
***Industrial Lubrication
& Oil Analysis
Reference Guide***

Rapid Hydraulic Cleaning Using Advanced Filtration Equipment

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The modern hydraulic system in mobile equipment requires a much more stringent level of maintenance in terms of cleanliness and general care. Once these systems go down, the task of bringing them back in service involves advanced cleaning procedures and sophisticated cleaning equipment. Additionally, keeping machines clean during normal operations may require the help of an advanced filter caddy, since certain applications can cause more contamination than the machine's own system can remove.

Having instant visibility to oil cleanliness as well as removing contaminants is feasible today. This involves removing fine particles and humidity. Everything can be accomplished all at once with an onsite practice using intelligent filter caddies. These filter caddies allow the technicians to accomplish successful repairs or extend hydraulic fluid and machine service life.

Why Do Hydraulic Systems Fail?

Different industry statistics show that the majority of failures of hydraulic systems are caused not by design flaws, but by contaminants, water or lubricant degradation. Contaminants are produced in different ways; they could be generated inside the hydraulic system, uninvited contaminants from the surrounding environment, or resident contaminants from the manufacturing process.

Solid particles are not the only contaminants. For instance, chemical reactions between lubricant additives and water can produce different chemical by-products that could be corrosive to vital components inside the hydraulic system. They could also destroy oil film strength where it is most needed. Air and high temperatures are also considered contaminants.

Typically hydraulic systems are designed to provide many years of trouble-free service. However, in many instances, the environment in which these components work could have been altered by some contaminants that were not detected in time and that the system's own filtration mechanism is unable to handle.

The second series of events occurs when the technician, ignoring the micro world on which the hydraulic system is so dependent, limits his actions to replacing the most affected component and the oil from the reservoir, leaving behind millions of destructive particles and degraded fluid lodged in lines, valves, coolers and crevices of all kinds. The results are always the same: premature failure of the main component and an even greater level of contamination. The story is repeated over and over again creating frustration among technicians and users of equipment.

What Happens Inside a Hydraulic System During a Failure in Progress and After Total Failure?

High particle counts tend to erode soft metals and increase wear in all

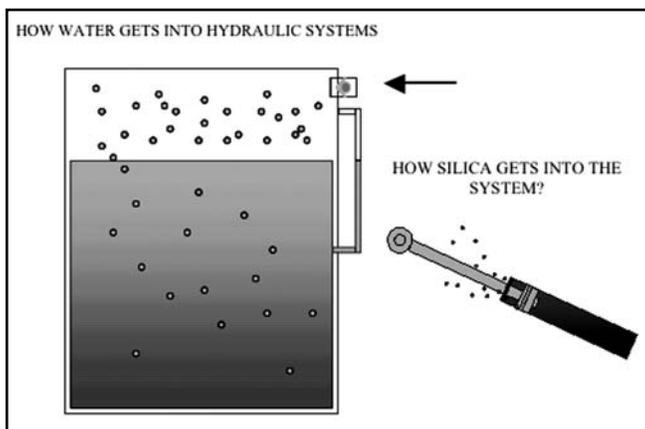


Figure 1.

moving parts. In addition, chemical reactions between additive and water or incompatible oils cause etching. Bronze etching, especially in high-pressure axial pumps, reduces pump efficiency, and increases internal leaks, thus causing the phenomenon known as "lifting." Lifting is the rapid hammering of the piston slippers from the swash plate which results in the self destruction of the slipper.

High temperatures, on the other hand, reduce oil additive life and destroy further ability of the lubricant to separate parts in motion. Metallic particles also contribute to rapid oxidation of the lubricant. The destructive pattern has begun and total failure of the most active components is imminent.

After a catastrophic failure, millions of metallic particles, fibers and contaminated oil reside in every corner of the hydraulic system. Replacing the oil from the reservoir accomplishes only one third of the actions required to restore the system.

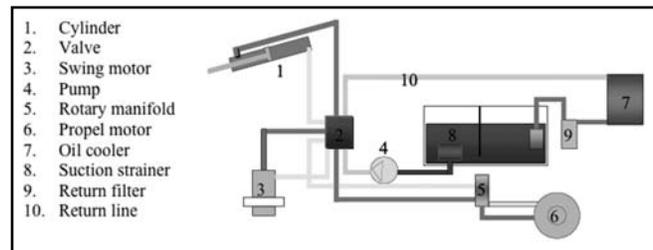


Figure 2.

Is the Filter Caddy Capable of Removing All Contaminants From a Failed Hydraulic System?

The answer is no. As explained in the previous point, the amount of hidden particles in the most secluded areas of the hydraulic system makes it impossible for any caddy filter to reach the intricacies of complex hydraulic systems. However, a filter caddy is an essential tool once the system has been totally disassembled, cleaned and put back together. At this point, the filter caddy becomes an essential tool.

Why is a Filter Caddy so Essential in the Successful Repair of Hydraulic Systems?

Once a hydraulic system has been overhauled and all components put back where they belong, the most critical part of the start-up procedure is when the hydraulic pump is turned for the first time. It is recommended that the hydraulic system be filled with a filter caddy that allows the washing of the reservoir until a pre-determined level of oil cleanliness is achieved. Then the pump needs to be bled and cylinders filled with clean fluid as well, and only then can the hydraulic system be put into operation. The caddy insures that the reservoir is clean before the pump is turned for the first time. This operation is not feasible without a filter caddy.

Filter Caddying Versus Flushing. What is the Difference?

Filter caddying, as described in the previous point, takes part in the final step of bringing a hydraulic system back to operational condition. Filter caddies are also a conditioning unit for hydraulic systems that only require cleaning. Flushing, on the other hand, is the total cleaning of the hydraulic system by actually removing all the fluid and the components and cleaning or repairing them as required.

At What Point can the Filter Caddy be Used to Clean the Rest of the Hydraulic System?

When the reservoir in a hydraulic system has been cleaned to a determined cleanliness level, the hydraulic system is considered to be ready for operation. Typically, the system is operated at low speed and relief valves are adjusted to the lowest possible pressure. By making the hydraulic pump start pumping oil slowly through the main valve, we assure that the remaining particles still in crevices, valves or lines are brought back to the reservoir through the return filter. A smart filter caddy must continuously monitor oil cleanliness after running. Once this is assured, the rest of the operating components on the hydraulic system are actuated, taking the same care to monitor particle counts coming from other components in the hydraulic system.

How Can Land Hoses be Cleaned?

The use of sponge projectiles is becoming popular. These allow cleaning of hoses and lines regardless of their length and angles. These sponge projectiles are shut with compressed air and, traveling at great speed, push contaminants out to cleanliness levels unattainable by conventional methods. The picture below shows a real case where metal chips coming from a failed pump had lodged in a main hose. Without the sponge projectile, the cleaning of this hose could have not been accomplished, and having this tool handy saved the owner from having to replace a second pump or valve.

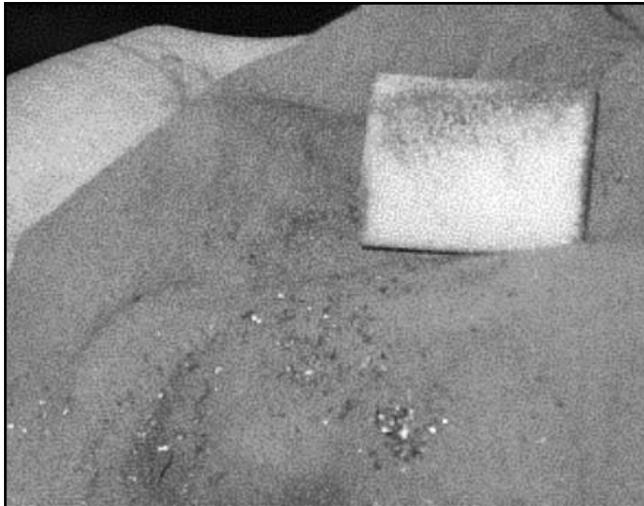


Figure 3.

Can Oil Coolers be Saved?

In catastrophic failures, the amount of debris collected in oil coolers makes it impossible to clean them to a safe level. However, in highly contaminated units where a massive failure has not occurred, the oil coolers can be flushed, assuring a safe cleanliness level. The filter caddy would be an ideal tool for this task.

What Should a Good Filter Caddy Provide?

- Fast cleaning cycle
- Particle count measurement
- Water monitoring unit
- Temperature reading
- Flow meter
- Fine particle removal
- Good dirt-holding capacity
- Good filter Beta ratio
- Free water removal
- Transfer function
- Automatic shut-off
- Variable flow capabilities
- Light weight
- Good balance
- Spill tray
- Hose wands in one side
- Drawer for connectors and manuals
- Sample valves

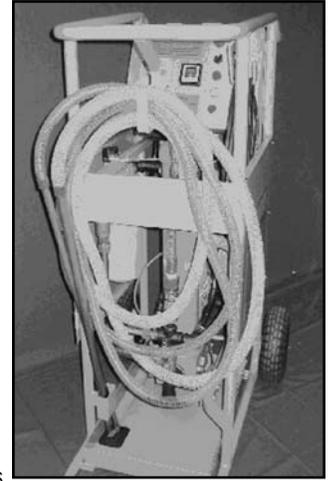


Figure 4.

How Can We Handle Different Oils? Can Different Oils be Mixed?

The handling of different oils needs special care. In general, mixing oils of a different nature, i.e., engine oil, hydraulic oil, or tractor fluids is not recommended. The additive concentrations and types are different. Engine oils, for instance, have good amounts of detergents, which oils are not necessarily present in hydraulics. Tractor fluids have EP additives that don't get along well with AW additives from hydraulic oils. The mixing of oils brings changes of viscosity and possible oil film strength loss. Besides, oil additives tend to fight for space over polar surfaces, debilitating either the corrosion or the anti-wear properties, increasing the level of metals in the fluid.

When using a filter caddy with different oils, it is a good practice to have different sets of hydraulic filters. The filter caddy operator can switch to a different filter set which are stored in identified PVC tubes protecting them from contamination.

What Micron Media and What Beta Ratio are Required in Filters?

When we talk about filter micron media we need to clarify what standards we are using. The current standard ISO 4406 from 1999 of 4.2 micron, for instance, is approximately equivalent to the pre-1999 standards at 2-micron. It is always good to refer to the latest standards. A current 6-micron media is extremely effective in removing the bulk of the particles and in achieving very good oil cleanliness. It is not a good practice to install the smallest micron media filters if you want fast cleaning, especially if the filter used does not have good efficiency. It would make no sense to use a 3-micron media filter if its Beta efficiency at 3 micron is poor. However, if the issue is silt level removal, it may justify the use of 3 micron media to take care of this situation.

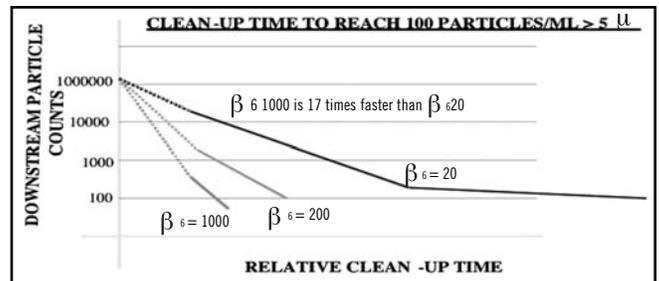


Figure 5. Courtesy of Pall Corporation.

Another issue to consider is the type of fluid being cleaned. Engine oils used as hydraulic fluids, for instance, have large amounts of detergents that will produce high 4-micron readings which are represented by these additives. Thus, getting to 22/15/12 cleanliness level is very normal and nothing to worry about. Pure hydraulic fluids, on the other hand, have little or no detergents, and getting a cleaner 4-micron reading is not difficult.

How Additives Fight for Space

Extreme pressure additives, namely sulfur and phosphorus, react to metal contact differently. They help by providing extreme pressure and anti-wear characteristics to the metals. Sulfur absorbs to the surface, and it is more stable imbedded to the metal. However, phosphorus only clings to the surface and needs to fight for space with corrosion inhibitors.

