on oil analysis."

There are two types of vibration. Free vibration occurs when movement in a mechanical system is initiated by an outside force. The mechanical system vibrates freely for a time but then invariably stops. Forced vibration occurs when an irregular force impacts a mechanical system—most often creating an imbalance. The frequency of the vibration and the frequency of the applied force are the same, but the magnitude depends on the structure of the mechanical system.

One of the advantages of vibration analysis is the ability to stave off damage by predicting when a specific type of vibration will occur before the fact and letting users know how to prevent it from happening. For very expensive pieces of equipment, the cost savings of this analysis methodology are significant.

TEST OPTIONS

Vibration analysis used to be as primitive as dialing an instrument to identify frequencies where vibration was prominent. All the user had to do was compare peak frequencies with operating speed. The final step was consulting the manufacturer's chart for possible causes. While this method left a lot of room for error and interpretation, it created a close link between the user and the equipment—allowing experienced users to sense exactly what was amiss without looking at the chart.

The current generation of vibration analysis equipment and software predict developing problems with remarkably accuracy. In fact, this equipment can display a full spectrum of vibration across three axes at once. But as with oil analysis, the plethora of cutting-edge software-based capabilities and features still require a basic understanding of vibration analysis to reap the full benefits.

The core tool for analyzing vibrations is the FFT (Fast Fournier Transformation) spectrum analyzer, which was developed in the mid-1970s. This tool samples the input signal, computes the magnitude of its sine and cosine parameters and then displays the spectrum of these measured frequency components. The primary advantage over analog spectrum analyzers is speed—up to several hundred times faster.

In the early 1980s, FFT spectrum analyzers became available in portable, handheld versions. Paired with software for condition monitoring data collecting and analysis, these were very powerful tools. Not surprisingly, the number of companies instituting vibration analysis to diagnose areas like imbalances, misalignments and bearing defects grew exponentially. These FFT analyzers continue to evolve, detecting peaks at higher and higher frequencies.

As vibration analysis becomes more sophisticated and training thus becomes more complex, organizations too small to justify the cost of in-house equipment and staff training opt to outsource vibration monitoring, analysis and reporting.

Some vibration analysis companies, like Marscher's, perform on-site detailed vibration analysis of high-value rotating machinery—a very valuable service for many customers.

Choosing machinery to monitor: The Criticality Index

The Criticality Index determines the logical extent of condition monitoring required for a piece of equipment. It takes into account such factors as:

- The importance of the machine's function.
- Whether or not there is another piece of equipment that can take over the function if that piece of machinery fails.
- The overall impact of downtime.
- The projected repair cost.

This index assigns all machines to one of the following three categories:

1. **Critical Machinery:** These are machines that are so important that the rest of the operating environment can't function without them, i.e., power plant turbines. Equipment in this category requires complete online and (where possible) inline condition monitoring, regardless of cost. The specifics of monitoring are often included in insurance policies and warranties. These pieces of equipment are prime candidates for predictive maintenance.

2. **Essential Machinery:** This equipment is key to the operating environment, but its failure does not cripple operations. Sometimes equipment that falls in this category would be considered critical if not for the fact that a backup piece of equipment is readily available. While testing is not as important as it is with critical machinery, it is recommended to circumvent costly repairs and inconvenience.

3. **General Purpose Machinery:** The balance of operations equipment is in this category. These machines are usually monitored informally and periodically.

One of Marscher's customers in Trinidad had a steam turbine that was making an alarming noise with associated shaking about every 10 minutes. To simply shut down and disassemble the turbine to determine the root cause would have taken several weeks at a cost of $250,000 per day, Marscher figures. Detailed vibration analysis was able to determine exactly what the internal problem was and provide the basis for a confident recommendation that continued operation until the plant's scheduled turnaround would not result in machinery failure. Because of this, the plant was able to continue operation during its high-production period and save about $8 million, Marscher explains.

Vibration analysis picks up increases in vibration levels that are too slight for the ear to detect or the hand to feel.

DATA COLLECTION AND INTERPRETATION

A complete vibration analysis requires a full-spectrum vibration profile on horizontal, vertical and axial axes—on both ends of the motor and the full piece of equipment. Some problems only show up on one axis. If maintenance workers take a reading on only one axis (as they often do) they'll miss a pending failure on another axis.

Since not all equipment operates at the same speed, looking at the vibration signature in relation to multiples of the rotating speed will simplify analysis. Rotor imbalance, for instance, usually shows up at rotating speed; while mechanical problems—such as a bent shaft, a bad coupling or an oversized bearing housing—tend to appear at 2x rpm.[1]

Vibration frequencies at higher multiples of the rotating speed correspond with the number of components in a specific rotating part, such as the number of balls in a bearing.

Vibration needs to be examined when the natural frequency of the entire assembly suddenly becomes close to the vibrating frequency of one part. This is most likely to occur when a new part with slightly different dimensions than the part it's replacing is installed. Other causes of a frequency change are early structural damage or failure.

Variable-frequency drives make interpreting data more difficult, since inverter-driven induction motors tend to operate significantly below the manufacturer's recommended speed. Frequency variation also makes electrical problems more difficult to diagnose.

Since concrete is prone to deterioration (especially when it's exposed to outdoor extremes), a defective foundation should always be one of the first considerations. Axis-specific problems caused by a problem related to the machinery's base are indicated by a high vertical reading. This may signify loose base-bolts, a loose structure or a separating sole plate. High horizontal readings are commonly associated with imbalance in the rotating elements.

High axial readings generally indicate misalignment. The cause may be external, like coupling misalignment, or internal, like a bent shaft. Looseness may be caused by a worn coupling, an oversized bearing housing or—with a sleeve bearing motor—excess bearing-to-shaft clearance.[2]

Experts suggest keeping a file on critical equipment, especially complex machinery. The file should include information on bearing brands and sizes, fan blades and rotor bars and a count of gear teeth.

Pairing vibration analysis with oil analysis is becoming more common in some industries and applications. Where there is expensive and/or complex machinery, vibration analysis combined with oil analysis is a must.

TEST SYNERGY

Vibration analysis and oil analysis are widely acknowledged as the best methods for monitoring equipment. The two techniques feature complementary strengths. Basically, vibration analysis monitors and controls balance, alignment and looseness, while oil analysis monitors lubricant quality and contamination, wear metals and alloys, rate of wear and also qualifies the type and size of wear particles generated through the use of analytical ferrography. Oil analysis does not control lubricant quality or contamination. Sometimes one technique will indicate a vague problem that the other can pinpoint.

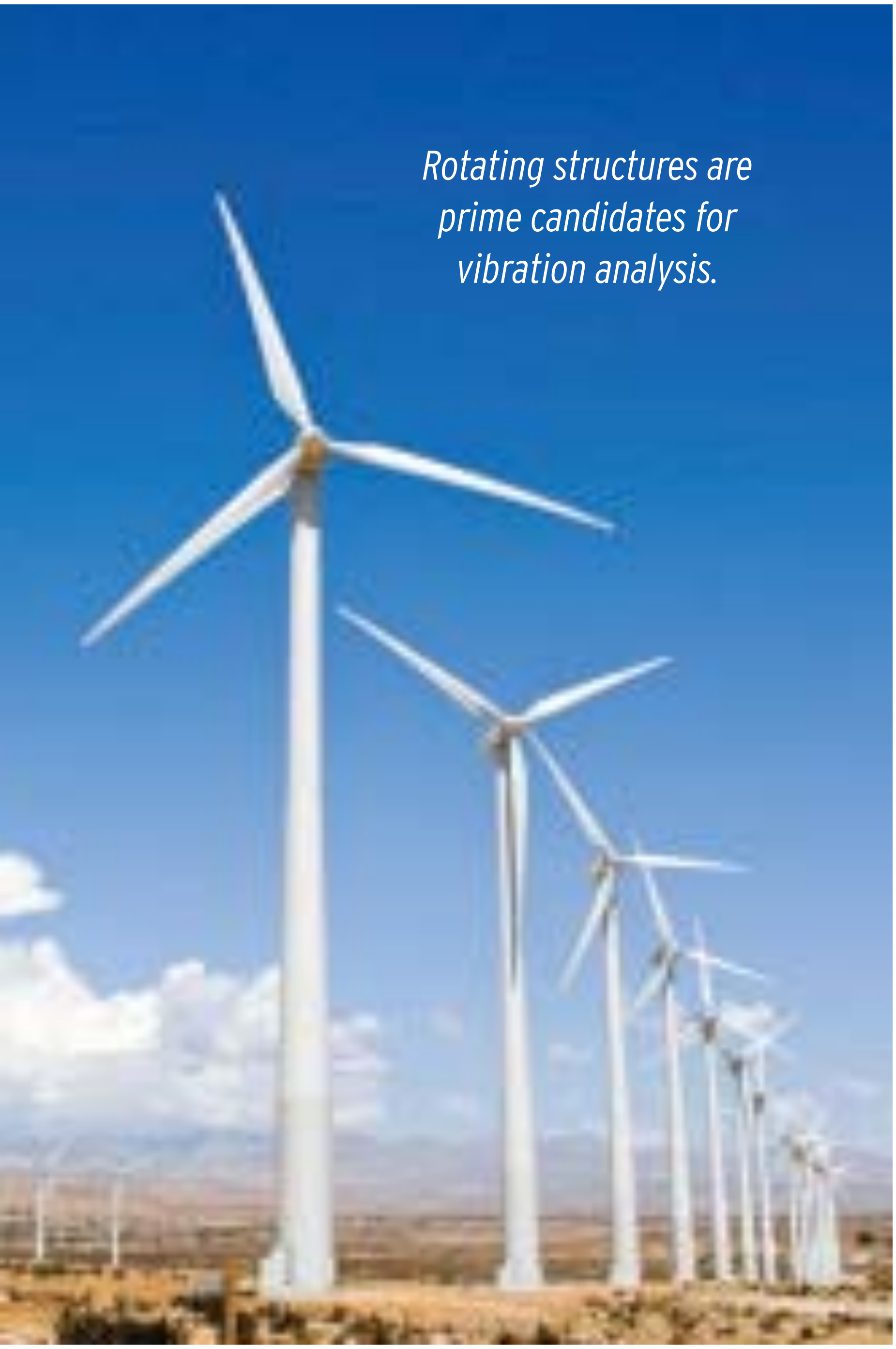
Vibration analysis is an excellent technology for detecting certain types of issues in certain types of equipment. It's best at detecting failures in high-speed bearing systems and often better than oil analysis at specifying the point of failure. While oil analysis cannot detect resonance, vibration analysis can.

In other applications, oil analysis alone will produce adequate and accurate results. Oil analysis is generally better at uncovering failures in gearboxes, reciprocating equipment and hydraulic systems. It's also better at determining which wear mechanism is causing the failure. Vibration analysis has limited success in detecting oil lubricated bearing wear, whereas oil analysis does this spectacularly.

Oil analysis excels at providing clear and timely information on specific types of wear and equipment conditions. It's the best indicator of gear problems and more effective than vibration analysis for motors bigger than 1,000 HP—one reason why it's the technology of choice for fleet industries. In many cases, oil analysis is the leading indicator of existing and ongoing machine wear. Because vibration analysis doesn't monitor low-speed machinery well, oil analysis is the better choice in those applications.