When the wrong formulation exists, anti-wear and EP additives may break the balance of these additives allowing metal to metal contact or lack of corrosion protection. This is the case with mixing different types of fluids.

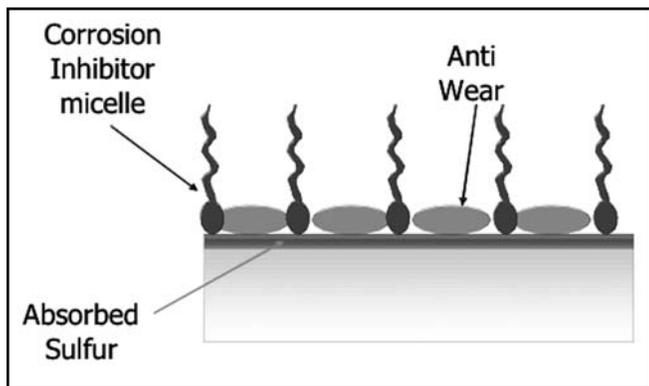


Figure 6.

Wouldn't Two Filters in Series at Different Micron Ratings be Better for a Caddy Filter?

The question of having one filter versus having two filters in series is a matter of economics. Some caddies have larger micron media to catch large particles and a smaller micron media filter for the fine particles. However, having one good micron media for all kinds of particles simplifies the operation and reduces the need to stock two different part numbers.

Water Removal Filters

Some water removal filters are made of water absorbent material. They can also act as particle removal units but their primary function is to remove free and sometimes emulsified water. Other technologies use highly restrictive cellulose filters that are also good at removing water and particles but at much slower speeds. Most of the oils have some level of water content, especially those containing detergents. Monitoring water content and having a water removal filter permanently installed are healthy practices. This would keep humidity within the range considered acceptable.

How to Interpret Water Content is the Question, PPM or Percentage of Saturation?

The question of how to interpret water content, if in percentage of saturation or in parts per million by weight (PPMw), is a matter of understanding the benefits of each one. The advantages of measuring water content in percentage of saturation are demonstrated in the chart from Pall Corporation below. Since oils change their water saturation point (their ability to hold water) with temperature, knowing their water percentage of saturation at different temperatures makes it much more usable than simply having a fixed figure on PPMw as we are accustomed to seeing. The

chart below shows that the PPMw remains unchanged during different temperatures, which is not very useful information.

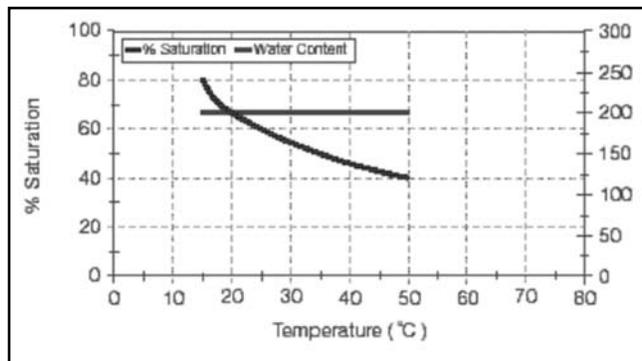


Figure 7. Courtesy of Pall Corporation.

Filter Dirt-holding Capacity.

The number of gallons of oil that can be cleaned to a higher cleanliness level with the same filter is subject to the design of the filter and its capacity to hold dirt. However, it is important to know because it will determine the cost per gram of dirt removed. The amount of dirt to be removed from hydraulic systems is directly related to the size of the system and degree of contamination in terms of grams of dirt. This should allow calculations of filter life when a continuous use of the filter caddy is planned. Certain hydraulic system contaminations make it impractical to clean them and one needs to determine the benefits of using a filter caddy. For example, to clean oil that is contaminated to the level of ISO 24/23/20 makes no sense if the condition of the additive package is suspect. Additionally, you need to consider the life of the filter caddy's pump.

Are Automatic Shut-off Devices Required on Filter Caddies?

The automatic shut-off devices are convenient for the operator since he can leave the unit running without having to baby-sit. The automatic shut-off devices operate in conjunction with the particle counter to trigger the shut-off mechanism when the oil has reached the selected oil cleanliness level.

GPM, at What Speed do we Want to Filter the Oil?

With modern equipment running large reservoirs, the time to clean the oil in the system, not just the reservoir, becomes an issue to be considered. While slow flows may appear to be better for cleaning purposes, high flows actually produce turbulence in the reservoir which washes walls and keeps particles in movement. From the labor and energy point of view, the most economical procedure is the fastest procedure.

Another issue to consider is the viscosity of fluid being cleaned. Engine oils used as hydraulic fluids like 10W-30 oil will have an ISO viscosity close to 75; compare this to pure hydraulic fluid at 46. Thus, cleaning time will be limited by a filter caddy's pump cavitation, especially if oil temperature is below 80 degrees F.

Service Shop Versus Field Units, how Large Does the Filter Caddy Need to be?

The practicality of size is directly related to the size of equipment the user is planning to service and the location of the equipment. While a large unit may allow the use of larger filters, increasing dirt-holding capacity, the mobility and logistics of the transportation of the unit plays a role. In a one-man service environment, you may need a filter caddy that is easy to move and transport and that can maintain its integrity during transportation. The concept of a lab truck may also become popular as the filter caddy is permanently installed in a truck, facilitating the operation to the technician.

Is Variable Flow a Requirement in Filter Caddies?

Variable flow is a desired feature to handle oils that are cold, during the wintertime or where initial pumping at the rated GPM is difficult. There are associated problems with pumping cold oils at full GPM. One of them is the possibility of cavitating the pump and producing air that interferes with

proper readings of the particle counter. Once the proper temperature is achieved, the resistance to flow reduces and the flow can be increased with the variable speed device. This device also allows special uses for the filter caddy like filtering small compartments where high speed is not needed or could even be a problem.

How to Set Target Cleanliness Levels for Contamination Control

By MARTIN WILLIAMSON B.Sc., NORIA UK LIMITED

The question of what is an appropriate cleanliness level is often asked when embarking on the introduction of an oil analysis program. This cannot be answered without considering the issues of production priority and costs, environmental restraints, safety requirements and reliability needs. A number of generic processes exist, but this method develops on the strategy of the reliability penalty and the contaminant severity. It is aimed primarily at fluid power equipment but is easily adjusted to consider the needs of other equipment types. The results obtained using this method will also dictate to some extent the appropriate method of sampling and the frequency thereof.

INTRODUCTION

The purpose of this paper is not to educate the user on the benefits of proactive maintenance, these are clearly documented elsewhere by many authors. This paper will not suggest specific targets that can be applied across a range of industries or applications from a menu selection. Nor is it the purpose of this paper to describe the meaning of the ISO 4406 codes used herein.

So what will the reader gain from this paper? To summarize James Fitch's statement, 'Proactive Maintenance in three easy steps,' the first is to set cleanliness targets, the second is to take specific actions to achieve the targets and the third step is to measure contaminant levels frequently. The aim of this paper, therefore, is to guide the user to consider each situation as a unique entity and work from that point forward with one goal in mind, to set the optimum target cleanliness level as per the first step. The use of the word optimum is very important, since one could feasibly achieve aerospace standards of cleanliness, but at an implementation cost that outweighs the financial benefits sought.

The paper describes a process that considers a factor or score based system to simplify the mathematics and to use a matrix to evaluate the operating reliability and safety issues against the sensitivity of the system to contamination.

Select Cleanliness

Having acknowledged that cleanliness and contamination is the key to a proactive maintenance strategy, the first step is already a long way towards implementation. Solid particles, regardless of their source, (built-in, ingested or wear debris) lead to lubricant failure and ultimately to increased wear levels in the system, so the lubricant cleanliness is a crucial aspect of best practices lubricant management.

In order to strike a balance between the cost of implementation and maintenance of the improved cleanliness control measures, and the benefits actually achieved, it is necessary to define a Reliability Penalty Factor and a Contaminant Severity Factor. These two factors should be used to set the goal-based limit for cleanliness. What is a goal-based limit? It is a limit that is set that brings a measurable level of improvement to the organization with a focused effort.

While manufacturers and vendors often supply guideline cleanliness limits, these should be viewed as a ceiling rather than a target. Unless it is a purpose built system, the machinery may be used in a variety of applications and environments, hence any sensitivity to contamination may be adversely affected by the conditions. For example, a gearbox operating in a semi-conductor plant is generally in a clean, dry environment. However, the same gearbox in a titanium grinding plant is subjected to extreme levels of very hard particulate dust and water.

Hence, use the OEM specification for cleanliness as a guide only and remember that as the user, the cost of failure and downtime is personal to the organization, not the OEMs.

There are a number of guideline values offered for cleanliness limits, which to some extent consider the operating environment since companies within an industry typically have similar conditions. Figures 1, 2 and 3 detail some of these guideline cleanliness levels.

Calculating the Reliability Penalty Factor (RPF)

In Figure 4, there is a chart detailing the scoring process for calculating the Reliability Penalty Factor (RPF). The scorecard covers four essential aspects to the cost of failure, namely; safety, cost of downtime, material and labor costs to repair, and the effectiveness of early warning systems. Each section carries a rating that must be used as objectively and consistently as possible. A group session among colleagues often helps define these numbers more realistically.

Safety Risks upon Failure

One's first thought is towards safety of personnel, which should always be held as highest priority over any other aspect of the business. While it might be simple to say that minimal risks are present to personal near the equipment, consider the long-term effects, and what environmental damage may subsequently cause a safety risk. Safety and environmental are equally important and are often allied. The health and safety officer should be consulted in these decisions since a Failure Modes Effects and Criticality Analysis (FMECA) may have already been undertaken, however, the officer concerned is best placed to define the risks associated with regard to the dangers of failure or lubricant leaks, particularly on high pressure systems or high speed rotating equipment. Based on the decision of the worst case for a machine point, place a score in the box.

Machine	ISO
Ball bearing	16/13/11
Roller bearing	17/14/12
Journal bearing	18/15/12
Industrial gear box	18/15/12
Mobile gear box	18/16/13
Diesel engine	18/16/13
Steam turbine oils	18/14/11
Paper machine oils	18/14/11

Figure 1. Guideline Cleanliness Levels (Ref: JCF, Pall, Exxon).

Cost of Downtime

Consider the downtime costs of the machinery and the time to rectify. These values are often known to the accounting and planning teams and can be applied accordingly. The scoring does require a weighted average to be considered for the scoring and in some cases; a unit's downtime and repair costs may vary widely depending on the nature of the failure.

Therefore, a weighting needs to be applied to the amount of times a serious failure occurs against a minor failure. It may be necessary to conduct an audit or survey to determine the criticality of each module of the plant since one unit may be a bottleneck and completely stop production, while other components may only impact a small area, or stockpiling may be used to allow a buffer period to rectify. Sometimes these bottlenecks, or critical points in the plant are easily identifiable and maybe the target of a productivity improvement process already. However, taking the lowest per hour downtime cost as zero and the highest cost for the site as three use the downtime cost against this ratio to select a score. In addition, rectification of a high cost of downtime unit may be short whereas a low cost of downtime unit may require a lengthy rectification. Again, the comments on a weighting occur since the time for rectification may vary. Once the two factors are scored, multiply the two values and place in the score box.

Operating Pressure →	1500-2500 psi		
	<1500 psi	1500-2500 psi	>2500 psi
Servo Valve	18/14/12	15/13/11	14/12/10
Proportional Valve	17/15/12	16/14/12	15/13/11
Variable Volume Pump	17/16/13	17/15/12	16/14/12
Cartridge Valve	18/16/14	17/16/13	17/15/12
Fixed Piston Pump	18/16/14	17/16/13	17/15/12
Vane Pump	19/17/14	18/16/14	17/16/13
Pressure/Flow Control Valve	19/17/14	18/16/14	17/16/13
Solenoid Valve	19/17/14	18/16/14	18/16/14
Gear Pump	19/17/14	18/16/14	18/16/14

Figure 2. Typical Hydraulic Fluid Cleanliness Targets (Ref: Pall).

Rolling Element Bearings:	ISO
STLE/CRC Handbook	14/12/10
SKF	13/10
FAG	12/9
Pall (Ball bearings)	15/13/11
Pall (Roller bearings)	16/14/12
Journal Bearings (Pall)	17/15/12
Industrial Gearbox (Pall)	17/15/12
Small-medium Size Gearboxes (SKF)	14/11
General Power Transmission Gearboxes (SKF)	15/12
Large, Heavy-Duty Gearboxes (SKF)	18/13
Mobile Gearbox (Pall)	17/16/13
Diesel Engine Lube (Pall)	17/16/13
Turbine Oils:	
ABB STAL (Industrial Steam), Westinghouse Trent (Gas)	14/11
ABB STAL (Gas), Siemens AG, GE (Industrial)	15/12
ABB (Utility Steam), Parsons	16/13
Westinghouse (Utility Steam), GE (Large Steam)	16/13
Paper Machine Oils:	
Pall	19/16/13
Exxon	16/13

Figure 3. Recommended Cleanliness Levels for Lubricants (Ref: Pall, Needleman).

Material and Labor Cost to Repair

Apart from the cost of downtime, the accounting and planning teams can assist in identifying the associated costs of material and labor to repair or rectify a failure, and the comments on weighting apply once more. Using the lowest cost to the highest cost for the survey apply a score accordingly. Bear in mind all the costs and do not forget costs such as subcontracting (such as for rebuild, crane hire, etc.) or the cost of stopping other functioning systems in order to affect the repair safely.

Effectiveness of Early Warning Systems

This may seem an odd parameter to consider when one is implementing a condition-based monitoring strategy. However, rotating equipment may have permanently mounted devices for vibration analysis, or magnetic detector plugs that may shut the system down in the event of being triggered. However, these are often predictive rather than proactive, and like the oil pressure warning light on the car dashboard, only trigger when the damage is done and avoid catastrophic failure at best. If no detection systems are in place then a score of three should be applied.

Composite RPF Score

By adding the four scores a number can be applied. In many cases this will vary between three and six for example, but in extreme cases may be as high as twenty. To avoid excessive values, a maximum score of ten should be used.

Calculating the Contaminant Severity Factor (CSF)

The questionnaire shown in Figure 5 is aimed at Hydraulic or fluid power systems, and is self explanatory in terms of the questions and the scoring. Again a maximum factor of ten is applied to avoid readings that are difficult to measure consistently, bearing in mind that the best practitioners may be able to measure an ISO 4406 reading of 11/9/6 via bottle sampling. An online instrument is perhaps better suited to numbers lower than this but not every site has access to such devices.

While the questions are focused predominantly at fluid power systems, the matter of moisture levels and particle abrasivity are of equal importance to other systems, particularly with regard to softer metal bearings, and gear teeth surface hardness etc. In many instances, scoring a factor of ten for the CSF would be overkill, and in the worst cases of the moisture and particulate abrasivity, a max score of 3.5 (rounding up to four) might be achieved which, depending on the scored RPF, might indicate a target ISO level of between 22/18/15 to 17/13/11 (Figure 6). For an average standalone gearbox ISO 17/13/11 may seem excessively clean, and realistically for self-contained lubricated systems that are generally more dirt tolerant, a maximum CSF should be set at five as opposed to ten. However, depending on the capital cost of the system, because gearboxes can cost as much as several million dollars per unit, then the RPF should be factored higher accordingly.

In addition to ensuring a higher RPF for cost reasons on non-fluid power, self-contained units where capital cost is an issue using a maximum CSF of 5, it should be noted that where differing units share a lubrication system, either treat the unit with the highest sensitivity as the worst case scoring scenario, or multiply the CSF for every system type that shares the lubricant. However, allow for a higher CSF than 5 but treat 10 as the maximum. For example, if bearings, and gearboxes share the lubricant, multiply the overall CSF by two.

Using the Target Cleanliness Grid (TCG)

Have scored both the RPF and the CSF, these two values can now be used in the TCG to determine a realistic and feasible target cleanliness level. The TCG is based on the ISO 4406:1999 standard and incorporates the 3 part code at >4µm, >6µm and >14µm. For users of other cleanliness levels, use a comparative number for calculating the target cleanliness level, for example, such as in NAS 1638.

To use the TCG, identify the RPF score on the vertical axis and move across to the column that represents the CSF shown on the horizontal axis. Read the ISO 4406 value in the box where the row and column intersect and use this as the target. However, it may be necessary to evaluate the process, and to fine-tune the target as historical data is gathered.

Reliability Penalty Factor (RPF)

Machine I.D.: _____
 Date: _____

Safety Risks Upon Failure				Score
None 0	Low 1	Medium 4	High 8	

Cost of Downtime				A x B
Hourly or Daily Downtime Costs (A)				
Low 0	Medium 1	High 2	Extremely High 3	
Typical Length of Downtime (B)				
Short 0	1	2	3	Long 4

Material and Labor Costs to Repair				Score
Low 0	1	2	3	Extremely High 5

Effectiveness of Early Warning Systems				Score
Highly Effective 0	1	2	3	Not Effective

Composite RPF Score

 10 Max

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Figure 4. Scoring the Reliability Penalty Factor (Ref: Noria Corp.).

Contaminant Severity Factor (CSF) - Hydraulics

Machine I.D.: _____
 Date: _____

Operating Pressure (psi)				Score
0 - 1,000 0	1,001 - 2,000 1	2,001 - 3,500 1.5	3,501 - 5,000 2	>5,000 3

Valves				Score
Manual and Solenoid 0	Cartridge 1	Proportional 1.5	Servo 2	

Pumps and Motors				Score
Gear 0	Vane 1	Fixed Piston 1.5	Variable Volume 2	

Cyclic Loading				Score
Constant Pressure 0	Frequency and Severity of Pressure Cycles Low 0.5	Medium 1	High 1.5	

Vomish Potential				Score
Low 0	Medium 0.5	High 1	Extremely High 1.5	

Water In Oil Contamination				Score
<100 PPM 0	<500 PPM 0.5	<1000 PPM 1	>1000 PPM 1.5	

Particle Hardness/Abn. Activity				Score
Low 0	Medium 0.5	High 1	Extremely High 2	

Composite CSF Score

 10 Max

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Figure 5. Contaminant Severity Factor for Hydraulics (Ref: Noria Corp.).

Checking the Benefits

At this point, it is necessary to either have conducted or be in the process of surveying current levels of cleanliness for the systems being targeted. At this stage, for many users, they will find that their existing, or current, levels are several numbers worse than the target value calculated. The next step in the 3 easy steps as mentioned earlier is to achieve the new target levels, and this means upgrading existing filtration, breathers and specifying fittings etc. for ease of sampling. On equipment where existing levels are similar to the target cleanliness level, then the question becomes, "Should the system be left as it is since it meets the target level, or should the target be adjusted to bring life extension?" While in the hectic world of maintenance, leaving things as they stand is tempting, but the point of a proactive maintenance strategy is to reduce lubricant consumption and extend asset life significantly to bring financial rewards.

The next step to be considered at this point should also be undertaken even where the new target cleanliness is significantly greater than the existing level. By understanding the financial benefits, one can calculate the savings against the implementation costs and thereby work out the Net Present Value, or Internal Rate of Return, which makes obtaining management approval a foregone conclusion, since the numbers calculated for the NPV and IRR are bound to be exceptional.

The Life Extension Table considers the current level of cleanliness, the new target level of cleanliness and the predicted life extension factor for the equipment. Because it is based upon earlier research by various institutions, the ISO 4406 is used as a two part code in the previous manner of >5µm and >15µm.

Reliability Penalty Factor (RPF) <small>Cost, Safety and Business Interruption Penalty From Failure</small>	Contaminant Severity Factor (CSF) <small>Sensitivity of Machine to Contaminant Failure</small>									
	1	2	3	4	5	6	7	8	9	10
10	20/16/13	19/15/12	18/14/12	17/13/11	16/12/10	15/11/9	14/10/8	13/10/8	12/9/7	11/9/7
9	20/16/13	20/16/13	19/15/12	18/14/11	17/13/10	16/12/10	15/11/9	14/10/8	13/9/7	12/9/7
8	21/17/14	21/17/13	20/16/13	19/15/12	17/13/11	16/12/10	15/11/9	14/10/8	13/9/8	13/9/7
7	21/17/14	21/17/14	20/16/13	19/15/12	18/14/11	17/13/10	16/11/9	15/11/9	14/10/8	13/10/8
6	22/18/15	22/18/14	20/16/13	19/15/12	18/14/11	17/13/10	16/12/9	15/11/9	14/10/8	13/10/8
5	22/18/15	22/18/15	21/17/14	20/16/13	19/15/12	18/14/11	17/14/11	16/13/11	15/11/10	14/11/9
4	23/19/16	23/19/16	21/17/14	20/17/14	19/15/13	18/14/11	17/14/11	16/13/10	15/12/9	14/11/9
3	23/19/16	23/19/16	22/18/15	21/17/14	20/16/13	19/15/12	18/14/11	17/14/11	16/13/10	15/12/9
2	24/20/17	24/20/17	23/19/16	22/18/15	21/17/14	20/16/13	19/15/12	18/14/11	17/14/11	16/13/10
1	25/20/17	24/20/17	23/19/16	22/18/15	21/17/14	20/16/13	20/16/12	19/15/11	18/14/11	17/14/11

Figure 6. Target Cleanliness Grid TCG (Ref: Noria Corp.).

Current Machine Cleanliness (ISO Code)	New Cleanliness Level (ISO Code)																					
	20/17	19/16	18/15	17/14	16/13	15/12	14/11	13/10	12/9	11/8	10/7											
26/23	5	3	7	3.5	8	4	>10	>10	6	>10	7.5	>10	9	>10	>10	>10	>10	>10	>10	>10		
25/22	4	2.5	4.5	3	6	3.5	6.5	4	7.5	5	8.5	6.5	10	7	>10	9	>10	10	>10	>10	>10	
24/21	3	2	3.5	2.5	4.5	3	5	3.5	6.5	4	8	5	9	6	10	7.5	>10	9	>10	>10	>10	
23/20	2	1.5	3	2	4	2.5	5	3	7	3.5	9	4	>10	5	>10	6	>10	8	>10	9	>10	
22/19	1.7	1.3	2.3	1.5	3	2	3.7	2.5	5	3	6	3.5	7	4	8	5	10	6.5	>10	8.5	>10	
21/18	1.4	1.3	2	1.4	3	2	4	2.5	5	3	7	3.5	8	4	8	5	10	6	>10	7	>10	
20/17	1.3	1.2	1.5	1.5	2	1.7	3	2	4	2.5	5	3	7	3.5	9	4	>10	5	>10	7	>10	
19/16	1.2	1.1	1.5	1.3	1.8	1.4	2.2	1.6	3	2	3.5	2.5	4.5	3	5	3.5	7	4	9	6.5	10	
18/15					1.3	1.2	1.4	1.5	2	1.7	3	2	4	2.5	5	3	7	4.5	>10	6	>10	
17/14					1.2	1.1	1.5	1.3	1.8	1.5	2.3	1.7	3	2	3.5	2.5	3.7	8	5	>10	>10	
16/13									1.3	1.2	1.4	1.5	2	1.7	3	2	4	2.5	6	3	8	5
15/12									1.2	1.1	1.5	1.3	1.8	1.5	2.3	1.7	3	2	4	2.5	6	3
14/11													1.3	1.2	1.4	1.5	2	1.7	3	2	4	2.5
13/10																	1.3	1.2	1.4	1.5	2	1.7

Figure 7. Life Extension Factor Table (Ref: Noria Corp.).