Mark Minges, chief operating officer for POLARIS Laboratories® in Indianapolis, says, "Oil analysis provides an earlier means of detection and can identify wear and contamination issues, fluid degradation or confirm that the wrong lubricant is being used—i.e., a hydraulic fluid has been used in a system requiring gear oil."

"In a gearbox, oil analysis can tell you a gear is wearing, but vibration analysis can pinpoint which gear in a gearset where multiple gearsets are lubricated by a common reservoir," Minges adds. "Vibration analysis can detect where a problem is occurring (a defect with a specific bearing or gear) and can identify mechanical problems such as improper alignment or situations where the equipment is not properly secured or bolted down."



Rotating structures are prime candidates for vibration analysis.

When both technologies are used in conjunction and pinpoint the same problem, the diagnosis and follow-up recommendations are nearly always accurate. Often one technology will pinpoint or predict the specific problem area while the other will pinpoint or predict the type of failure.

Although the correlation between oil analysis and vibration analysis is generally strong, sometimes one test indicates a problem and the other does not (or they contradict each other). The negative correlation between sliding wear and vibration rate is an example. Another example is a fractured gear tooth, which vibration analysis can easily detect, but because of the large fragment size, oil analysis usually cannot.

Marscher says that imbalance and misalignment account for roughly 80 percentof machinery shaking problems and associated bearing, seal and coupling failures. "Vibration analysis is ideal for identifying imbalance and most situations of misalignment," he says. "Oil analysis also can pick up these problems if they lead to excessive force at the bearings which is often—but not always—the case. Even when oil analysis picks these issues up, however, it typically will not do so as quickly as appropriate types of vibration monitoring can.

"Also, vibration can be evaluated in terms of its 'frequency content,' which provides direct clues concerning what the specific reason for the problem is, Marscher adds. "For example, if the vibration frequency is 1x running speed, it is very likely that the vibration is due to imbalance. Vibration analysis generally picks up rubbing impact problems better than other forms of condition monitoring unless the rub and/or impact is in the bearing, in which case oil analysis would also be a good indicator."

However, Minges adds that, "Rubbing wear can be detected at very early stages through wear debris analysis such as analytical ferrography."

JOINT OIL & VIBRATION ANALYSIS

The Palo Verde Nuclear Generating Station in Wintersburg, Ariz., pioneered the integration of the two condition monitoring technologies. Facility personnel combined both analyses into a single division and brought its oil analysis on-site. After conducting a results assessment, the researchers concluded that oil analysis was responsible for 40 percent of the defects found, vibration analysis was responsible for 33 percent, and both techniques converged on the remaining 27 percent of the defects found.

The predictive maintenance department documented approximately $3.7 million in savings in one year. Over a three-year period, they figured that for every dollar spent on these condition monitoring techniques, they saved at least $6.50 in maintenance costs.[3]

The School of Engineering at Australia's James Cook University conducted a research project to investigate the correlation between vibration analysis and wear debris analysis.

Where there is expensive and/or complex machinery, vibration analysis combined with oil analysis is a must.

The school's researchers built an experimental worm gearbox driven by an electric motor. The choice of a worm gear for this study was designed to mimic real-world conditions—both rolling and/or sliding wear processes are common in industrial rotating equipment. This would allow the replication of both types of mechanical friction in one experimental test rig. They then conducted a series of studies on the device, utilizing different machine defect conditions under controlled operating conditions. Wear debris analysis data was then compared with vibration analysis data in order to quantify the effectiveness of both vibration analysis and wear debris analysis in predicting and diagnosing equipment conditions.

They employed proven wear debris analysis technologies—a high-quality particle analyzer, a confocal laser scanning microscope (CLSM) and an electron probe microanalyzer. Three tests were conducted under the following conditions:

Test 1: Normal operation
Test 2: Lack of proper lubrication
Test 3: Contaminant particles in the lubricating oil

Oil samples and vibration data were collected regularly. Wear debris analysis included the study of particle concentration and size distributions, along with the examination of particle morphology and types to determine possible wear mechanisms, wear rates and wear sources. Vibration analysis consisted of analyzing both the time and frequency vibration signals from the test rig to determine the onset and severity of active wear, and to help diagnose the root cause.[4]

Researchers collected an oil sample each week from each of the three tests during 18 weeks. Each oil sample was scrutinized and compared. A particle analyzer was used to determine oil sample particle concentrations in order to assess gearbox condition trends. Both wear debris and vibration analysis techniques were used to assess the gearbox condition and diagnose problems during the three tests.

Following are the results:

Test 1: The results from wear debris analysis indicated a normal condition with a slightly high number of wear particles due to roughening gear surfaces near the end of the test.

Test 2: Both methods discovered the lack of lubrication problem between the gear surfaces, although the wear particle analysis gave a more conclusive result. The presence of severe sliding particles from metal-to-metal sliding was a good indicator of inadequate lubrication.

Test 3: Wear debris analysis found a large number of wear particles with a relatively smooth surface. Because iron powder was involved in the wear process and its form was modified, the wear process may be called a three-body rubbing wear process. In contrast to normal three-body wear processes, which include hard contaminants such as sand, the three-body wear process in this study did not generate cutting particles associated with cutting wear. It did, however, generate significant wear debris. The iron particles accelerated the wear process. Vibration analysis confirmed the wear process due to the increase in the peak at the shaft running speed, and the presence of a mound of energy near the bearing frequency.[5]

Researchers concluded that vibration analysis provided quick and reliable information on bearing condition, and wear debris analysis provided solid information on the wear rate and gear mechanism. Integration of these two condition monitoring techniques in all three worm gearbox tests provided a nearly complete picture of the operating condition.

Marscher says, "Combined vibration plus oil analysis is ideal for applications where sliding is inherent in the system. For example, reciprocating piston rings or where bearing stiffness is extremely high—machine tools are a good example."

SPECIFIC APPLICATIONS

Some applications are better candidates for integrated condition monitoring than others. Three that are of particular interest to tribologists are gearboxes, reciprocating combustion engines and hydraulic systems.

Gearboxes. The most common gearbox failure modes are gear tooth fractures and wear. Vibration analysis has trouble picking up these failures because they involve a cacophony of signals. Oil analysis, on the other hand, can easily detect wear (abrasive and adhesive) and contact fatigue. Then there is the broken gear tooth problem mentioned above—vibration analysis can detect it, oil analysis often cannot because the debris falls to the bottom and never gets included in a sample until it's oxidized and dissolved metals leach into the oil.

Reciprocating combustion engines. While vibration analysis is the method of choice for monitoring grease-lubricated electric motors, oil analysis has always been the first choice for reciprocating combustion engines. For mobile plants, oil analysis is the primary condition monitoring tool for the entire drivetrain, but for fixed equipment, vibration analysis is useful for monitoring the condition of other parts of the machine train—pumps and generators in particular.

Hydraulic systems. While hydraulic systems vary enormously, oil analysis is the most prevalent technology for monitoring them. But where speed and load can be fixed throughout the sampling procedures, vibration analysis is useful for some pumps and motors.

Oil analysis detects early stage rolling element bearing failures better than vibration analysis, although both tests will detect faults. This is a classic case where, when the two technologies are used together, the results are nearly always accurate. Also, experts agree that both oil analysis and vibration analysis are needed to accurately detect and analyze root cause failure.

OTHER TESTS AND TECHNIQUES

In addition to vibration analysis and oil analysis, there are other tests that are sometimes conducted in conjunction with each other to ascertain equipment condition. These tests include visual inspections, thermography, ultrasonics and performance analysis.

VISUAL INSPECTION

This is the most primitive test, but when conducted by an experienced operator it can be one of the most effective. Issues such as leaking, cracking and rust often are readily apparent. A side benefit is that this is without a doubt the least expensive form of condition monitoring.

THERMOGRAPHY

Although slight surface temperature variations are easy to spot, another more comprehensive option is non-destructive thermography. The basic premise is that heat indicates failing components, particularly electrical contacts and terminals. Thermography also works well for detecting the level of deposit build-up in storage tanks and analyzing the condition of couplings, rollers and high-speed bearings. "Using thermography in conjunction with oil and vibration analysis provides the best diagnostic evaluation," Minges says.

Creating an integrated condition monitoring program

After selecting technologies and developing a strategy, the condition monitoring team must be organized to implement these technologies effectively. An audit document provides a good framework if it spells out how to:

- Evaluate the knowledge and experience of condition monitoring team members.
- Assess the condition monitoring training these individuals have received.
- Evaluate condition monitoring instruments and software tools currently in use.
- Appraise the effectiveness of each of the condition monitoring technologies implemented.

Once that framework is in place, it will be most successful if:

1. The entire condition monitoring team performing all technologies has been brought into one common area–allowing free information transfer and improvement in the accuracy and reliability of diagnostic decisions as well as root cause analysis.
2. All condition monitoring personnel report to a single plant program manager who directly reports to plant management.
3. All condition monitoring personnel are cross-trained in at least one other condition monitoring technology, giving them greater confidence and a more complete perspective.
4. All condition monitoring personnel work full-time in their field (they may occasionally assist in performing certain corrective actions but are not expected to do this on a regular basis).
5. All condition monitoring personnel receive formal training in their areas of expertise at least one week per year in order to keep them up-to-date and to further advance their knowledge.

Source: James E. Berry, P.E., Technical Associates of Charlotte[6]

ULTRASONICS

Digital meters measure high frequency signals from bearings and display the result in dBuVs (decibels per microvolt). Using trend analysis, these values will flag potential bearing defects caused by contact conditions such as rubbing and friction. The dBuV value is also used to predict proper intervals for relubrication. Ultrasound pairs particularly well with vibration analysis.

'While both vibration analysis and oil analysis have their merits, they are most valuable when used in conjunction with one another.'

PERFORMANCE ANALYSIS

This involves comparing actual operating statistics with the manufacturer's original parameters, which are usually posted on the machine's nameplate.

There are other intriguing technologies currently in limited use such as motor current analysis and stress wave analysis. On the horizon are embedded wear debris detection sensors and embedded vibration detection sensors that monitor conditions around the clock and continuously supply data, and analysis feedback. If used correctly, this technology has the potential to nearly eliminate failure and downtime caused by gradually occurring conditions.

IN THE END

Many considerations are involved in choosing which condition monitoring method(s) to use, with cost versus benefit being primary for most organizations. While most condition monitoring providers have traditionally offered one technology, this is changing. Today more companies are offering a full spectrum of tests creating an economy of scale and thus lowering costs to customers.

So how do users decide if a piece of equipment should be tested by more than one method? There are three factors: (1.) the applicability of the test to that type of equipment, (2.) the importance of the equipment to operations and (3.) the equipment's replacement cost.

When it comes to in-house testing, aside from cost, the main roadblock to employing both oil analysis and vibration analysis simultaneously is that the two methods are typically performed by two disparate divisions—with vibration analysis performed by the condition/vibration monitoring team and oil analysis performed by the lubrication team. This means that technicians in the two areas tend to be isolated from each other. Ideally, both types of analysts should work together in a unified program, with each having a foundational knowledge of the other technology.

Minges concludes, "While both vibration analysis and oil analysis have their merits, they are most valuable when used in conjunction with one another." TLT

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Mike Johnson

Managing sump condition control

Five testing techniques can help manage contamination threats to your machine.