Using the Life Extension Factor Table (LEF)

There are two ways to use this table (Figure 7). Let's assume the scenario as discussed above whereby the new calculated target cleanliness is significantly lower than the current level. For example, currently a gearbox operates at ISO 24/21, which is fairly common. The calculated RPF is seven and the CSF is three. Reading off the TCG, the target cleanliness level should be ISO 20/16/13, which in effect is 256 times cleaner than currently. With the fitting of an off-line filtration circuit (or at least quick connectors for a filter cart) and a simple desiccant breather the improvement should exceed the target.

Knowing that the cost of this gearbox is in the order of \$10,000, and the implementation costs is \$2,000 for the improvements and the ongoing upgrade cost is perhaps \$500 per year, then what benefit does this expenditure bring? If the gearbox currently lasts three years, then by referring to the LEF, looking at the current ISO level on the vertical axis and moving across the row until reaching the column representing the target value of ISO 16/13, the LEF can be read off in the lower right corner of the box as four. This then means that the expected life of the gearbox, all other things remaining equal in operating terms, should be twelve years as opposed to three years. By reducing the annual asset depreciation cost by a factor of four against the implementation and running costs of the improved filtration, it is a simple mathematical exercise to justify the expenditure to management.

On the converse, using the table to set a new target is also a possibility and one that can be used instead of the TCG in less complex situations. However, this should only be done where the issues of safety and asset cost

are not an issue. Taking the example above for a similar gearbox operating in a cleaner environment with a current level of cleanliness of ISO 18/15, and based on an RPF of five and a CSF of two, the target cleanliness level should be ISO 18/15. This is already being achieved, but in the pursuit of improved maintenance and financial benefits, a life extension is sought, then, it would be necessary to determine an appropriate life extension factor. This needs to be considered realistically, since the remaining life of the plant may be a known value and any life extension that would go beyond this point would not be feasible. Therefore, for the purposes of this example, consider an LEF of two based on a current 5-year life. Then, by reading across the row representing the current ISO 18/15 value, and then reading up the column from where the factor of two is indicated, a new target cleanliness of ISO 13/10 is required. Again, this may be easy enough to achieve, but using this approach requires that safety and operational issues are considered, and that the capital gain in life extension exceeds the implementation costs of the upgraded filtration.

CONCLUSION

Setting target cleanliness levels is always subjective because no two sites are the same, nor are industries typical. In the end, it is the user's organization that pays the cost of maintenance, not the OEM or a component supplier, so setting a target is the responsibility of the user. Guideline numbers are acceptable in so far as they are to be seen as a starting point or guideline. The method outlined in this paper offers the user a means of determining a more appropriate guide based on their unique scenario. As mentioned, tuning and resetting the targets may be required as historical data is gathered.

How to Read Your Oil Analysis Report

BY CHERYL HUFF AND CHARLES BOSWELL, PdMA CORPORATION

Abstract

The final laboratory report – whether received as an electronic form or as a hardcopy – is the axle upon which the practitioner's oil analysis program turns. Without a solid grasp of the underlying principles of reading and understanding the analysis report, the recipient is likely to grow frustrated with trying to make sense of the accumulating test data. This presentation acquaints the oil analysis user with best practices for getting the most out of the data revealed by the report, including a review of basic result interpretation. In your body, a measure of your health correlates with your heartbeat. Therefore, success in interpreting oil analysis results will be dependent on how strong your PULSE is.

INTRODUCTION

Many of us may have heard the phrase, "Oil is the lifeblood of the equipment." Oil analysis is very similar to running a blood test. Blood tests help give us early warnings of health problems as well as a glimpse of what might be going on in our bodies. Oil analysis can do the same for your equipment, and it may help prevent failures while telling us what is going on inside our machinery. There are many people who do oil analysis but have no idea what to do with the results. The items discussed in this paper will hopefully give you an outline to maintain a healthy PULSE. In terms of oil analysis, your PULSE is composed of: Prepare, Understand, Look, Set, and Execute.

Prepare

Before you can interpret the report, you need to be aware of a few simple steps to ensure you receive the most accurate data. You need to be prepared in order to achieve a quality program. Your oil analysis program begins with labeling your equipment and having labels that match the equipment identification. If your equipment is labeled the same as the labels to be placed on the sample bottles it will make it easier on the technician who pulls the samples. There have been some cases in which a technician mixes up equipment identification. Another item to keep in mind is that there are often different technicians pulling the samples. Therefore, it is very important to have the technicians that will be pulling samples using the same procedures. The sample must be pulled in the same fashion each and every time it is pulled. You may be surprised but this consistency will show up in your results. This is especially important for the tracking and trending process. Finally, the last item to be aware of is the sampling location. You need to pull the sample in the place that will give you the most representative condition of the oil.

Understand

- The next step is general knowledge of the types of testing you may have. It is necessary to have a basic understanding of the most common testing offered by labs. The list below will give you an idea as to the information displayed with the possible tests and a few of the possible testing instruments. Knowing which ASTM procedure the laboratory performs will also be useful if you are trying to compare one laboratory with another. There are many different procedures, as well as modified procedures, which can be used to perform a test.
- Spectroscopy will give you an idea about the amount of wear metals, contaminants, and additive metals in your lubricants. Common methods include Atomic Absorption, X-Ray fluorescence, Arc-spark emission, and Inductively-Coupled Plasma (ICP).
- Percent Solids will tell you the percentage of solids in your oil. It is determined by centrifuging oil in a solvent and measuring the amount of precipitate. More sophisticated methods, such as pentane and toluene insolubles can also be run.
- Percent Water will tell you the percentage of water that is in your oil. It is determined by crackle test and centrifuging oil in a solvent and measuring the amount of liquid precipitate. Infrared analysis can also be used to determine percent water. More sophisticated methods, such as

Karl Fischer Water Titration and water by distillation can also be used.

- Viscosity is one of the most important physical properties of a lubricant. Viscosity is an oil's resistance to flow. The viscosity can help determine if there is any lube contamination, fuel, water, or solvent contamination. Typical viscosity determinations are measured in Centistokes and correspond to an ISO lube grade.
- Acid & Base Numbers indicate the overall acidity or basicity of a lubricant. Acid Number is used to determine the amount of oxidation for industrial oils and the Base Number measures the reserve alkalinity in the oil for crankcase oils. Both properties are useful for tracking and trending purposes.
- Particle Count is used to determine the number of particles present in your oil. Two of the more common methods for determining particle contamination are optical laser and pore blockage particle counting. Each methodology has strengths and weakness that should be evaluated prior to selecting one over the other.
- Direct Reading Ferrography is another technology that can help determine the amount of ferrous contamination present in your oil. It works especially well on engine lubricants or samples contaminated with water. Direct reading ferrography measures iron particles in two size ranges – small and large. Small readings correspond to iron particles 1 to 2 microns in size, while large readings correspond to iron particles greater than 5 microns in size.
- Infrared is another useful tracking and trending test. This test monitors the molecular composition of the oil. Due to the unique molecular structure of lubricants, this test is sometimes referred to as the fingerprint of the oil. Typical results are reported in absorbance per cm. Areas often looked at utilizing infrared analysis include oxidation, nitration, and additive depletion.
- Analytical Ferrography is a powerful technology that can help determine the different types of wear mechanisms occurring in a lubricated system. Some of the wear mechanisms commonly observed by this technology include rubbing wear, sliding, and cutting wear.

Look

Now that you have a better understanding on the types of testing, you need to know what to look for in your oil analysis reports. As you look at the report, you should be able to see the history of the previously tested samples. Most laboratories will mark or bring to your attention any value or values which seem out of the ordinary. Some of the items that will concern the laboratory are discussed below.

- The spectrometric analysis should have the element names and their respective values for easy interpretation. It is very important to understand the potential cause for an element to change over time. It is also important to realize this technology has a size limitation associated with the testing methodology. Drastic changes are cause for concern.
- Viscosity results should fall within plus or minus ten percent of the listed value or new lube sample. Values that exceed these ranges should be acted upon immediately to prevent catastrophic damage.
- Increases in the acid number should be watched carefully.
- Significant decreases in base number could be an indication it is time to

change the oil.

- Water contamination usually is not present in oil. The presence of water can help promote the oxidation process and should be a cause for concern if observed.
- An increase in particle count values can indicate either abnormal wear may be present or your system is getting contaminated with dirt particles. Both situations should be thoroughly investigated.
- An increase in abnormal wear modes observed by analytical ferrography, indicates equipment should be monitored closely.

Set

Now that you have an idea what to look for in a report you can set alarm limits based on your equipment and develop a plan to react. It is important that you have good communication with your laboratory about the alarm limits you want set on your specific pieces of equipment. When you are setting the alarm limits you need to be aware of the equipment surroundings. It is also a good idea to be familiar with the different types of lubricants you are using. Lubricant contamination will be hard to determine if you are unfamiliar with possible sources of contamination. It may also be worth categorizing results so appropriate actions can be set following receipt of the report.

A stop light approach may be beneficial for setting your action items. A plan that is easy to set up can include sorting your results into three categories: green, yellow, and red. The green category, or normal, is classified for those samples that are consistent with the history of the sample and warrant no further action. The yellow category, or caution, is for samples that deviate from historical or known values, but do not require immediate action. These may be samples that you want to resample, or watch the results on the next report you receive. The red category, or critical, is for samples that require immediate action because they are so severe.

When setting your action plan, it is important to realize all the variables involved in the sampling process and that it may be a good idea to pull a second oil sample before reacting too quickly. This stop light approach will help maintain an effective oil analysis program while allowing you to set the appropriate response.

Execute

The last step in taking your PULSE is execution of your oil analysis program. All of the preceding steps will be meaningless unless your program is executed properly. It is important the appropriate people receive the information from the oil analysis report. Appropriate personnel will be determined by their knowledge of the process. If the knowledge is not present in your organization, it is important that a plan is executed which will begin the learning process for the chosen employee. Furthermore, staying abreast of changes in technology should be a cornerstone of your execution process in order to continue building a robust oil analysis program. Once the personnel are in place it is imperative that they are given the authority to execute solutions when problems arise. It is also worth noting that execution should be tempered with the knowledge of the process. The last thing you want is a rash decision being made when a more cautious approach may be warranted.

Summary

You should now have an excellent idea on how to get the most out of your oil analysis program. You need to be prepared in order to get the best results possible, to understand the types of tests offered, to look at the results and interpret the analysis, to set alarms and plan, and finally execute the plan you set. In your body, a healthy pulse is necessary for a long, prosperous life. Likewise, your oil program will also have a long and prosperous life if you start with a healthy PULSE.

Analytical Ferrography for Root Cause Analysis and Failure Prevention

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Abstract

There are many tests available for used fluids analysis. Some tests are qualitative while others are quantitative in scope. One test often overlooked is Analytical Ferrography. Complete Analytical Ferrography is often referred to as the oil analysis equivalent of criminal forensic science. The test method relies on a visual, microscopic evaluation of particles, extracted and deposited on a microscope slide called a Ferrogram. Based on an examination of the shape, color, edge detail, the effects of a magnetic field and other diagnostic tests such as heat treatment and the addition of chemical reagents, an assessment of the active wear mechanism can be made.

Analytical Ferrography, when performed with other analysis tests, is capable of determining the Root Cause of failure, which can lead to failure prevention. Analytical Ferrography utilizes microscopic analysis to identify the composition of the material present. This technology will differentiate the type of material contained within the sample and determine the wearing component from which it was generated. This test method is used to determine characteristics of a machine by evaluating the particle type, size, concentration, distribution, and morphology. This allows a skilled diagnostician to determine the root cause of a specific tribological problem.

INTRODUCTION

Analytical Ferrography can predict potential equipment failures and is an effective tool in determining the root cause of machine component failure. Analytical Ferrography is a qualitative rather than quantitative analysis that provides digital imagery of the actual particles present. Powerful magnets trap the ferrous particles, which are then placed on slides for microscopic analysis. Particles are analyzed based on being metallic or non-metallic alloy via heat treatment, shape, size, color, and if possible, source.

Analytical Ferrography is one of the tools of fluids analysis in the group called Wear Debris Analysis (WDA) or Wear Particle Analysis (WPA). Other WDA/WPA tests include Particle Count, Micropatch, Direct Reading Ferrography, and the Particle Quantifier.

The technique of Wear Debris Analysis (Analytical Ferrography) is gaining popularity in the field of Condition Based Maintenance System. WDA is a method of predicting health of equipment in a non-intrusive way, by the study of worn particles. The continuous trending of wear rate monitors the performance of Machine/Machine components and provides early warning and diagnosis. Oil condition monitoring can sense danger earlier than Vibration technique. This technique holds good for both oil and grease samples.

Analytical Ferrography, with supporting physical and chemical tests, can help to determine:

- The start of abnormal wear.
- Root cause of wear/failure.
- The component(s) that are wearing.
- Usability of lubricant beyond its rated life.

The particles contained in a lubricating fluid carry detailed and important information about the condition of the machine components. This information can be deduced from:

- Particle shape.
- Particle composition.
- Particle size distribution.
- Particle concentration.

When a fluid analysis report indicates a problem, it can be characterized in two dimensions: ambiguity and importance. When the problem is ambiguous and important, root cause analysis can be justified. For many reasons, fluids analysis is a powerful root cause tool, yet few take full advantage of its capabilities. Despite the fact that hundreds of fluids analysis tests are available and useful to the analysis, few venture beyond the 10 to 12 tests most common to used fluids analysis.

Vernon C. Westcott is credited with inventing the ferrograph in the early 1970s. Mr. Westcott passed away in September 2003 at the age of 84. Initially, the ferrograph was used mainly by the military. Today, ferrography is a fundamental tool of used fluids analysis and reliability maintenance.

Analytical Ferrography is among the most powerful diagnostic tools in fluids analysis today. When implemented correctly it provides a tremendous return on your fluids analysis dollars. Yet, it is frequently excluded from fluids analysis programs because of its comparatively high price and a general misunderstanding of its value.

In his article "Wear Analysis," Mark Barnes states, "Complete analytical ferrography is often referred to as the oil analysis equivalent of criminal forensic science. The test method relies on a visual, microscopic evaluation of particles, extracted and deposited on a microscope slide called a ferrogram. Based on an examination of the shape, color, edge detail, the effects of a magnetic field and other diagnostic tests such as heat treatment and the addition of chemical reagents, an assessment of the active wear mechanism can be made. This allows a skilled diagnostician to determine the root cause of a specific tribological problem."

"While ferrographic analysis is an excellent tool when attempting to diagnose an active wear problem, it too has its limitations. The test is a qualitative test, which relies on the skill and knowledge of the ferrographic analyst. While this can have definite advantages, the interpretation is somewhat subjective and requires detailed knowledge, not just of analytical chemistry, but also machine and tribological failures. Also, because of the time and skills required to perform the test, it is usually considered too expensive for routine oil analysis. Nevertheless, used as an exception tool when a wear problem is suspected based on other test results, complete ferrographic analysis is one of the most enlightening of all wear analysis methods."

The test procedure is lengthy and requires the skill of a well-trained analyst. As such, there are significant costs in performing analytical ferrography not present in other fluids analysis tests. But, if time is taken to fully understand what analytical ferrography can uncover, most agree that the benefits significantly outweigh the costs and elect to automatically incorporate it when an abnormal wear condition is encountered. As with all fluids analysis samples, I cannot overstate the importance of a properly taken sample of the fluid. Samples should be taken that are representative of the conditions that are going on inside the equipment. Representative samples are dependent on the way the sample is taken and the location where the sample is taken from. This is especially important when using Analytical Ferrography.

Another critical factor in fluids analysis and Analytical Ferrography in particular, is the need of the customer to provide as detailed as possible the specific information about the machine/component from which the sample was taken. This includes lubricant information, component manufacturer, model and type of component. The more detailed the machine/component information, the better the diagnosis of the test results.

To perform analytical ferrography, the solid debris suspended in a lubricant is separated and systematically deposited onto a glass slide. The slide is examined under a microscope to distinguish particle size, concentration, composition, morphology and surface condition of the ferrous and non-ferrous wear particles.

This detailed examination, in effect, uncovers the mystery behind an abnormal wear condition by pinpointing component wear, how it was generated and often, the root cause.

Analytical ferrography begins with the magnetic separation of machine wear debris from the lubricating fluid in which it is suspended using a ferrogram slide maker. The lubricating fluid sample is diluted for improved particle precipitation and adhesion. The diluted sample flows down a specially designed glass slide called a ferrogram. The ferrogram rests on a magnetic cylinder, which attracts ferrous particles out of the oil (Figure 1).

Due to the magnetic field, the ferrous particles align themselves in chains along the length of the slide with the largest particles being deposited at the entry point. Nonferrous particles and contaminants, unaffected by the magnetic field, travel downstream and are randomly deposited across the length of the slide. The deposited ferrous particles serve as a dyke in the removal of nonferrous particles. The absence of ferrous particles substantially reduces the effectiveness with which nonferrous particles are removed.

After the particles are deposited on the ferrogram, a wash is used to remove any remaining lubricant. The wash quickly evaporates and the particles are permanently attached to the slide. The ferrogram is now ready for optical examination using a bichromatic microscope.

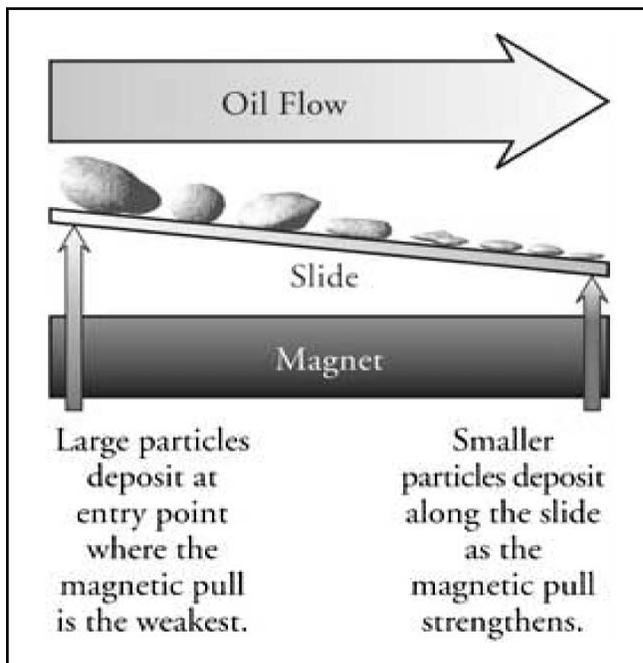


Figure 1. Ferrogram Slide Maker Separates Particles from the Oil.

The ferrogram is examined under a polarized bichromatic microscope equipped with a digital camera. The microscope uses both reflected (top) and transmitted (bottom) light to distinguish the size, shape, composition and surface condition of ferrous and nonferrous particles (Figure 4). The particles are classified to determine the type of wear and its source.

Particle composition is first broken down into six categories: white nonferrous, copper, Babbitt, contaminants, fibers and ferrous wear. In order to aid the identification of composition, the analyst will heat-treat the slide for two minutes at 600°F.

- White nonferrous particles, often aluminum or chromium, appear as bright white particles both before and after heat treatment of the slide. They are deposited randomly across the slide surface with larger particles getting collected against the chains of ferrous particles. The chains of ferrous particles typically act as a filter, collecting contaminants, copper particles and Babbitt.
- Copper particles usually appear as bright yellow particles both before and after heat treatment but the surface may change to verdigris after heat treatment. These also will be randomly deposited across the slide surface with larger particles resting at the entry point of the slide and gradually getting smaller towards the exit point of the slide.
- Babbitt particles consisting of tin and lead, Babbitt particles appear gray, sometimes with speckling before the heat treatment. After heat treatment of the slide, these particles still appear mostly gray, but with spots of blue and red on the mottled surface of the object. Also, after heat treatment these particles tend to decrease in size. Again, these nonferrous particles appear randomly on the slide, not in chains with ferrous particles.
- Contaminants are usually dirt (silica), and other particulates that do not change in appearance after heat treatment. They can appear as white crystals and are easily identified by the transmitted light source, that is, they are somewhat transparent. Contaminants appear randomly on the slide and are commonly dyked by the chains of ferrous particles.
- Fibers, typically from filters or outside contamination, are long strings that allow the transmitted light to shine through. They can appear in a variety of colors and usually do not change in appearance after heat treatment. Sometimes these particles can act as a filter, collecting other particles. They can appear anywhere on the ferrogram; however, they tend to be washed towards the exit end.

Ferrous particles can be broken down to five different categories, high alloy, low alloy, dark metallic oxides, cast iron and red oxides. Large ferrous particles will be deposited on the entry end of the slide and often clump on top of the other. Ferrous particles are identified using the reflected light source on the microscope. Transmitted light will be totally blocked by the particle.

- High Alloy Steel - particles are found in chains on the slide and appear gray-white before and after heat treatment. The distinguishing factor in the identification between high alloy and white nonferrous is position on the slide. If it is white and appears in a chain, it's deemed to be high alloy. Otherwise, it's considered white nonferrous. The frequency of high alloy on ferrograms is rare.
- Low Alloy Steel - particles are also found in chains and appear gray-white before heat treatment but then change color after heat treatment. After heat treatment they usually appear as blue particles but can also be pink or red.
- Dark Metallic Oxides - deposit in chains and appear dark gray to black both before and after heat treatment. The degree of darkness is indicative of the amount of oxidation.
- Cast Iron - particles appear gray before heat treatment and a straw yellow after the heat treatment. They are incorporated in chains amongst the other ferrous particles.

- Red Oxides (Rust) - polarized light readily identifies red oxides. Sometimes they can be found in chains with the other ferrous particles and sometimes they are randomly deposited on the slide surface. A large amount of small red oxides on the exit end of the slide is generally considered to be a sign of corrosive wear. It usually appears to the analyst as a "beach" of red sand.

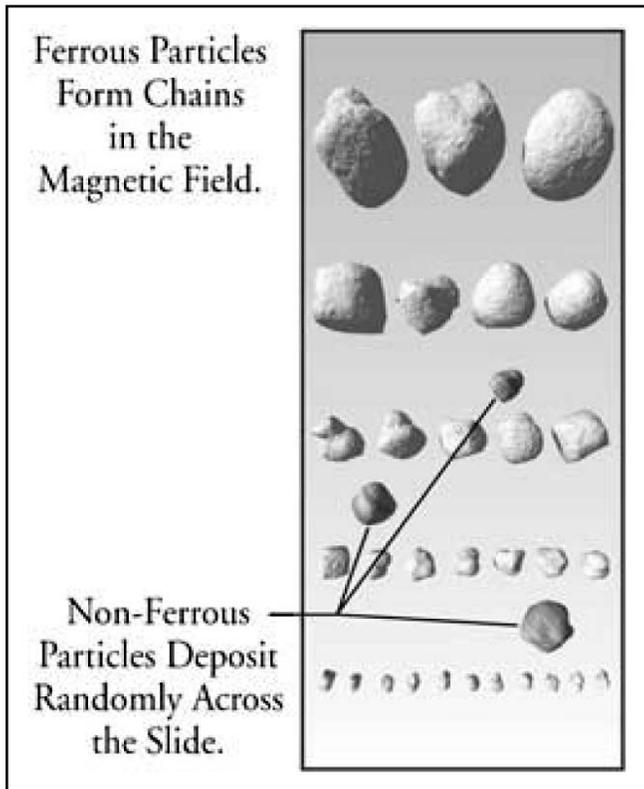


Figure 2. The Metal Alloy of the Particles Determines Whether They Line Up On or Adjacent to the Magnetic Field.

After classifying the composition of particles the analyst then rates the size of the particles using a micrometer scale on the microscope. Particles with a size of 30 microns or greater are given the rating of severe or abnormal. Severe wear is a definite sign of abnormal running conditions with the equipment being studied.