KEY CONCEPTS

- Air, water, particulate and heat each represent a destructive threat. When they occur simultaneously, the threat is dramatically increased.
- Lubricant-based testing gives the reliability engineer the best possible information about the nature of the sump contamination threat.
- On-site testing using a combination of simple tools and instruments can provide the user with adequate information to take corrective actions.

In the September 2009 issue of TLT, we asserted that contamination control of machine sumps is a vital requirement to preserve machine function and component health for all mechanical systems (**Editor's note:** digital edition available at **www.stle.org**). However, it is important that we take another look at this issue from a condition monitoring perspective.

Contaminants enter lubrication sumps and initiate a variety of destructive chemical and physical reactions and interactions. The immediate contaminant and its inevitable collection of changes can cause both direct and indirect harm to the machine and lubricant. Without corrective action, lubrication effectiveness and machine health is lost.

In addition, a contaminant is defined as any material or energy that constitutes a chemically reactive hazard or that mechanically impairs the proper functioning of the equipment and the performance of the system[1]. This article focuses on in-house and laboratory-based test methods used for identifying the common offenders: air, water, airborne dust and machine-generated wear debris.

MEASURING FOR AIR POLLUTION

Oxidation starts with oxygen, which starts with air contamination. Following initial chemical reactions involving oxygen, oxidation morphs into a variety of chemical reactions, which collectively destroy the lubricant.

Air may exist in any one of three different states within a tribosystem:

- Dissolved
- Entrained (small and large bubbles)
- Free

Dissolved air is present in stable and low percentages in new, healthy lubricating oils, which is both understood and accepted. Under normal operating conditions (fluid churning, change in lubricant chemical properties, systems operating under pressure) the amount of dissolved air increases, can form stable bubbles in the body of the oil or stable foam on the surface of the fluid. Both conditions are a problem, but both are evident with sample collection and visual inspection.

Particularly for hydraulic and circulation systems, the amount of dissolved air increases linearly as system pressure increases. Pressurized systems contain increasing amounts of dissolved air as the pressure increases. As the highly aerated fluid experiences pressure drop on the pump inlet, this dissolved air can form bubbles and cause cavitation and damage in a variety of ways. Unfortunately, one cannot simply observe increased amounts of dissolved air in the fluid.

For high-priority circulation and hydraulic systems, samples should frequently (weekly to monthly) be collected and tested for elevated concentrations of dissolved air. A few shop-floor devices are available for this purpose, including this low-cost Squeezer DualAir™ by PAPEC, as shown in Figure 1. This device enables the user to quantify air by volume in a fluid system. A sample is collected and placed in the instrument and air is measured and compared to concentrations in the new fluid. If the percentage is determined to be too high (>10 percent total = caution, >20 percent = alert, >40 percent total = critical) then vacuum distillation can be used to return the fluid to its original state.

Since it is impossible to prevent air-to-oil contact, it is necessary to test for and equip machines with the means to tolerate the presence of air and other gases and to condition the fluid as needed based on testing. The product shown in Figure 2 passes the contaminated oil across a membrane that removes air and other gases based on molecule size and holds promise to remove air from lubricating sumps. Also, machine sump design should favor options to enhance air release as quickly as possible. The June and August 2010 issues of TLT addressed a variety of sump considerations (available digitally at **www.stle.org**).

MOISTURE MEASUREMENT

Most lubricants are based on materials that don't easily combine with water. Mineral oil and PAO basestocks are nonpolar. These two categories account for the majority of industrial lubricants. However, many of the additives used with these fluids to create finished lubricants are polar and do have the capacity to attract water to the lubricant. Additionally, many common industrial chemicals (process chemicals, water treatment chemicals, soap, other lubricants) have the ability to change the surface tension characteristic of the lubricant, which will, in turn, increase its tendency to hold water.

Figure 1 | **The Squeezer DualAir™ is used to test lubricant for excessive air contamination.** [2] *(Courtesy of PAPEC)*

Figure 2 | **An innovative membrane technology designed to assist in moisture control.** *(Courtesy of Compact Membrane Systems, Inc.)*

Like oxygen, moisture is a prevalent contaminant. Much of the water contamination problem is introduced to the lubricant by contact with humid air. As humidity in the air increases, water concentrations in the lubricant also increase. Once in the oil, water may exist as either dissolved (individual molecules), emulsified (microscopic drops) or free forms. Temperature has an influence on the lubricant's tendency to soak up water. As the temperature increases, the lubricant can sustain more water; conversely as the temperature decreases water solubility decreases.

Emulsified or entrained water is seriously damaging to both lubricant and machine load-bearing surfaces. Fortunately, it is obvious and plant personnel are already tuned to observe oil in/on level indicators for any evidence of cloudy conditions. Dissolved water is impossible to detect visually, and free water is difficult to detect in a sump because one cannot easily look through the oil to the bottom of the reservoir.

Lubricant analysis for moisture control begins with visual observation, but this is only useful to detect high concentrations of water. Given that, per bearing manufacturers, roughly half of bearing lifecycle potential is lost by the time the lubricant achieves only 500 ppm (.05 percent). It is important to have a method to detect concentrations below the lubricant's cloud point. This will differ between lubricants, depending on their basestock and additive type and concentration.

Moisture analysis can be done on-site well enough to make follow-on decisions for work to be done, beginning with highly subjective on-site tests to quantitative lab-based analysis.

Following are five types of tests, two of which are qualitative. The other three involve instruments, are quantitative and should be conducted at the plant site.

Level 1: Crackle Testing. This fully qualitative/subjective approach requires little more than motivation to conduct. A best-case approach would require the use of a laboratory or kitchen hotplate turned up to 350 F. A few milliliters of oil dropped on the hot surface will respond turbulently, depending on the amount of water. As shown in Figure 3, water boils off of the lubricant, changing phase and either bubbling (very low concentration) or popping (high concentration) upon contact with the hot surface.

Even on the low end of the scale (≤500 ppm), there can be enough water to harm the machines. Crackle indicates gross contamination and a strong positive certainly is enough to know to condition the fluid with a dehydrator but is not strong enough to reliably identify low concentrations. Therefore, another technique is needed to identify low concentrations.

Level 2: Calcium Hydride Testing. A qualified estimate is provided by the use of calcium-hydride type testers. A few companies provide test cell packs that enable the user to qualify down to a level of a couple hundred ppm. The technique involves mixing of a sample with a reagent to initiate a chemical reaction in the test cell. The greater the amount of moisture, the greater gas pressure is produced, which correlates to moisture level. This technique does not provide for exacting trending of results over time but does enable quick decision-making in response to rising moisture.

Level 3: On-site Electronic Sensors. This growing field includes sensors developed by several manufacturers. The sensors represent a combination of continuous (online) and intermittent (sample bottle) testing for moisture. The results are provided in a variety of units. Water in parts per million (ppm) is widely recognized and is likely the most comfortable unit for machine operators to work with, but other options exist. These sensors have varying levels of sensitivity but are collectively useful as a low-cost replacement to the subjective options noted above.

Level 4: Off-site FTIR Scan. Many labs provide Fourier Transfer Infrared Spectroscopy (FTIR) scans routinely to evaluate multiple parameters. One of those parameters is moisture/water. FTIR indicates presence of moisture by recognition of hydrogen bonding to water between 3,000 cm–3,700 $cm.^{-1}$ Water is measured indirectly and doesn't provide an actual concentration, but it does provide impetus to proceed automatically with a hard count. The FTIR provides multiple benefits that justify its routine use beyond water measurement. This should be a default test for all test slates, alongside traditional wear metals analysis.

Level 5: Off-site Karl Fischer. This gold standard for water concentration measurement is well known and widely used. If a company wishes to engage in systematic improvements to suppress water contamination in machines, then quantitative analysis via KF is warranted. There are different KF techniques that can be selected depending on the type of lubricants being analyzed (ASTM D1744 and D6304), both of which report accurately to the low double digits.

Filter manufacturers have devised a variety of moisture-removal systems around these physical response characteristics. One of the most effective methods to drive water off is the vacuum dehydration filter method. The lubricant is pumped into a vacuum chamber where the pressure is decreased (25" Hg) and the temperature is raised to a level that will allow water to boil (133 F/56 C) at a low temperature. Other removal methods include absorbent media (low-volume, low-efficiency), centrifugal separation (high-volume, moderate-efficiency) and thermal dehydration (high-volume, high-efficiency).

The use of membrane separation techniques are also attractive options. Figure 4 shows a membrane separation technique predicated upon super-dry air passed across the lubricant's headspace. The Stealth dehydrator,

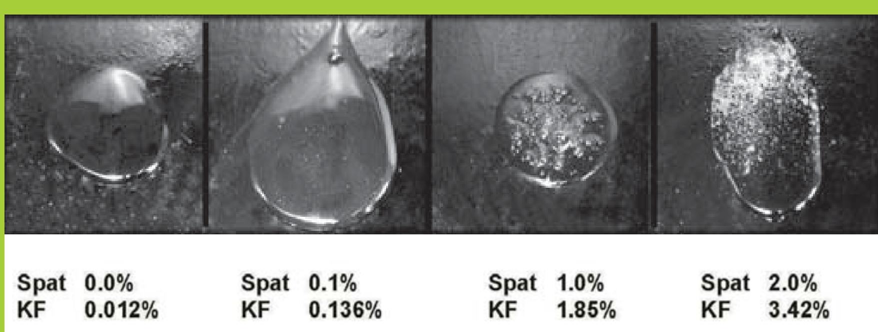

Figure 3 | **Karl Fischer (KF) laboratory-based result compared to a subjective crackle test.** *(Courtesy of Condition Monitoring International)* provided by Fluitec International, feeds low-pressure super-dehydrated air (dew point at -40 C) into the reservoir headspace. The moisture from the oil is drawn into the super-dry air and is decanted continuously until moisture levels are very low. Additionally, the device noted in Figure 2 is designed to remove moisture in an approach similar to its removal of air. This dual-purpose function has added benefits.

PARTICULATE MEASUREMENT

Solid particles are very common, represent a strong threat to the component surfaces and control mechanisms in all types of lubricated production machines. Some of the airborne dust particulate that can migrate into lubrication systems are harder than the machine metals used in machine construction. Microscopic particles promote micropitting, fatigue and three-body wear in proportion to density, hardness and toughness (friability), shape and their concentration in the oil. This is a difficult machine care problem.

There are several different ways to measure a contaminant concentration, including patch inspections, distribution and size estimates, centrifugal aggregation measurement and gravimetric measurement. This section focuses on visual observation and density analysis methods. Beginning with shop tools and on-the-floor analysis, the use of patch testing is a maligned but viable starting point.

Patch Testing. The use of patch test-based review and correction is not unlike the use of quantitative particle counting techniques. However, instead of assigning a caution and critical limit based on ISO grade, the limit is based on the patch result. For instance, the Millipore kit provides a tint-comparator that the analyst uses to grade the patch based on different shade-grades (1-6). There is a brown scale and a gray scale for different oil types. The reliability engineer could begin his methodical improvement process with a low-cost patch generator and assign grades according to machine criticality

Figure 4 | **The StealthEHC system is designed to remove moisture from contaminated oil.** *(Courtesy of Fluitec International)*

and function.