Often, the shape of a particle is another important clue to the origin of the wear particles. Is the particle laminar or rough? Laminar particles are signs of smashing or rolling found in bearings or areas with high pressure or lateral contact. Does the particle have striations on the surface? Striations are a sign of sliding wear, perhaps generated in an area where scraping of metal surfaces occurs. Does the particle have a curved shape, similar to drill shavings? This would be categorized as cutting wear that can be caused by abrasive contaminants found in the machine. Is the particle spherical in shape? To the analyst, these appear as dark balls with a white center. Spheres are generated in bearing fatigue cracks. An increase in quantity is indicative of spalling. According to Jim Fitch in his article "Today's Oil Detectives Have a New Bag of Tricks," "The truth is, oil analysis is detective work, plain and simple. Today's detectives are empowered with a growing bag of tricks but frankly, only a few of these tricks involve traditional 'oil analysis.' Let's take a closer look at what's involved in real oil detective work. But before we do, remember that the primary job of the oil analyst is not troubleshooting chronic machine problems but rather the

activity of machine health management, that is, maintaining and controlling machine wellness. Proactive maintenance is always where the big payoff is found. Still, even the best proactive maintenance programs can't completely rid machines of random failures and occasional abnormal wear conditions. It is in these cases when the oil detective earns his keep." "A problem is still a problem whether it is detected early or kept out of sight. Out of sight may be of momentary convenience, but for process-critical machines, problem penalties can grow if not corrected early. Compounding and/or chain-reaction failures can cost millions of dollars or even one's life. You've seen it before - the worse things get, the faster they get worse."

"By the time a problem has been detected and localized, the cause of the problem is often discovered as well, but not always. A suspect cause (misalignment, degraded oil, etc.) may need further confirmation or there may be two or more causes working in concert. Knowing the true root cause is vital to prescribing a remedy that works. Slowing the rate of progress may, in many cases, be the best response, enabling complete correction at the next scheduled outage."

"Defining the wear mode is where the real strength in microscopic Wear Particle Analysis (Analytical Ferrography) lies. Properly sampled lubricants often contain particles of unique shape and size that characterize how they were created. The skillful eye of a well-trained wear particle microscopist can be invaluable."

CONCLUSIONS

In the hands of a skilled analyst, Analytical Ferrography is capable of detecting active machine wear and can often provide a root cause based on the morphology of the wear particles. Used in conjunction with treatments of the ferrogram like heating and chemicals, it can pinpoint the root cause of specific wear problems. The advantage of Analytical Ferrography is that the source, cause and scope of equipment wear can easily be determined. The analysis determines both the type and metallurgy of the wear particle, allowing the analyst to see inside operating equipment to identify abnormal wear conditions.

Due to the method of sample preparation, Analytical Ferrography is biased but not necessarily limited to ferrous particles. The test is non-quantitative and its effectiveness is critically dependent on the knowledge and experience of the analyst. Due to the analyst skills required and the time the analysis takes, it can be fairly expensive compared with other test methods. Used as an exception test based on results from other less expensive tests, Analytical Ferrography can be an effective fluids analysis tool for most machine components.

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7. "Wear Analysis," Mark Barnes, Practicing Oil Analysis magazine

7 Steps to a Quality Used Oil Analysis Program: It's the Details That Count

By JOHN C UNDERWOOD, (CLS, OMA I) DuPont ENGINEERING TECHNOLOGY

Starting a new oil analysis program from the ground up, or just looking to improve your existing program? Here is a proven 7-step process that I guarantee will improve the overall effectiveness of any used oil analysis program.

As we move through the 7 steps you will come to understand that all phases of the plant's lubrication program can and will have an effect on the accuracy of used oil test results. We must assure that lubrication best practices are being followed throughout the entire lubrication process, plant-wide, so we get the most value from the used oil analysis program.

Step 1 – The Equipment Survey

The first order of business will be to determine which equipment we want to include in the used oil analysis program. Then we need to gather all the pertinent information about this equipment so we can provide the required information about the equipment to your oil analysis vendor.

This same information would be of value even if used oil analysis testing is being done on-site.

The following equipment should be considered for inclusion in the used oil analysis program:

- Plant process or PSM critical equipment whether spared or un-spared.
- Unspared equipment or critical support equipment that could impact the production process (reduced/lost production).
- Splash lubricated equipment in excess of 20 gallons capacity (gearboxes).
- Oil lubricated equipment that is being evaluated with other PPM technologies.
- Any other equipment that could benefit from used oil analysis.

Plant process or PSM critical equipment should always be included in the used oil analysis program. Generally this equipment tends to be our physically larger equipment with circulating oil systems that are directly involved in the manufacturing process. If this equipment shuts down or worse, fails unexpectedly, it normally results in lost production that can run into the thousands of dollars per hour, or could even result in process material releases that have negative effects on employees, the general public and the environment with substantial financial impacts. For this class of equipment, we want to use all the PPM resources at our disposal to assure safe reliable operation.

Some equipment falling into this category: plant air compressors, steam or gas turbine power generation units, process compressors, recycle compressors, process reactors, extruder gearboxes, natural gas engines, and diesel engines to name a few. Most plants already have a list of PSM critical equipment; our job is to make sure this equipment is also included in the used oil analysis program if appropriate.

Unspared equipment or critical support equipment that could impact the production process should also be considered for inclusion in the program. While this equipment may not be as physically imposing as our main process equipment, they can still have the same financial and safety related impacts as their big brothers.

Equipment in this category could be: high speed pumps and compressors (Sundynes), high pressure process pumps (polymer pumps, LEWA diaphragm pumps), seal oil systems (both high and low pressure) on mixers or transfer pumps, cooling tower water pumps, auxiliary steam driven equipment (pumps, compressors), environmental control equipment (blowers, vacuum pumps) and list goes on an on.

Splash lubricated equipment with 20 gallons capacity should also be included in the program. At Dupont facilities, this generally describes mixer gearboxes on process vessels and cooling tower gearboxes but could also include other industry specific equipment.

Why 20 gallons capacity you might ask? Well, this is generally a financial breakeven point between the cost of the analysis program and the cost of the lubricant in the equipment. If the lubricant is mineral oil based and being changed on a preventative annual basis, then the cost of the analysis program could be equal to or even more expensive than just changing the oil. But, if you are using oil analysis to gather as much information as possible about the condition of the unit itself, then by all means, include it in the program.

Other oil-lubricated equipment that is being monitored by other PPM technologies should also be considered for inclusion in the program. At DuPont facilities, all oil-lubricated electric motors are monitored by vibration analysis, and we have opted to include these units in the site's used oil analysis programs.

What information do we need about equipment to be included in the program?

- Unit and component descriptions
- Manufacturer
- Make and model
- Serial numbers
- Lubricant in service
- System capacity
- Filter system type (full flow or kidney loop)
- Filter element number/type and performance ratings
- Unit and component hours since installation or last overhaul
- Oil hours since startup or last oil change
- Cooling system type and additives (freeze depressants, corrosion inhibitors, biocides)
- Any other equipment specific information required by our oil analysis vendor

Because there is a lot of information to keep track of, we should probably capture in a computer data base program such as Excel or Access for ready reference.

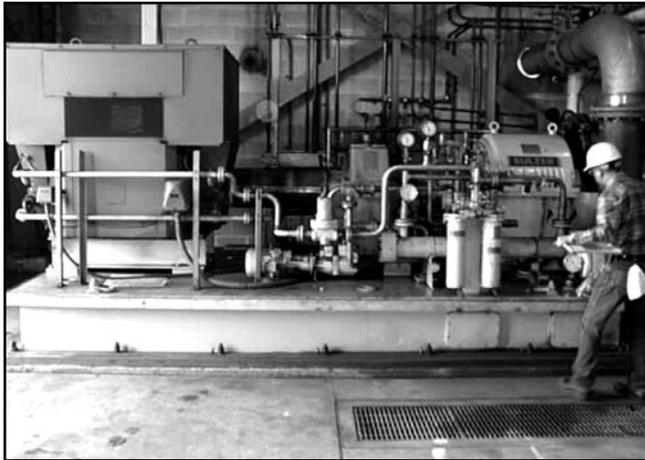
Okay, we know the equipment and everything about it, what's next?

Step 2 – The Hardware Sampling Survey

Wow, equipment comes in all shapes, sizes and complexity, how are we going to get repetitive, representative, information-rich samples from our equipment so we obtain the best information and full value from our program? Answer: we need to perform a sampling hardware survey to understand the machine layout and identify any special sampling equipment needed to obtain used oil samples. On every machine we need to select a Primary Sample Point that will provide the most information about

the machine condition as well as the condition of the lubricant. For multi-component systems such as the compressor shown in the right hand photograph, the primary sample point will probably be the main return line just as the oil returns to the oil reservoir. For circulating systems that use the housing as the oil reservoir, sampling from the oil pump discharge may be an acceptable location, but always before any filters or strainers in the lube oil piping. For splash lubricated equipment, sampling directly from the crankcase, gearbox housing, or bearing housing may be the only location available. Even drain line sampling can be done effectively and efficiently, but special sampling hardware is required and special installation techniques need to be used for installation.

Secondary Sampling Points for multi-component machines are highly recommended to assist troubleshooting when abnormal conditions are detected in the sample taken from the primary sampling location. Debris



detected at the primary sampling location could be coming from any component within the system. Secondary sampling points help pinpoint the offending component in complicated multi-component system to reduce repair costs and downtime. A typical secondary sampling location is shown in the photograph on the left. Samples are taken from secondary sampling points only when required based on changes in condition from the primary sampling location. Special analytical techniques such as analytical ferrography or micropatch can be employed to better identify wear particle composition to narrow down the offending component.



Specialized sampling hardware is available from many well-known sources in the industry and most vendors will be represented at the Lubrication Excellence conference. Be sure to visit their respective booths to see what new and existing hardware is available to assist your sampling needs.



Step 3 – Test Package Selection and Sampling Frequency

Next we need to select the appropriate test make sure we receive the information necessary to properly monitor the condition of the unit as well as the lubricant. Then we need to decide how often we want to sample each unit to make sure we get the information back in sufficient time to respond to changing conditions.

The test package selection depends upon the type of unit being tested as well as its importance to overall plant operation.

Within the DuPont Oil Analysis Program, we have seven preprogrammed test packages as follows:

- **MDDE** is for diesel or automotive gasoline driven units, or non-critical process natural gas engines.
- **PNG** is for process critical natural gas engines, providing additional specialized testing for these units.
- **PDD** is the lowest cost program and is intended to be used only for non-critical auxiliary plant equipment, primarily when oil condition is of primary concern. It is the program of choice for new lube reference samples as well.
- **PDREF** has been specifically designed to provide the correct testing of refrigeration compressor lubricants, including an extracted 40C viscosity to eliminate the dilution effects of the stray refrigerant that may be trapped in the oil.
- **PDR** is primarily for splash lubricated gearboxes or machines that could show high levels of magnetic metallic contamination. The program provides Direct Read Ferrographic results where magnetic components are concentrated on very sensitive photo detectors using magnetic fields

to concentrate metallic contamination.

- **PDKP** is for circulating systems on hydraulic applications and non-critical gas and/or steam turbines. This program is optimized for systems that generate non-magnetic contamination and provides very accurate moisture determinations in ppm. We also measure system cleanliness per ISO 4406-99 in this program.
- **PDKPD** is the top of the line predictive maintenance program for plant/process critical equipment. It contains the most comprehensive lineup of individual tests, up to and including analytical ferrography, but only if they are needed based on sample condition. Not surprisingly, it is also the most expensive test program.

The chart below provides a summary of the individual tests contained within each preprogrammed test package:

PACKAGE	PDD	PDR	PDKP	PDKPD	PDREF	MDDE	PNG
TEST							
21 Metals	*	*	*	*	*	*	*
Viscosity	*	*	*	*	*	*	*
Total Acid No.	*	*	*	*	*	*(1)	*(1)
Total Base No.						*(1)	*(1)
Water – IR	*	*				*	*
Karl Fischer, Water			*	*	*		
ISO Particle Count (2)			*	*			
DR Ferrography		*		*			
Large Particle Spectroscopy							*
Fuel Dilution						*	
Infrared						*	*
Analytical Ferrography (3)				*			

(1) Total Base Number can be substituted for Total Acid Number for medium to high ash oils.
 (2) Ultra clean sample bottles are required for Particle Count Analysis.
 (3) Analytical Ferrography performed only when conditions of report require more in-depth study.

While the above test packages are specific to the DuPont Oil Analysis program, I am sure that your oil supplier or oil analysis vendor can supply information on their program offerings that provide the technical equivalent level of testing to any of the Dupont standard program offerings.

Selecting the appropriate sampling frequency depends upon the criticality of the equipment to the process and, of course, the value of the equipment to the production area.

Critical equipment should be sampled at least every 30 days or more frequently if conditions warrant. Remaining equipment can be sampled at up to 90-day intervals. We do not recommend routine sampling at less than 90-day intervals, as the response time to abnormal conditions would be too long for us to take meaningful corrective action should abnormal conditions be detected.

Now select the appropriate test package and the desired sampling frequency and enter them into the spreadsheet we started in Step 1.

Step 4 - Pre-load Oil Analysis Vendor Database with Equipment Information

The importance of this step cannot be overemphasized! It really is true that the job is not finished until the paperwork is done.

Conveying this key data to the oil analysis laboratory will “Help Them

Help Us” to put a twist on a memorable line from the movie Jerry Maguire.

The more detailed unit/component information we can provide to the laboratory data analysts, the more exacting job they can do in interpreting the test data and making corrective action recommendations if/when abnormal conditions are detected in the used oil samples.

DuPont’s oil analysis vendor has developed a component registration form we use to record all the appropriate information about a specific sampling point. A copy is attached at the end of this article for your information and guidance. All oil analysis vendors probably have their own preferred methods/forms to provide the necessary information needed to set up a unit in their database. Spend the time and fill out the forms to the best of your ability.

Primary contact information

Secondary contact info – very important

Section II: Contact Information	
Name/Title	
Phone #	
Fax #	
Name/Title	
Name/Title	
Phone #	

Please, please be sure to provide accurate contact information to the laboratory and maintain this information with them at all times. Always provide a secondary contact in case you are out of the office or on vacation so the lab can get in contact with a live person when abnormal/critical conditions are detected.

Provide useful unit identifications when possible that describe the function of the unit, such as Process Compressor, Main Generator Turbine, and Main Extruder.

Section III: Unit Information	
Unit ID	_____
Unit manufacturer	_____
Unit model	_____
Work Site	_____
Please add any additional comments that apply (set-time maintenance, abnormal conditions, common problems)	
<div style="border: 1px solid black; height: 100px; width: 100%;"></div>	

Try to avoid using accounting codes or maintenance system identification numbers that don't mean anything to the real users of the data.

Providing manufacturer and model numbers allows the data analysis to apply more detailed OEM specific used oil limits and action guidelines to data interpretation and action recommendations. Work locations can be important to large account users to make sure the data gets where it is supposed to be so action can be taken when needed based on sample results.

Now enter the component information using standard descriptions such as gearbox, engine, reservoir, inboard bearing, outboard bearing and so forth.

Provide accurate commercial descriptions for the lubricant in use as it helps the data analysts refer to the appropriate new lube reference tables for additive fingerprints and ISO viscosity ranges.

Section IV: Component Information		
Component ID _____		
Component manufacturer		
Component model		
Serial number		
Oil Mfg	Brand	Grade
Sump/reservoir capacity _____ <input type="checkbox"/> gals <input type="checkbox"/> qts <input type="checkbox"/> ltrs		
Coolant type		
Coolant additives		
Oil Filters: no.	type	rating
Fuel additives (engines)		

Sump capacities are extremely important as even small changes in wear metals concentrations in large capacity systems can be an indication of critical wear conditions.

The presence of coolant systems and any coolant additives used in these systems will help identify the potential sources of water ingress into systems. Coolant additives, typically sodium and potassium based borate compounds, are detectable in extremely low concentrations in the spectrochemical analysis, allowing early detection of very minute water leaks before they become bigger problems.

Of course filter information is important for systems equipped with on line filters as significant increasing particle counts could be the result of by-passed or even ruptured filters, or even installation of a less efficient filter allowing more debris to circulate in the lube oil system with predictable negative results on equipment reliability.

Be sure to review this information for accuracy and completeness before initiating the sampling program.

Step 5 – Area Lubricants and Contamination Control Survey

Now it's time to make sure we know which lubricants are actually being used in the plant equipment and to make sure the lubricants are being properly handled from the storage area to the machine; otherwise,

contamination might be occurring that can alter the used oil test results, creating abnormal conditions and confusion at both the oil analysis vendor and at the plant level.

As part of the standard survey activities, be sure to take New Lube reference samples from the active oil storage and send to the laboratory for baseline analysis testing that, at a minimum, should include:

- ISO viscosity at both 40 C and 100 C,
- a calculated viscosity index,
- spectrochemical analysis for typical additive metals,
- either total acid number (TAN) or total base number (TBN) as appropriate, and
- Moisture content.

We need to know the chemical fingerprint of each new lubricant so we can determine what is happening with the used lubricants. Cross contamination due to poor handling practices is a common problem and is easily detected using used oil analysis.

The reference viscosity of all lubricants is also important in identifying lube mixing or contamination from external sources. Industrial lubricants should not undergo significant viscosity changes during normal operation. Slight increases in viscosity are normal the longer the lubricant is in service; however, viscosity decreases are very unusual and warrant concern and immediate corrective action when detected.

Other tests such as Rotary Pressure Vessel Oxidation Test for long life turbine and compressor fluids or FTIR for crankcase lubricants may also be of value when examining the used lubricant for degradation.

Once base lines are established, annual new lube reference sampling is recommended just in case the lubricant formulations may have changed and you were on vacation the day the announcement was made by the manufacturer. Formulations and their associated chemical fingerprints can and do change!



How we store and handle lubricants can have a significant impact on both lubricant quality and machine reliability and will definitely be reflected in the used oil analysis test results. New lubricants should be stored on their sides with bungs at the 3 and 9 o'clock position.

If they must be stored outside, please use drum covers to prevent potential contamination of the new lubricant from foreign debris and moisture!

Lubricants should not be handled in common transport containers and certainly not in open top containers that are nothing more than magnets for airborne contaminants and moisture.

Once opened, lubricant containers (drums, kegs, pails) should be stored inside and, if possible, in temperature and humidity controlled environments to prevent external contamination and premature product degradation.



The photograph below shows an excellent line of lubricant transport containers with interchangeable lids for easy dispensing of all types and viscosities of lubricants.

They are available in several different sizes and the manufacturer now offers different color lids for easy product family segregation.

Speaking of segregation, be sure to practice family segregation in both lubricant mini-bulk storage areas as well as their respective transport containers!



Family product segregation is a very important requirement that is often overlooked in these excellent, compact handling systems. Due to additive carryover concerns, not to mention incompatible product concerns, separate pumping systems and transport systems must be provided for different product families. Turbine and circulating oil families should be kept

separate from hydraulic oils, separate from gear oil families and, of course, from any potential contact with any automotive or heavy-duty crankcase formulations.

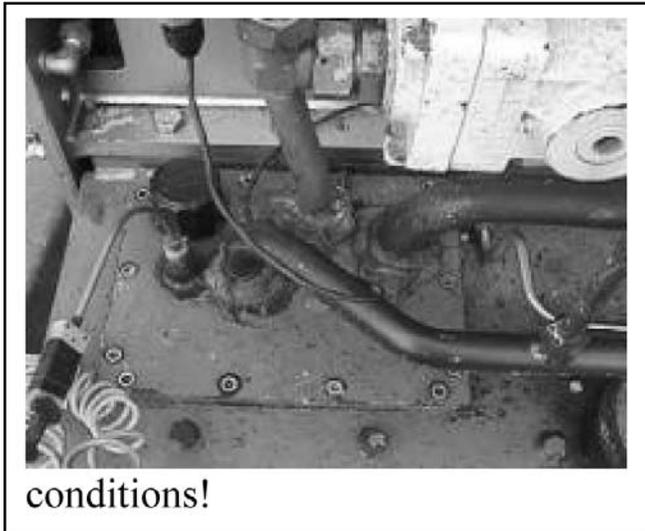


Synthetics should be kept separate from mineral oil products and we should follow the same family segregation rules for synthetics products as their functional mineral counterparts listed above. Food grade lubricants should always be handled in dedicated equipment, period!

New oil is clean oil, right? Not! Bulk and drummed lubricants should always be filtered while being offloaded from transport containers or from drums when being transferred to either mini-bulk storage or into a specific machine reservoir during a normal overhaul.



This step is often overlooked and, for systems being monitored by particle counting, will show immediate and unexplained significant decreases in cleanliness (increased particle counts) as a result of normal lubricant additions.



Pay special attention to machine conditions to make sure breathers are in good shape and gaskets and piping connections to reservoirs are tight, neat and clean. If abnormal conditions are found, correct them before starting the oil analysis program. Garbage in certainly does equal garbage out under these conditions!

Step 6 – Program Management Technology

Well, we are almost there. Now we need to determine what type of electronic program management system we are going to employ to quickly and effectively handle, store and analyze all the newfound data we will be receiving from our used oil analysis program.

Electronic transmission of sample results is an absolute must to reduce response time to abnormal and critical machine conditions. Many lubricant suppliers and all oil analysis vendors offer several methods of electronic data delivery via the Internet or company email systems.

They also offer very functional proprietary software systems for receiving, converting, analyzing and storing oil analysis test results. At DuPont, we used a well known provider of vibration analyzers with proprietary software that will accept used oil data downloads from most oil analysis vendors to enable customers to store their vibration data and oil analysis data in a common location for easy comparative analysis, while most sites use proprietary software developed by our contact oil analysis laboratory.

All these programs/systems are of excellent quality and functionality, so pick the one that will work best for your respective needs.

I can't emphasize enough that unless someone within your company or plant has value for a quality used oil analysis program, takes ownership of the program and remains actively involved in the program, it will surely die a natural death.

Successful programs at DuPont sites have an effective Lubrication Coordinator and/or Lube Champion who assures program goals are reached and successes documented to plant management. While these titles are strictly honorary, these highly motivated individuals understand the significant positive impact that world class lubrication practices and a high quality used oil analysis program can have on equipment reliability and uptime.

Step 7 – The Last Step

Finally what we have all been waiting for, the all-important last step on our road to used oil analysis program utopia:

Now that we have successfully:

- Identified equipment to be included in the program
- Identified sampling locations and installed the appropriate sampling hardware
- Selected the proper test packages
- Entered the equipment in the oil analysis vendor's database
- Baselined our new lubricants for comparison purposes
- Controlled contaminants both in storage/handling and in operation
- Selected the appropriate program management methods and software.

Can you say – Just Do It!

How to Set Alarms for Oil and Wear Debris Analysis

By MATT SPURLOCK, NORIA CORPORATION

A recent client reported they received an oil analysis report for a conveyor gearbox. The report had results very different from any historical data in all aspects of the spectrometer results. Upon evaluation, it was apparent the spectrometer results were that of a diesel engine that had a coolant leak from the lube cooler. Comments on the lab report indicated that all parameters were within normal levels. How did this error make it past the laboratory personnel?

Lubricant and Machinery Analysts rely on the creation and utilization of alarm levels to trigger abnormalities of oil and wear debris analysis results. Proper setting of these alarm levels is vital in estimating the severity of the results and the overall presence of an abnormal condition. The methods of setting alarms are such that the individual end user can easily configure custom alarms to allow for precise monitoring. This session will focus on the various methods used in establishing alarms and limits for oil and wear debris analysis.