For instance, for a gearbox, the acceptable score could be a 3, where with a low-criticality hydraulic system it would be a 2, and for a high-criticality hydraulic or turbine system it would be a 1. Following the patch generation, a decision can be made to filter the oil where needed. Although subjective, this approach is viable.

Figure 5 gives a loose correlation between a patch test and a particle count.

Automatic Particle Counters. There are several manufacturers of particle counters that make units for both in-plant and laboratory-based use. Most use the ISO 11171 instrument calibration and reporting method and accordingly report in units of particles per milliliter based on concentrations of 4, 6 and 14 micron-sized particles. Although these are not commonly reported, additional units include concentrations of 21, 38 and 70 micron-sized particles. All concentrations are reported per milliliter. In the May 2011 issue of TLT, we provided insight into using wear debris analysis to examine changes in machine health (available digitally at **www.stle.org**).

Site-based particle counting is done by using a probe from the instrument to select fluid directly from the machine, bypassing the sample collection step or using a sample bottle on a desktop. Probe-on options are subject to interference from entrained air and water passing through the machine and bottle-based sample options are subject to interference from the sample collection process. Techniques are recommended by instrument suppliers for overcoming

Turbine Oil (New)	Turbine Oil, In use	Gear Oil, In Use
Patch Grade = 1	Patch Grade = 2	Patch Grade = 4
ISO Code 14/11/8	ISO Code 18/15/10	ISO Code 22/21/18

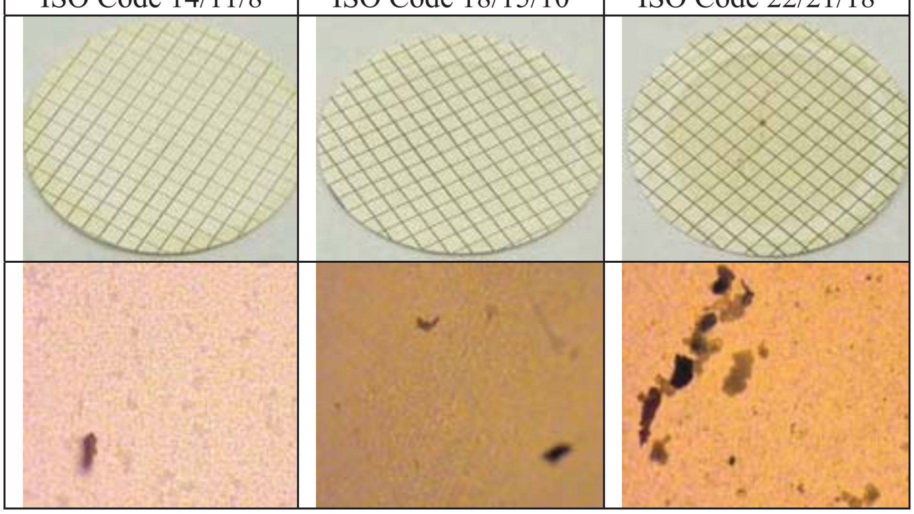

Figure 5 | **Patch testing and particle count results shown side-by-side** *(Courtesy of MRG Labs)* these problems. Both filter element and instrument suppliers offer thresholds to consider for different machine types, criticality and operating conditions.

For instance, as shown in Figure 6, Schroeder Filter Co. provides suggested cleanliness levels to assure maximum component effectiveness based on component type and operating state.

Automated Electron Beam with Automated Particle Feature Particle Analysis. A recent enhancement to long-standing laboratory-based test includes the use of an electron beam to scan a portion of the surface area of a sample passed through a patch, measure particles by size and shape, diagnose the material content and log the results as a combination particle count, morphological profile and elemental analysis.

This approach is a step forward from the traditional approach of using scanning electron microscopy to evaluate elements of particulate found on a sample. By adding feature analysis software and automating the use of the electron beam to focus randomly selected cross-sections of a prepared patch, this new technique enables the laboratory to diagnose the particle concentration, provide a particle count and a characterization of the wear mode based on particle morphology. It also provides a spectrometric profile of the scanned particles through an x-ray spectrometer integrated into the electron-imaging beam.

Although the test is time-consuming versus a traditional particle count, it provides considerably more information than traditional methods, which is most useful when diagnosing systematic problems within a machine sump.[3]

After it is determined that the concentration of debris in the oil is beyond a recognized limit, filtration can be applied to correct the condition. Filtration product suppliers are able and willing to provide thorough technical support to offer improvements.

Component Type	System Pressure	Suggested Cleanliness Code
Servo Valves	<1000	16/14/12
	1000-3000	15/13/11
	>3000	15/12/10
Proportional Valves	<1000	17/15/13
	1000-3000	17/14/12
	>3000	16/14/11
Variable Volume Pumps	<1000	18/16/14
	1000-3000	17/16/14
	>3000	17/15/13
Vane Pumps Fixed Piston Pumps Cartridge Valves	<1000	19/17/15
	1000-3000	18/17/14
	>3000	18/16/13
Gear Pumps Flow Controls Cylinders	<1000	20/18/16
	1000-3000	19/17/15
	>3000	19/17/14

Figure 6 | **Suggested ISO cleanliness values to assure system performance.** *(Courtesy of Schroeder Filter Co.)*

SUMMARY

Contaminant monitoring and control is of paramount importance to machine productivity. Air, water and particulate (atmospheric and wear related) are dominant contamination threats to industrial machines. Using techniques that clearly diagnose each threat and setting specific responses to each exception is at the heart of defect elimination and condition improvement for industrial machines.

It is useful to drive these diagnoses to the shop floor and assign condition monitoring technicians the task to use available technologies to make quick and dependable decisions. There are many options to choose from covering all three points of interest. Laboratory testing is typically more quantitative, takes longer and provides for stronger long-term trending of data for pattern diagnosis. At a minimum, lab-based analysis done following recorded exceptions from shop floor analysis is essential to a healthy program. TLT

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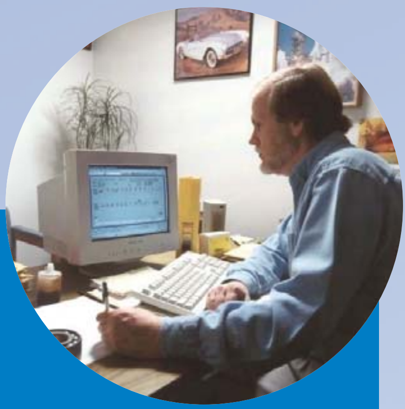
Charles A. Gay

This 30-year training veteran and senior data analyst discusses strategies in testing and interpreting oil samples.



(Photo courtesy of Analysts Inc.)

Charles Gay The Quick File:

Work Experience

Currently a senior data analyst at Analysts Inc., Atlanta, Ga. Involved in data interpretation of test data, providing corrective action comments and proactive maintenance recommendations for customers along with training and sales support. Specializing in heavy industry involving analytical ferrography, micropatch and magnetic plug evaluation, refrigeration/refrigerant test data interpretation, power generation, including nuclear, coal and wind power, fuels, coolants and specialty lubricants. Since 1980 he has provided technical support and training for Komatsu North America. Previously worked as a laboratory manager for a joint venture lubricant testing laboratory in Jakarta, Indonesia.

Education

Associate of Science in Business Administration – DeKalb College, 1976

Honors & Accomplishments

- STLE member since 1983
- STLE Atlanta Section chairman, 2000-present
- Oil Monitoring Analyst (OMA I), 2000
- Certified Lubrication Specialist, 1995
- Developed magnetic plug debris analysis matrix, 2004
- Developed visual exam of debris/micro-filter patch test matrix, 1998

TLT: What is the relationship with oil sampling among end-users?

Gay: It has been my experience that from an end-users' perspective, oil sampling can be a love/hate relationship. During my 37 years of working in the industry, the strength of an oil sampling program depends heavily on educating and communicating with the end-user.

A successful relationship between an oil analysis lab and oil-sampling program requires that the lab educate its clients in order to sell services or to retain the customer. Fortunately, thanks to STLE's efforts there are local section presentations, the annual meeting, certification programs, education courses and Webinars that cover a wide variety of topics on oil analysis that help to educate both the novice and the expert.

Meanwhile, there are several industry training companies and other similar organizations that are usually associated with major fluid testing labs which provide services to the typical end-user. However, fluid analysis companies continue to be the preferred education provider for their clients.

TLT: What factors should you consider in choosing an oil analysis provider?

Gay: There is a wide variety of testing facilities available in the marketplace that are affiliated with independent laboratories, oil companies, lubricant distributor programs and major equipment manufacturers. The testing offered and associated costs vary widely.

However, there are four key factors to consider when choosing a provider to meet your fluid testing needs: pricing, depth of knowledge, operational needs and reporting requirements. The general rule of thumb is that basic testing may meet your needs for easy-to-repair or replacement equipment, however, testing on more

As the cost of lubricants and disposal increase, fluid analysis continues to be a key component in determining when a fluid needs to be changed.

sensitive equipment with high uptime requirements and expenses may require a more complex lubricant and component-monitoring program.

Education and communication play a major role in the program user's ability to select the appropriate testing for their operation. Recommendations are usually provided from the service provider, but the overall effectiveness of the program is ultimately managed by the end-user. You should select a program that you and your staff can use properly and understand.

TLT: What makes a good fluid analysis program?

Gay: Obtaining a representative sample of the in-service fluid from a component is a requirement for a good fluid analysis program. Every application has an ideal sampling method, and maintenance personnel should consider which is most appropriate for their operation and environment.

A good fluid analysis program involves educating sampling personnel of the importance of their role. Experience shows that in many cases the individuals taking the samples usually do not completely understand the reasons for sampling. As a general rule, new hires in plants, mines or shops are usually assigned the task of taking samples and typically do so with little or no training. Before throwing them to the wolves, make sure to provide training for new hires to ensure having a good fluid analysis program.

Proper sampling methods are critical in obtaining representative samples, and laboratory analysis and recommendations can only be given based on the sample submitted. A non-representative sample usually leads to questioning the validity of the sample by the laboratory or incorrect assessment of the fluid and component conditions. Both of these are costly to the end-user and are completely avoidable.

TLT: What are the issues with oil sampling?

Gay: Proper and consistent sample labeling are major issues in the industry. Well-trained, established and knowledgeable sampling personnel are more likely to identify the component being sampled consistently. Inconsistent labeling is particularly common in large industrial plants with many different sections or profit centers and a large number of components of the same make and model. Labeling or tagging the components with a unique identifier usually works best. A good approach offered by some labs is to generate a label for each component with the customer's chosen unit identification and a corresponding unique number in the laboratory database. If the reference points don't match, you should contact the customer before proceeding.

In cases where clients aren't dealing with the same equipment and identifiers every time, a sample information form should be filled out completely and consistently and submitted with the sample for analysis. As the sample information form is typically provided by the testing facility, it indicates the testing to be performed, payment selection, the distributor network and the destination of the sample report. Well established sampling programs with properly trained personnel typically submit sufficient information with their samples.

Sometimes, sample bottles are labeled or marked at sampling, and the sample information form is filled out later by office personnel. Though this can work well, a well-intended technician can easily be bitten by untrained office personnel. Thus, proper training of office personnel in recording the correct information on the form is a must if this approach is taken.

Though training of these individuals and the time it takes to fill out the form correctly are time-consuming, the importance of these tasks cannot be over emphasized. It is not just busy work, and the gains realized in the sampling program usually result in a positive reaction. In some cases, obtaining sufficient proper information on the samples submitted is still an issue. This is astonishing as lacking or improper information usually causes delay in processing at the laboratory and may result in thousands of dollars in costs. A good laboratory must stress the importance of sample information as part of their training programs.

Submission of samples to testing facilities is also a recognized problem of significant proportion. Most service providers track the sampled date (if provided), date it was received at the laboratory and the date of report generation. This is also true of hand-delivered samples. However, all too often, a call is received stating a sample or group of samples will be sent via overnight carrier only to be later determined the sample was not received the following day. The follow-up call inquiring about the outcome of testing (usually the day after supposed shipping), almost always begins with, "How was the sample shipped?" A typical response is that the sample was passed along to someone in the office or shipping department. Almost always, the instructions requiring overnight shipping did not get communicated to shipping personnel. The sample is either still on their desk or was shipped by other means. These types of communication errors also contribute to delays and may potentially lead to thousands of dollars in costs. Thus, conveying the importance of sample submission is also a critical portion of any training program. If the sample doesn't make it to the laboratory, testing cannot commence and the status of the fluid and the component it came from remain unknown.

TLT: What are the challenges in interpreting oil samples?

Gay: As previously mentioned, data generated on a sample and the resultant interpretation of the fluid and component is critically dependent on receiving a representative sample and sufficient information about the component and lubricant in service. If this information is incomplete or the testing performed is not broad enough for the application, a proper assessment of the lubricant or component can't be made. Incorrect information on the component will lead to incorrect application of guidelines established based on thousands of data points from like or similar equipment. Though sometimes broad in nature, some OEMs also provide guidelines which can't be applied if the information is not present.

Overcoming these challenges can sometimes be accomplished with the use of trend analysis. This works well by

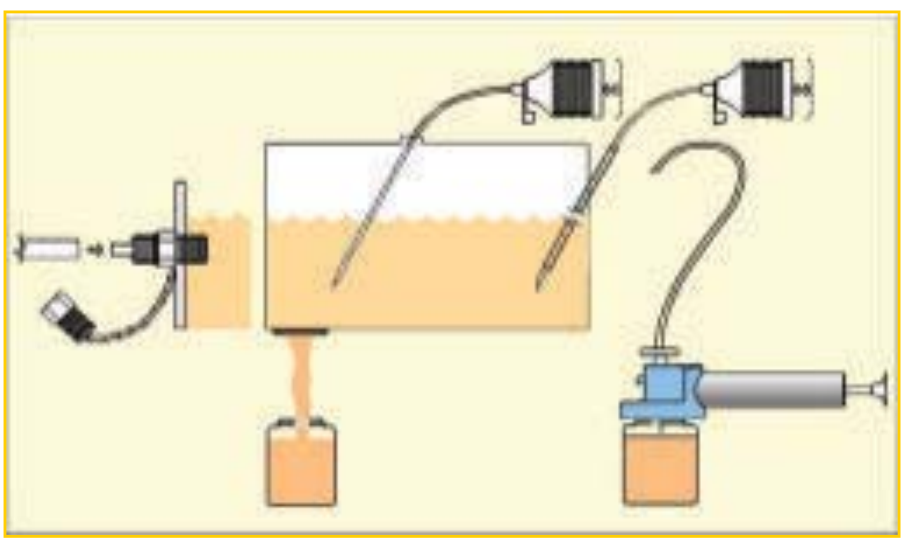


Figure 1 | **Illustration of some sampling methods including the QSS sampling valve, bellows bottle, vacuum pump and drain.** *(Courtesy of Analysts Inc.)*

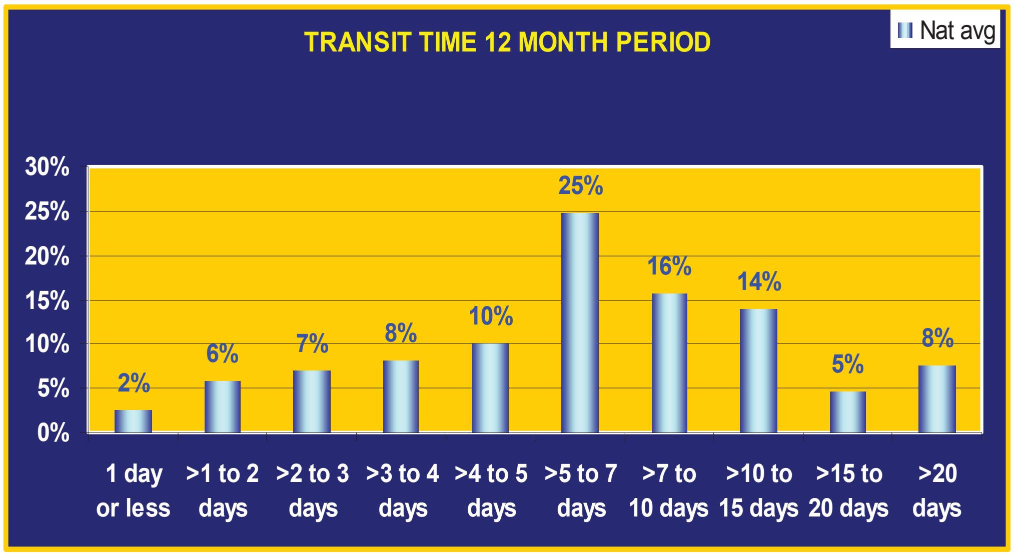


Figure 2 | **Transit time in days for hand-delivered samples, overnight, second-day delivery and USPS.** *(Courtesy of Analysts Inc.)*

close examination of percent change in test results in comparison to sample histories from the component. This too is limited by the testing and information provided. Differentiation in testing methodology, one-of-a-kind components and components without a sampling history are the most common factors that hinder establishing and applying the correct guidelines.

Increased communications with the client about the component and lubricant application are critical in overcoming the challenges faced. Only then can the change in results and lubricant/component conditions be fully understood. This communication may result in the recommendation of additional testing or result in a broader scope of testing for the application. For example, higher volumes of in-service lubricant generally require more in-depth testing to actually assess the serviceability of the fluid. A major misconception commonly encountered is that the service provider already knows everything related to the client's equipment, maintenance capabilities and lubricant in service. This misconception may be part of the reason samples are frequently received with no information on the form or oil in an unlabeled sample bottle.

TLT: What future developments do you foresee in oil analysis programs?

Gay: The future of oil analysis programs shows great promise in bridging the communication gap with the use of computer systems common on most new equipment. The computer systems make obtaining the necessary information easier for end-users and equipment manufacturers. At some point, they may even be integrated with laboratory databases and provide more accuracy and information available to data analysts, resulting in better overall assessment of lubricant and component condition.

In addition, field technicians will be better educated than ever before on broader subject matters, as there are now several courses being offered to maintenance technicians and management personnel. This increase in knowledge is one of the best things to have happened in our industry. Changes in technology and enhanced laboratory instrumentation continue to be a factor in developing better maintenance programs. However, having a knowledgeable client-base has been one of the largest factors in having a good fluid analysis program.

TLT: What steps can practitioners take to get the most out of their oil sample?

Gay: The fluid analysis that *you* are hopefully using is one of the least expensive components in a maintenance program. This analysis allows for a proactive approach to maintenance in terms of detecting and correcting minor problems, leading to lower costs and less downtime. As the cost of lubricants and disposal increase, fluid analysis continues to be a key component in determining when a fluid needs to be changed. As we all know, keeping your lubricants clean and dry is the first steps to enhance a lubricant's life.

As lubricant costs increase, other methods of monitoring fluid conditions and reclamation or reconditioning of fluids have increased in popularity. Online sensors for vibration, magnetic chip detectors and temperature-monitoring devices, which have been the norm in the aviation industry for many years, are now becoming the norm in some industrial and automotive applications. Furthermore, online fluid testing has been around for over 30 years and will continue to grow in popularity and effectiveness. There are even online warning sensors that alert the operator of significant changes and when further investigation is required. However, these techniques only contribute a portion of what is necessary for a successful maintenance program.

The best programs contain a well-devised maintenance and sampling plan, well-educated plant engineers and maintenance personnel and the appropriate testing conducted at a well-informed and experienced oil analysis laboratory. TLT

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Jeanna Van Rensselar / Contributing Editor

Used-oil analysis for predictive maintenance

KEY CONCEPTS

- Predictive maintenance is a proven, cost-effective tool for certain types of machinery.
- Predictive maintenance is not the same as preventative maintenance.
- Industries such as power generation are prime candidates for predictive maintenance.

An arsenal of techniques allows end-users to safely extend drain intervals—without jeopardizing equipment.

AMONG OTHER FINDINGS, a 2008 study conducted by the California Department of Toxic Substances Control (DTSC) concluded that end-users should follow manufacturers' recommendations for oil change intervals and institute routine oil analysis programs to extend oil change intervals.

In fact, the fleet manager survey, a part of the study, confirmed that the average oil change interval is considerably shorter than the maximum suggested by oil condition-based analysis results. The conclusion reads in part as follows:

"The oil analyses showed that oil drain intervals can be extended for all vehicle types studied. Oil sampling results indicate that in many cases, oil drain intervals can be extended beyond the maximum level recommended by the vehicle manufacturer.

"For fleets that have already extended their oil drain intervals to the maximum recommended by the manufacturer, many can further extend oil change intervals by using better oil and by establishing oil analysis programs to determine the optimum drain interval. Routine oil analysis is an important tool that ensures good oil condition and provides safety for the engine."

"In some cases, oil sampling alone can be used to extend drain intervals. A basic oil analysis program including physical and chemical parameters, like viscosity, TBN, oxidation, nitration and common oil contaminants, like water, dirt and wear metals, would be sufficient to ensure oil condition and satisfy fleet managers.[1]"

This comes as no surprise to the companies that have been relying on oil analysis programs for many years and have seen the benefits—mainly substantial cost savings and increased equipment reliability. But others still need convincing.

Aside from the real possibility of being able to extend drain intervals, oil analysis can be a powerful predictive maintenance tool that can:

- Increase equipment reliability
- Reduce unscheduled downtime
- Reduce overall maintenance expense
- Pinpoint abnormal conditions and wear trends
- Streamline maintenance procedures
- Optimize repair parts inventory
- Document warranty claims
- Improve repair scheduling
- Identify human error and neglect
- Extend equipment life.

Predictive maintenance determines the condition of in-service equipment in order to forecast maintenance. This leads to cost savings over other methods because maintenance intervals are usually extended. Corrective maintenance can be scheduled when it's convenient without risking equipment failure.

The *predictive* aspect of predictive maintenance results from forecasting future conditions using trend analysis. This approach relies on established statistical process-control principles to determine exactly when and what maintenance is necessary. Most predictive maintenance inspections are performed while equipment is running, minimizing operational disruption.

PREDICTIVE VERSUS PREVENTATIVE

Most people don't know the difference between predictive and preventative maintenance—thinking they're the same thing. Not so. Preventive maintenance occurs on a predetermined calendar or run-time schedule, while predictive maintenance is based on the actual condition of the equipment. The differences are significant, but the two types of maintenance have the following three goals in common:

1. To maintain the production equipment and plant utility systems equipment in the best possible operation condition.

No two pieces of equipment are alike and no two pieces of equipment operate in exactly the same conditions using the same horsepower.

2. To have all equipment ready to start up with as little unplanned downtime as possible.

3. To complete all work on a regularly scheduled basis without exceeding the point of diminishing returns on investment for the labor, tools and materials required to perform the work.[2]

A simple analogy is an automobile. Owners have two choices when it comes to determining oil change intervals. They can either follow the manufacturer's recommendations or those of the neighborhood oil-change facility. Most people opt for the former because the manufacturer has more credibility and oil change intervals are usually longer.

However, what if, instead of bringing the car into the dealer for an oil change, owners brought it in regularly to have the oil tested instead? After a few tests, the dealer would be able to establish a trend for that particular car and tell the driver exactly when the oil needs changing.

This would have obvious advantages such as reducing the need for oil changes—less cost, less hassle for the driver. But in this case, the cost of paying for the oil analysis would offset paying for fewer oil changes. However when it comes to expensive and critical commercial equipment, it's a different ballgame. For commercial equipment there are many other considerations—most notably the cost of shutting down equipment for routine preventative maintenance or the cost of shutting down an entire production line—in the event of equipment failure.

It takes about 30 minutes to change the oil in your car, but it can take hours to change the oil in a large piece of plant machinery. During that half hour, you're reading a newspaper and sipping coffee. During those hours, one or more plant operations are down—very expensive.

PREDICTIVE MAINTENANCE BENEFITS

When comparing reactive, preventive and predictive maintenance, it's not surprising that studies consistently show that, regardless of the industry, reactive maintenance is the least cost effective. In the electric power industry, detailed case studies and an associated 2006 "Plant Maintenance Cost

Justification" study were generated in the U.S. by the Electric Power Research Institute (EPRI) and these show the following results:[3]

Comparative Maintenance Costs (Total Maintenance Expense/HP Used Per Year)

1. Reactive: $17.
2. Preventive: $13 (= 24% reduction from reactive maintenance).
3. Predictive: $9 (= 47% reduction from reactive maintenance).

The EPRI studies show that, when compared with the reactive approach, an overall maintenance cost reduction of 47% is generally obtained by using predictive maintenance techniques.

In addition, Pat March, a senior mechanical engineer at the Tennessee Valley Authority (TVA) Engineering Laboratory, prepared the following summary based on the results of a multi-industry survey of firms that had used or were using predictive maintenance techniques:[4]

Benefits of Predictive Maintenance

- Maintenance cost reduced 50% to 80%.
- Machinery breakdowns reduced 50% to 60%.
- Spare parts inventories reduced 20% to 30%.
- Total machine downtime reduced 50% to 80%.
- Overtime expenses reduced 20% to 50%.
- Machine life increased 20% to 40%.
- Overall productivity increased 20% to 30%.
- Profit increased 25% to 60%.

From 1970-2003, U.S. aircraft carrier maintenance planners have used a machinery condition analysis program (that included oil analysis) to determine the specific condition of more than 400 pieces of rotating machinery on each carrier. This information has been used to make decisions on whether equipment should be repaired or overhauled and if maintenance could be safely deferred. In all, they conducted 5,659 machine tests at an average cost of $161 per machine.

The cost benefit ratio broke down as follows:[5]

- Year: 1977 cost benefit 18.8/1
- Year: 1988 cost benefit 19.0/1
- Year: 2000 cost benefit 19.5/1
- Year: 2001 cost benefit 20.0/1
- Year: 2002 cost benefit 20.9/1
- Year: 2003 cost benefit 23.0/1

This information made the maintenance and repair planning process more accurate and cost effective and reduced the incidence of failures and unscheduled repairs for these machines.

TREND ANALYSIS VERSUS INDIVIDUAL REPORTS

No one would argue that it's always best to analyze used-oil data based on regular samples taken over time. Trend analysis is the core component of predictive maintenance. It's important to establish a baseline and a strategic interval to extract oil samples from the engine.

STLE-member Jason Papacek, data analysis manager for POLARIS Laboratories® in Indianapolis, explains, "The real value of oil analysis is not in reacting to individual reports but to trends that are identified through regular sampling. An individual report represents one moment in time. Trending documents the entire journey up to that point and provides much more information as to why or how you got there and can greatly affect how you react to the results."

While specific limits are noted by all engine manufacturers, trending toward those limits may indicate that a problem is developing in the engine before the limit is reached. For example, upward movement of both viscosity and acid numbers over time is an indication of thermal degradation or oxidation. For every 18 degrees above 160 F, the oxidation rate of an oil doubles.

Analysis of wear metals is important to monitor the condition of the individual wearing components of a system. In engines you are looking at many components—pistons, rings, liners, bushings, bearings, camshafts, crankshafts, gear train, etc. An absolute limit in wear metals is not nearly as useful as the rate of wear or upward or downward trend of wear metals. This metals-trend monitoring identifies slowly progressing damage that would not be obvious in a single sample. Papacek posed the following examples:

FOUR TYPES OF MAINTENANCE APPROACHES

According to STLE-member Evan Zabawski, senior reliability specialist for Fluid Life in Edmonton, Alberta, Canada, when it comes to equipment maintenance, there are four basic approaches.

1. **Reactive Maintenance.** Example: Your tire goes flat (fails) and you fix the leak or replace the tire. Action based on reaction.
2. **Preventive Maintenance.** Example: You replace a complete set of tires based on time or mileage only. Action based on schedule only.
3. **Predictive Maintenance.** Example: You replace a tire or set of tires based on measuring tread depth. Action based on measurement.
4. **Proactive Maintenance.** Example: You check your tire pressure routinely because you know from past failures that this action prolongs the life of the tire. You still check tread depth for signs of failure, and you are vigilant when the mileage approaches the equivalent mileage of your last set of tires. Action based on learning from past failures, i.e., never let it fail for the same reason twice.

Example 1. You suspect a problem and take a sample. The report shows particle count is unusually high. Your first instinct may be to change the oil to fix the problem. Had you been trending results over a period of time, a sudden jump in particle count wouldn't necessarily be reason for panic. You would be more inclined to ask questions as to why there was such an abrupt change. Did someone new take the sample? Was it taken from a different sample point? Did the contamination occur after the sample was taken? Your reaction would be different and could prevent unnecessary maintenance action.

Example 2. You get an abnormal vibration reading and a sample is taken. The report shows elevated silicon (dirt) and iron (wear metal) levels, indicating that wear is occurring, likely due to dirt contamination. If the same unit was sampled regularly, dirt ingression could have been detected earlier and identified a deteriorating seal before a wear condition developed. Damage to the unit could have been minimized or prevented altogether.

"Trending is absolutely necessary for a successful condition-based maintenance program because you're making maintenance decisions based on the health of the lubricant and the component," Papacek says. "For example, let's say the preventative maintenance on a compressor is every 1,000 hours. This could be too long to wait if a serious contamination issue arises and is not detected. It could be too early if the component is well-maintained and the oil is suitable for use beyond 1,000 hours.

"Oil analysis can pinpoint sudden changes and help you determine if an oil change should be made prior to the scheduled preventative maintenance or if it can safely be extended beyond it, saving additional lubricant costs and labor," Papacek adds.

A study by the Electric Power Research Institute revealed that predictive maintenance reduced total maintenance costs 47% compared to reactive maintenance.

EXTENDING DRAIN INTERVALS

Most original equipment manufacturers recommend or specify oil drain intervals and the type of oil. These recommendations are often specified in the warranty. And while they provide a good baseline for maintenance, these recommendations don't take into account all operating conditions and applications.

For example, taking into account the operating length (in terms of miles and/or hours) on both the oil and the engine is key to determining the most accurate drain interval recommendation. The ability to compare these measurements with the test results allows the analyst to accurately and safely pinpoint an optimum drain interval. Also remember that no two pieces of equipment are alike and no two pieces of equipment operate in exactly the same conditions using the same horsepower.

There's really only one way to know if the OEM's drain intervals are optimal for a particular piece of equipment—regular independent oil analysis. End-users can feel confident that they are extending drain intervals safely if they take into consideration the OEM's specifications, their own oil analysis results and independent laboratory recommendations.

Monitoring total base number (TBN) along with both oxidation/nitration and viscosity trends and tracking contamination and wear is the best way to optimize diesel engine drain intervals. The bottom line is that you should always consult with the OEM, the lubricant supplier and the laboratory analyst before exceeding the OEM's specified drain interval.

"Lubricant consumption and labor costs can be greatly affected by extending drain intervals," Papacek says. "For example, take a plant with four compressors that are scheduled for monthly oil changes. Sump capacity for each is 150 gallons. Changed monthly, this totals 7,200 gallons per year. Assuming compressor oil costs range \$15-\$25 a gallon, the annual lubricant cost will range from \$108,000-\$180,000. Oil analysis has the potential to reduce the number of oil changes to four times a year, reducing lubricant costs to between \$36,000 and \$60,000—an annual savings of \$72,000 to \$120,000."

He continued, "Take this a step further and let's say each oil change takes a technician an hour to an hour and a half. Twelve per year, per compressor, represents 48 to 72 hours in labor. Reducing the number of oil changes from 12 to 4 per year, per compressor, is 16 to 24 hours in labor—a savings of 32 to 48 hours in labor per year that maintenance personnel can use to focus on other issues."

INDUSTRY APPLICATIONS

Why is predictive analysis more important in some industries than in others? There are a number of considerations:

- The purchase and replacement cost of the equipment.
- The machine's degree of criticality—what happens if it goes down?
- The physical difficulty of changing the oil.
- The scale and cost of the oil and filters.

Two industries that deal with all four of these factors are the power generation (particularly wind turbine) industry and the aggregates industry.

Power generation. When it comes to power generation, there's very little margin for error. With few exceptions such as medical devices, equipment doesn't get much more critical than this. On Dec. 8, 1998, a massive power outage that affected more than 350,000 customers in the San Francisco area occurred when a utility worker tried to place a substation online while it was still grounded for maintenance (which likely included an oil change). This drew so much power from the transmission lines that 25 other substations in the area automatically and immediately shut down. Power was out from 8 a.m. to 4 p.m. Considering that the power outage spanned almost an entire workday in a major metropolitan area and that this happened in the era before widespread implementation of data disaster recovery, it's surprising that total losses were estimated only in the tens of millions.

Then there are wind turbines. Think its fun to change the oil about 400 feet above a raging sea in an offshore turbine? If ever there was an industry that could benefit from safely extending oil change intervals, wind turbines—with extremely expensive equipment and highly difficult to access mechanical parts such as gearboxes and generators—is it.

Any company in any industry dealing with one or both of these issues should take notice of an exhaustive study and 2006 report cited by the World Wind Energy Association. After running through seven cost-benefit case studies, the report concludes the following: "The above case studies clearly show the direct economic benefits of using predictive maintenance strategies and highlight the special importance of using such strategies in the context of wind turbines, where their unique operational considerations create additional abnormal stresses and strains.[6]"

Aggregates. It's not hard to imagine that the aggregates industry is heavily dependent on oil analysis and predictive maintenance. Much of the equipment involved is large, relatively expensive and critical to operations.

Keith Pittman, equipment manager for Aggregates USA in Macon, Ga., is responsible for 13 quarries. He says that while his company budgets for maintenance at regular industry-established intervals, regular oil sampling and the information it provides allows them to delay major rebuilds and significantly extend repairs.

"We've gradually been moving away from a preventive maintenance program toward a predictive maintenance program," he explains. "Oil sampling analysis provides insight into what is going on with each component on the machine. It gives us the opportunity to make educated decisions on rebuild intervals. We currently budget repairs at 25% longer life than manufacturer-recommended intervals, and oil analysis allows us to push these out even further."

He added that because of its aggressive oil analysis program, Aggregates USA has moved all oil-change intervals past 500 hours. Pittman believes the three most important requirements for a successful oil analysis program are:

1. **Education:** educating the mechanics taking the samples.
2. **Trend analysis:** taking enough samples to establish a trend.
3. **Follow-up:** repairing the machine when analysis indicates a problem.

Pittman explains that Aggregates USA saves resources, time and money through its oil-sampling initiative. "Our environmental-compliance people like it for obvious reasons, operations likes it because of the increased equipment up time we've experienced, mechanics like it because they can spend more time troubleshooting issues and less time servicing machinery, and the bean-counters like it because we spend less money on unneeded services."

Studies consistently show that, regardless of the industry, reactive maintenance is the least cost-effective.

OIL DEGRADATION STANDARDS

Following are a few standard and newer tests, in addition to viscosity index and total acid number (TAN), that labs most often use. The specific tests and frequency vary from lab to lab and company to company.

Fourier Transform Infrared Analysis (FTIR). ASTM D7418 Infrared Spectroscopy (Fourier Transform Infrared Analysis or FTIR) is a method for measuring the chemistry of organic molecular components. FTIR monitors additive depletion, organic degradation byproducts and a host of possible contaminants. It can verify the level of oil degradation by the identification of the functional groups (e.g., ketones, carboxylic acids) in molecules. It is an excellent test to measure chemistry changes of the fluid basestock in addition to identifying what is responsible for the fluid degradation.

The new ASTM standard for FTIR is a significant improvement over E2412. There are also several other specific methods that have been created:

- **D7214-07a:** Standard Test Method for Determination of the Oxidation of Used Lubricants by FTIR Using Peak Area Increase Calculation
- **D7412-09:** Standard Test Method for Condition Monitoring of Phosphate Antiwear Additives in In-Service Petroleum and Hydrocarbon-Based Lubricants by Trend Analysis Using Fourier Transform Infrared (FTIR) Spectroscopy.
- **D7414-09:** Standard Test Method for Condition Monitoring of Oxidation Antiwear Additives in In-Service Petroleum and Hydrocarbon-Based Lubricants by Trend Analysis Using Fourier Transform Infrared (FTIR) Spectroscopy.
- **D7415-09:** Standard Test Method for Condition Monitoring of Sulfate Antiwear Additives in In-Service Petroleum and Hydrocarbon-Based Lubricants by Trend Analysis Using Fourier Transform Infrared (FTIR) Spectroscopy.

Ultracentrifuge Test. This test uses gravity to extract and settle any oil contaminants—basically it isolates all insolubles. The sediments are compared with established sedimentation rates in order to determine the oil degrada-

RECOMMENDED OIL DRAIN INTERVAL EXTENSIONS[7]

Participating Fleets	Number and Type of Vehicles	Filter Make and Model	Miles Accumulated During Study	Oil Samples Collected	Original Drain Intervals	Proposed Drain Intervals	Projected Payback Period (yrs)
Department of General Services (DGS)	40 passenger cars	Fram X2	798,000	212	6,000	10,000	0.2
California Department of Forestry and Fire Protection (CAL FIRE)	13 two- and three-axle trucks	OilGuard EPS 60	134,980	42	5,000	18,000	3.1
California Department of Transportation (Caltrans)	5 two- and three-axle trucks	OilGuard EPS 60	160,711	39	6,000	18,000	1.3
Fresno Area Express (FAX)	10 city transit buses	OilGuard EPS 60	179,099	56	6,000	18,000	3.7
Fresno Unified School District (FUSD)	14 school buses	Luberfiner ZGard LPF9750	116,618	34	9,000	36,000	2.5
Long Beach Unified School District (LBUSD)	26 school buses	Luberfiner ZGard LPF9750	505,115	57	10,000	36,000	6.8
California Department of Corrections (CDC)	11 coach buses	puraDYN TF 40	949,649	100	10,000	50,000	3.6

tion. In the lab, the sample spins at 20,000 rpm in a centrifuge for 30 minutes. The minimum value of 1 represents no to low-total insoluble levels. The maximum value of 8 represents a critical level of insolubles. One of the limitations is that the process also can remove additives such as VI improvers, dispersants and sulfonates.

Membrane Patch Colorimetry Test (MPC). This test, designed to pinpoint soft contaminants, identifies the varnish potential rating and is based on colorimetric analysis. A direct correlation is made from the color and intensity of the insolubles to oil degradation. This test is highly sensitive and reliable. The procedure is currently going through an ASTM round robin to determine the precision of the method in an effort to publish a standardized test procedure.

STLE-member Greg Livingstone, executive vice president–business development for Fluitec International in Tucson, Ariz., explains that MPC is a combination of well-established patch testing methodologies that have been used for decades for fuel and lubricant contaminant analysis and research done by STLE Fellow Dr. Akira Sasaki on colorimetric testing. The method has been optimized for testing in-service turbine oils and assessing the fluid's potential to develop deposits.

"Most other oil analysis tests will not detect the accumulation of degradation products in a fluid that may lead to sludge and varnish," Sasaki says. "MPC is currently being used around the world to measure varnish potential in turbine oils and has proven to be indispensable as an early warning indicator of a fluid's deposit tendencies."

Gravimetric Analysis. This test determines the level of oil degradation by measuring the weight of residual components.

Rotating Pressure Vessel Oxidation Test (RPVOT) ASTM D2272. Oxidative stability is an important property of lubricating oil. The RPVOT test is a controlled, accelerated oxidation test that measures the performance of remaining antioxidant additives. Results are evaluated and compared to new oil levels.

Not knowing what you want to accomplish makes it hard to determine what you should be doing.

Linear Sweep Voltammetry (LSV). ASTM D6971 LSV (also known as RULER) determines the oxidative health of a lubricant by measuring the primary antioxidants it contains. LSV is a patented process of identifying the type and relative concentration of primary antioxidants in lubricants and greases. It's currently in five ASTM procedures and provides deeper insight into the health and remaining useful life of the fluid. Alternative methods of measuring primary antioxidants rely on indirect measurements, such as determining the oxidative stability of the fluid through stress tests like RPVOT. Although there is value in performing oxidative stress tests in many situations, LSV has proven advantageous in monitoring in-service fluids used in oxidative environments because of the test's higher precision and faster results.

Livingstone explains, "MPC and LSV tests are complimentary in nature and are often coupled together when performing analysis on in-service turbine oils. LSV is also applicable in a wide range of other lubricants used in oxidative environments ranging from diesel engine oils and helicopter jet turbines to specialized synthetic fluids used in offshore wind power."

EDUCATING USERS

According to STLE-member Cary Forgeron, national sales manager for Analysts Inc., in Hawthorne, Calif., there are three common user pitfalls regarding predictive maintenance programs.

1. **Thinking that one technology is enough.** "A common misconception many inexperienced practitioners have is that one technology can tell them everything," Forgeron says. "There are limits to every technology. Utilizing a single technology leaves the practitioners vulnerable to potential problems that are not detectable by that technology. For example, oil analysis cannot identify a misaligned bearing until sufficient damage has occurred. Not knowing what tool to utilize in your predictive toolbox can leave you blind."

2. **Doing too much too soon.** "A predictive maintenance program requires a lot of planning and education before it can get off the ground," Forgeron says. "I have been to many facilities to help review their oil analysis programs. The first question I always ask is, 'Why are you doing oil analyses. While the responses vary, a common answer is, 'I don't know.'"

Forgeron says that not knowing what you want to accomplish makes it hard to determine what you should be doing. He adds that starting with a clear and measureable objective (i.e., reducing the number of bearing failures) is the best way to begin. From there users can choose the predictive tool most applicable to accomplishing those goals. He suggests starting small with 5-10 critical pieces of equipment and expanding from there.

3. **Not understanding the sampling process.** "The biggest drawback I see for an inexperienced practitioner, as it relates to my field of oil analysis, is understanding the sampling process," Forgeron says. "Oil analysis is a science, and the tests are only as accurate as the sample they are performed on." Improper oil sampling can lead to a false positive, which results in shutting down equipment unnecessarily. Even worse, it can lead to a false negative, which can lead to an unidentified equipment failure. The person taking the sample is just as important as the person interpreting the results, but insufficient training

Trend analysis is the core component of predictive maintenance.

often leads to the sample taker being the weakest link in the predictive maintenance chain.

The objective of oil analysis is to provide early detection of incipient lubricant degradation, identify contaminant ingression and monitoring machine health by trending the addition of wear metals.

"Lubricant analysis can be considered in two ways: from a mechanical perspective and a chemical perspective," Livingstone says. "Seldom do we see someone have a strong aptitude in both fields. The first sign of fluid degradation is detectable by chemistry changes in the lubricant, making oil analysis such a strong predictive tool for reliability engineers. Eventually, as the fluid degrades it impacts the mechanical functioning of the equipment. At this point however, the plant is forced to take much more resource-intensive, reactive maintenance actions."

He adds, "In order for oil analysis to be an adequate predictive tool, the correct tests must be done at appropriate intervals. Although this sounds obvious, far too often we see valueless tests being done at inappropriate intervals in order for the program to provide significant predictive value. The biggest challenge that we have as oil analysis practitioners, however, is translating laboratory results into real-world knowledge that allow plant operators to assess the risk of taking action versus not taking action. Ultimately, this requires the marriage of chemical and mechanical knowledge. However, plants that bridge these two disciplines gain tremendous value and competitive advantage by using oil analysis to increase the profitability of their operations."

If performed correctly by an experienced lab and experienced technicians, predictive maintenance is one of the most cost-effective equipment maintenance procedures around for many types of equipment. The key to a successful program that consistently yields a significant return on investment is choosing the right equipment and the right lab. **TLT**

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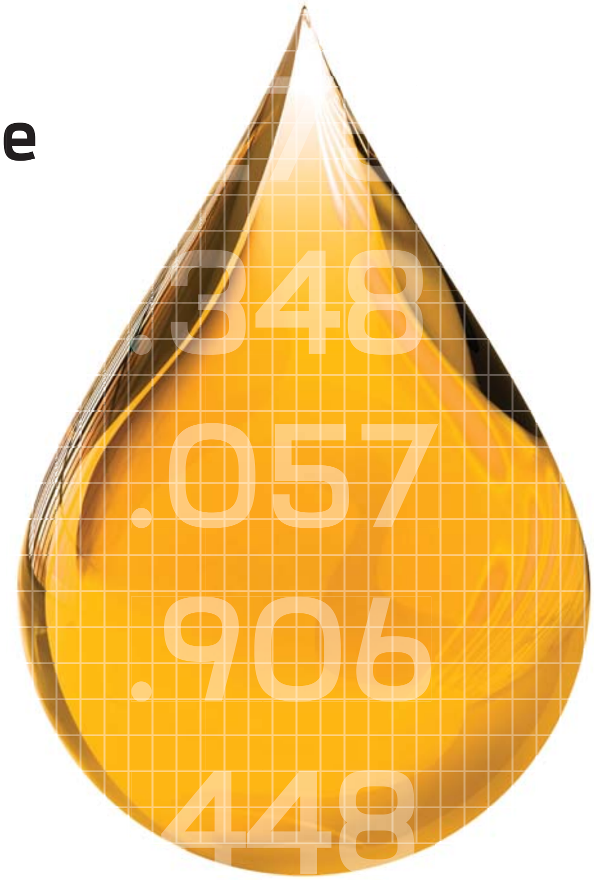
How will oil analysis change five years from now?



Nearly two-thirds of TLT readers believe that oil analysis is on the cusp of major changes compared to how it's traditionally been conducted. More real-time testing with handheld instruments (potentially mobile devices) at the machine's location is expected. Most everyone agreed results would be generated quicker and delivered to the customer faster. Asked about the most important elements of oil analysis, readers noted the importance of proper sampling techniques, providing accurate information about the machine's usage and operating environment, taking consistent reports to establish baselines as opposed to reacting to a single value and acting on the report's recommendations. Many TLT readers noted the ongoing battle in getting senior managers to buy into the program. "Without their support, the program's longevity and effectiveness are weakened," said one respondent.

It will give faster results.

More recovery or decontamination efforts. Offline filtration systems. Possibly more on-site equipment or built-in inline testing.

Basic analysis will occur on-site.

More synthetics, more on-site particle counting equipment.

Sensor technology will make oil analysis substantially different.

It will most likely be more done with portable instruments at the plant sites by reliability personnel.

There will be new ASTM tests to better evaluate the suffering points of the newer oil technologies.

As the cost of finished lubes continues to rise, the end-user will want to extract the most value out of a lubricant.

I would expect more automated oil analysis at the local level so samples are no longer sent to an analysis lab but are analyzed by a handheld device that provides results almost immediately.

We will see a significant increase in the use of mobile devices to screen oil condition at first line.

Oil analysis in the field as accurate as any lab.

Less hands-on work as technology becomes more prevalent.

I can definitely see mobile apps and more employees understanding and being trained in oil analysis.

I doubt much will change in the next five years.

I expect real-time, online oil analysis sensors installed directly onto equipment.

The price will be lower and the technology nearer the people.

Testing laboratories will have to get creative and find ways to justify their services. I suspect they will have to offer more than just data.

Increased use of full synthetic lubricants. Increased use of oil analysis requiring better ways to monitor and act on incoming data.

In the future, your reports will come from lab to phone for viewing on the fly.

Testing should remain the same or similar to adapt with new products. However, reporting should certainly be accessible with mobile devices and other Internet access/platform.

I don't really think it can go much further. With the technology available, it is providing great insights into failure analysis and product life.

Less reliance on the laboratory results. With handheld and bench devices in-house, answers are available within minutes instead of hours/days. Of course, the lab report is still needed.

A continuous inline condition monitoring gadget in diesel truck fleets could dramatically reduce the number of samples sent to traditional used oil analysis labs.

As oil quality continues to improve, there will be a greater percentage of certain applications, such as automatic transmissions, that will be filled for life. As inline oil analysis and remote monitoring capabilities expand, there is likely to be more remote monitoring through a centralized hub.

The use of new technologies will enable more equipment to notify owners when oil needs to be changed.

I think results will be available quicker, and each sample will have more parameters tested.

I think there will be more real-time and online oil analysis, giving operators instant information about when the fluid needs to be changed and when equipment is having issues.

It will be exactly the same. No one will bring a mobile device into a dirty machine shop floor. Maybe in a lab there will be more tablets, but that's a big maybe. I still like writing on paper.

I think portable devices will continue to gain acceptance and market share. Ultimately, miniaturization of tests to the point of having a "lab on a chip" type design is the goal.

More oil analysis on the fly. Real-time oil analysis will be more common.

I would like to see a reasonably priced portable unit that can do a thorough analysis in the field in real-time.

In-service grease analysis will be more mainstream.

I think with wireless monitoring and the growing understanding of world-class maintenance, more analysis will be done in-house.

More rapid responses focusing on root of problems.

More online real-time analysis. Will trends be monitored adequately?

There will be more exchange of information electronically for sample registration, tracking and reporting. The use of sensor technologies and on-site testing will increase. These will provide basic rapid information to the users. Laboratories will need to become more specialized in filling in the gaps in this information through proper advanced test selection. While sample volumes will drop, revenues should increase due to the increase in specialized services.

Do you think oil analysis is on the cusp of major changes compared to how it's traditionally been conducted?

Yes	63%
No	37%

Based on responses sent to 13,000 TLT readers.

All samples will be barcoded for identification and registered using a smartphone app.

Oil testing will be more of an on-site application with the site-maintenance expert conducting the analysis.

Much easier for routine analyses. Much more powerful for specialized analyses.

We see wide variations in analysis use, from zero by some companies, to complete programs covering almost all equipment. I believe in five years we will see more companies taking the plunge and investing more resources to obtain the data. The most important thing is to act on that data.

What is the most important issue in analyzing oil analysis reports?

Diagnosis: Is the equipment right or wrong?

Each report is a peek into a specific time element that, in itself, is not necessarily relevant. Trending is the issue.

Read the data yourself. Lab technicians don't have the time to interpret and often misread data, arriving at wrong conclusions. If you don't look for yourself, it will cost you.

Trending is just as important as established limits.

Knowing the correct data such as specific lubricant, machine data and seeing a trend.

In addition to lubricant condition, equipment condition also can be determined.

Interpreting how the lubricant condition will affect machine serviceability and condition.

Trends are more important than any particular number of a single constituent.

Proactively understanding oil condition is important in helping customers understand when they need to take actions to change oil and maintain the equipment.

Accuracy of oil analysis to determine oil conditions.

People need to understand these reports can be quite subjective. Often results depend on the person doing the analysis.

Understanding the application and piece of equipment.

Fault diagnosis: Make a judgment on the fault and its main cause.

Relationships between perceived severity of results and actual asset risk.

Trending is critical as well as full information regarding the oil sample.

That the data is only as good as the procedures used to gather the sample.

What a normal sample of that particular product should look like and trending it over time.

Understanding how your current report relates to the new oil and also trending patterns.

The machine's operating conditions.

You need to understand the chemical processes that may be degrading the fluid.

Trend analysis. Not focusing on just a single sample but how past, current and future data relate to each other.

To actually know what you're looking at and what you're looking for.

Knowledge of additive composition and chemistry.

How and where the sample was made.

With best practice sampling and frequent sampling, the results are better understood. Interpreting the data is then simple and not guesswork.

Improper sampling (technique, location, etc.) may create false alarms or a false sense of security.

Taking action on the data is the reason for the program.

Remember that oil analysis is a trending tool. The results of a single oil analysis determination can be inaccurate with regard to the true condition of the lubricant and the equipment.

How are you going to use the data? For example, is it to schedule downtime?

You need to know more about the starting point lubricant formulation before you can really understand what you are monitoring.

Fitness for purpose and evidence of wear or overheating.

Experience and a knowledge of the specific equipment. Don't do things in a vacuum.

Assuming the test results are accurate, having the proper background information about the sample is important for properly interpreting an oil analysis report.

History—comparisons on a given oil in a given engine in comparable operating conditions.

What it actually means and what the data shows as compared to new oil.

Baselines and how trended analysis is deviating from this baseline.

It is very important to understand the equipment being sampled and environment where the equipment is located.

The importance of reading the recommendation comments from the laboratory prior to reviewing the numerical results. The comments are a good summary of the data to follow and address changes in wear and lubricant physical properties. Jumping directly to the data often brings minor data changes to the front that have no real diagnostic value.

Look for multiple signs and symptoms to diagnose the machine's condition.

The health of the fluid.

The limits that should be set for that specific type of equipment.

What the numbers mean and how a trend is established.

Trending shows change in operating conditions and wear rates.

What's wrong and why.

What are the most common mistakes people make with oil analysis?

Improper sample taking and incomplete information.

Improper flush of sample valve and/or tube. The importance of drawing during flow without disturbing sample valve or introducing external dirt, which can result in concentrated, contaminated or unrepresentative sample.

Expecting that the oil analysis is going to describe exactly where the failure is.

Besides cleanliness issues and lack of continuity, it's thinking that one sample makes a trend.

Trusting the comments section of the report.

Failure to provide the required sample information to provide an accurate oil analysis.

Not following up when a condition indicates a potential problem.

Being solely dependent upon oil tests and not considering other factors such as vibration, operating parameters and maintenance practices.

They do not fully understand the implications of some of the minor constituents and therefore make errors in application of the analytical information.

People assume oil analysis has the same properties in engines.

Waiting until they find problems with equipment before starting to test on oil. This is often too late as the equipment has started being affected from the "bad" oil's condition.

Oil renewal based on oil analysis.

Relying on the report without taking into account everything that is going on with the specific equipment and operating systems.

They go through the motions of pulling samples but don't follow through when the reports come back.

Ignoring reports with no alarmed values, waiting for values to exceed alarms before reacting and not properly evaluating what triggers an alarm.

Not understanding how to read the reports and what the data is telling us.

Ignoring environmental factors.

Providing sketchy supporting information to the lab. Not taking actual runtime into account when reacting to changes in results.

Not taking secondary samples.

Sample contamination.

Only looking at highlighted areas or zeroing in on the area where it is passing (green) concerned (yellow) or needs changing (red) and not actually reading the entire report and individual results.

Only looking at the comments and not the actual test data.

Not reading the reports or knowing how to interpret them.

They don't see trends and element rise (Fe, Cr, Cu).

Assuming that the sample received is representative of the bulk of the oil.

Not recognizing contaminants and diluents.

Equipment and lubricant decisions based on a single set of analysis results.

Testing only when there is a problem.

Most people cannot interpret the results and lack a baseline to understand what those changes really mean about the fluid performance.

They make a conclusion before completing all the tests. They jump the gun with a couple test results when they don't have the full picture.

Not recognizing that competing physical and chemical processes can counteract each other.

Taking action without confirming an abnormal finding.

Not viewing all results holistically.

Not doing it often enough. The real value is in wear trending and optimizing lubricants and change intervals.

Failure to interpret properly the trending of results away from baseline data, resulting in the customer thinking the oil is satisfactory for continued use when, in fact, it is not.

The program is not sold to the top managers.

People think in terms of Go/No Go when they read reports. Data are seen in black and white with no room for nuance in interpretation.

Sending in samples without a reference point.

They only react to cautions or alerts, have very little ability to understand the data that the analysis produces and don't do consistent periodic reviews to identify suffering points.

Mislabeling samples can create a lot of false red flags.

Not requesting the correct test slate to meet their goals.

Waiting too long to retest to confirm results.

Taking the analysis as a be-all and end-all. One should take time to make sure that the analysis is a value-added item that enhances equipment life. TLT

Editor's Note: *Sounding Board is based on an e-mail survey of 13,000 TLT readers. Views expressed are those of the respondents and do not reflect the opinions of the Society of Tribologists and Lubrication Engineers. STLE does not vouch for the technical accuracy of opinions expressed in Sounding Board, nor does inclusion of a comment represent an endorsement of the technology by STLE.*