Depending on the test being monitored, limits can be set as upper, lower, or both. Generally speaking, there are three stages of machine or lubricant condition. These are normal, caution, and critical. In some instances, it may be warranted to create more levels within these three. There are labs that break the caution and critical level down to low or high caution/critical resulting in five severity levels. Others do not consider the caution level resulting in either normal or abnormal. When this is the case, the abnormal is sometimes broken in to various levels of severity or priority (low, high, critical). It is ultimately up to the client on how he/she determines the severity of the report and the appropriate reaction to that report. For the sake of explanation, we will concentrate on the three-level reporting of normal, caution, and critical.

In setting alarms and limits, it is important to understand the various types that can be utilized.

	Lubricant	Equipment
Target Limits	X	
Aging Limits	X	X
Statistical Limits		X
Rate-of-Change		X

Figure 1. Alarm Types.

As seen in Figure 1, there are multiple methods of setting alarms. Each type will be discussed in separate sections below.

Target Limits

Target limits, sometimes referred to as goal-based limits, are those that are proactive by nature. These limits are set based on several parameters including equipment criticality, historical MTBF, any recurring maintenance concerns, etc. Targets limits define goals of performance and not an impending failure.

These limits are set to lubricant properties and contamination tests. These tests include:

- Particle Count (ISO Cleanliness Levels)
- Moisture Level
- Glycol/Fuel Dilution
- Viscosity
- AN/BN

In setting the target values for testing, it is important to consider the cost involved to reach and maintain the desired target. It is very possible to overprotect a piece of equipment.

Aging Limits

Aging limits signal the approaching end of useful life. These limits can be placed on both lubricant and equipment. While aging limits are relatively easy to set for the lubricant, it takes extensive research to set aging limits on wear debris. It is true that a component can only generate so much debris before failure occurs. Like the target limits, aging limits are considered as proactive limits. Taking action based on aging limits will reduce the opportunity for catastrophic failures.

Monitoring the lubricant properties with aging limits will assist in identifying whether or not a lubricant is maintaining its expected life. These limits can also point to other types of problems such as confirming water ingress, indicating excessive heat, etc.

Tests that include the use of aging limits are:

- Viscosity (impending oxidation)
- Voltametry (additive depletion)
- AN/BN (additive depletion and impending oxidation)
- Zinc, Phosphorus, Calcium (additive depletion)
- Copper production (other wear debris)
- Dielectric Constant (impending oxidation)

Statistical Limits

Statistical limits are those generally given to wear debris. These limits take into account actual historical results based on several possible parameters. Some of these parameters include:

- Component Type (Gearbox, Hydraulic System, Compressor, etc.)
- Application (Elevator conveyor, Drag conveyor, Agitator)
- Component Make (Falk, Sumitomo, etc.)
- Component Model (170FZRK4AS105.9)

This information will allow for statistical analysis to be performed to a relatively tight point for a broad range of equipment.

The method for performing statistical analysis and setting alarm limits based on these results is quite simple. The use of averaging and standard deviations is typical in setting these alarms. When finding the average, one must gather all data relevant to the alarm being studied. For example, if you are setting an alarm for the category gearbox, obtain all historical data for units with the equipment type of gearbox. If you are setting an alarm set for Falk agitator gearboxes, use only data from these specific units. Additionally, if you are setting an alarm set for one specific unit, only historical data from that unit should be considered.

When compiling the historical data for analysis, care should be taken to ensure that only relevant data is included in the study. If, in a set of data, a value is significantly out of range in comparison to the rest of the data, do not include the value. Using out of range data, both high and low, can reduce the sensitivity of the alarms by resulting in overly estimated averages and standard deviations. Determining the data that is considered

out of range is subjective at best; however, this task can generally be accomplished effectively by an individual familiar with the data without resulting in bogus alarm values.

To compute the average, simply add all values together and divide by the total number of values calculated. The mathematical formula for figuring the standard deviation, identified by “σ” is as follows:

Formula for Calculating the Mean: $\bar{\Delta x} = \sum |\Delta X_i|/n$

Formula for Calculating the Standard Deviation:

$$s_{\Delta x} = \sqrt{\frac{\sum (|\Delta X_i| - \bar{\Delta x})^2}{n-1}}$$

Where ΔX_i = each value
 Δx = average of all values included
 n = total number of values included
 \sum = summation

When applying alarms to statistical analysis results, a caution alarm is generally placed at $x+\sigma$ with the critical alarm set at $x+2\sigma$. A recent study of all gearboxes from a single client site resulted in Table 1 when utilizing statistical analysis to set alarm limits:

Readings: 823	Data Range: 0-9999	
Significantly Incorrect: 43		
	Data Used	
	All	Corrected
Average	143	85
Std Dev	432	100
Caution	575	184
Critical	1007	284

Table 1. Gearbox Statistics.

After sorting the gearboxes into application type, statistical analysis and limits result in Table 2 for those listed as Belt Conveyor gearboxes:

Readings: 385	Data Range: 0-1475	
Significantly Incorrect: 19		
	Data Used	
	All	Corrected
Average	113.3377	71.13115
Std Dev	213.7547	78.62276
Caution	327.0924	149.7539
Critical	540.8471	228.3767

Table 2. Belt Conveyor Statistics.

Ideally, it is best to run statistical analysis on an individual component if possible. All equipment wears at a different rate depending on the operating conditions. If two units are sitting side by side, all parameters equal (model, lubricant, contamination control measures, load, etc.), one can expect a difference in wear rates and trends. As can be seen in the following example, significant differences in results are possible between equipment of the same type.

	BC-14	BC-42
Average	9	328
Std Dev	2	32
Caution	10	360
Critical	12	392
Readings:	7	6
Out of Ran	0	1
Data Rang	5-10	282-358
Period:	3-yrs	3-yrs

Table 3. Belt Conveyor Comparison.

As time passes, more data is gathered for each component. As more data is available, new alarms can be set to include updated information resulting in more precise alarm values. Statistical analysis can be performed with as little as four samples and still maintain credible alarm levels. Although it is generally thought that >30 points of data should be gathered prior to running statistical analysis, early statistics will allow for credible alarms to be fine tuned with time.

There are other parameters that must be considered when running statistical analysis and creating alarms from this analysis. Filter upgrades, lubricant upgrades, increased precision in alignment, etc. must all be considered as these items can and usually will have significant impacts on the debris generated by the component. If any major change occurs within the system that is meant to make these types of changes, the statistical analysis process must start over in order to consider the new procedures in place.

In the example discussed previously with Table 3, note that BC-42 had one piece of data considered out of range. The value of this result was 10 ppm iron. This value is significantly different than the historical samples, therefore, was not included for the alarm set in this example. In reality, this unit received a lubricant change, lubricant upgrade, desiccant breather, external sight gauge, and quick connects allowing for periodic offline filtration. All of these upgrades have resulted in a significant drop in wear debris present. This unit will have new alarm sets in place once sufficient data is obtained.

Statistically Derived Rate-of-Change Alarms

As previously mentioned, applying statistical alarms to a single component based solely on information provided by that component allows us to set fairly precise alarms; however, we can employ a higher level of precision by utilizing statistically derived rate-of-change alarms.

When establishing this type of alarm, we are focusing not so much on the actual value, but more so the rate at which the value changes from the previous sample. This type of alarm is more sensitive in that we utilize actual operational time as a parameter in the analysis. The unit of measure for operational time is generally given as hours, miles, or cycles.

When gathering data to use for the statistical analysis for rate-of-change, Figure 2 shows how the changes can go both up and down. This will result in positive and negative changes in value. For instance, an unfiltered gearbox has developed 100ppm of iron in 100 hours. This effectively suggests a rate of 1ppm iron generation per hour of operation. During the next interval of 100 hours, 160ppm iron is generated. This gives us 1.6ppm iron generation per hour of operation, resulting in a rate of change of 0.6. The third sample results are 110ppm iron meaning 1.1ppm iron generated per hour. This is a decrease by .5 resulting in a -.5 rate of change.

As noted in the formula for calculating standard deviation, we must first calculate the mean, or average. In order to compensate for the negative values that can arise from a drop in the rate of change, the typical formula for the mean and standard deviation are modified to take the absolute value of the rate of change result. When utilizing the absolute value, simply do not use the sign of the value. For instance, in the example above, under the normal formula for averages, the values used would be 1+1.6-.5/3. When using the absolute value, the values would be 1+1.6+.5/3. Using the absolute value will allow for the measuring of values from the baseline in both positive and negative trends. We are simply measuring the rate at which the value has changed. Figure 3 shows the modified formulas for calculating the mean and standard deviation.

Formula for Calculating the Mean: $\overline{\Delta x} = \sum |\Delta X_i|/n$

Formula for Calculating the Standard Deviation:

$$s_{\Delta x} = \sqrt{\frac{\sum (|\Delta X_i| - \overline{\Delta x})^2}{n-1}}$$

Where:

- $\overline{\Delta x}$ = Arithmetic mean, or average, of the slope
- s = Standard deviation
- Σ = Summation
- $|\Delta X_i|$ = Absolute value of the slope of a single observation from the last sample to the current sample
- n = The number of observations

Figure 3. Modified Formulas.

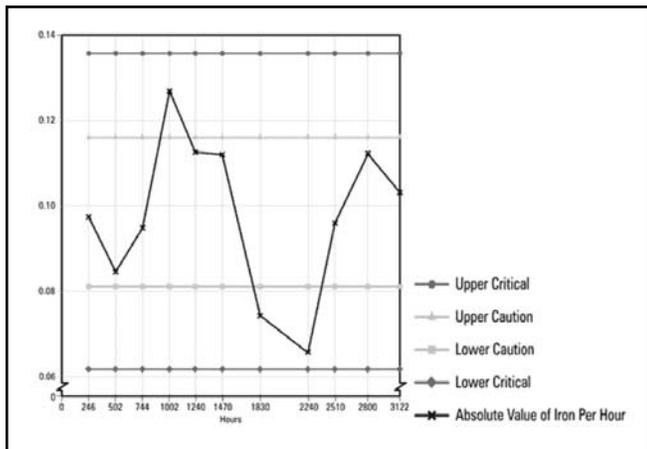


Figure 2. Rate of Change Limits.

Utilizing rate of change alarms can be very valuable in machines that inherently generate wear debris. In the example in Table 4, it is obvious that an increasing value of iron is present. When utilizing regular statistical limits, this unit would be well into the caution alarm, >248, and nearing the critical level of 340. This would likely cause the analyst or site personnel to begin to investigate causes of the increased wear. However, when utilizing rate of change alarms, we can clearly see the rate of change has remained relatively steady at or below 0.1. This has resulted in very tight alarm levels due to a low standard deviation.

When rate of change alarms are applied, it becomes evident that there was one occasion in which this gearbox went into a state of caution alarm on an increasing trend. This was the sample taken at 1002 hours.

Hours	Iron	
	Reading	Absolute Value of Iron per Hour
0	0	Baseline
246	24	0.09756
502	46	0.08594
744	69	0.09504
1002	102	0.12791
1240	129	0.11345
1470	155	0.11304
1830	182	0.07500
2240	209	0.06585
2510	235	0.09630
2800	268	0.11379
3122	302	0.10559
Average		0.09904
Standard Deviation		0.01837
Upper Critical		0.13578
Upper Caution		0.11741
Lower Caution		0.08067
Lower Critical		0.06231

Table 4. Gearbox Data.

Since this type of alarm setting is time-based, it is important to track the time in operation closely. This can be done fairly easily with mobile and construction equipment as meters are generally already installed. Stationary plant equipment can usually be tracked within the operations computer

software. If not, hour meters would need to be installed in order to utilize this type of alarm. It is important that the lubrication technician annotate the meter reading when pulling samples.

Summary

Like the full array of predictive technologies, alarm levels give the best information when combined with one another. It is difficult to determine a cause of failure or possible failure by simply using a single type of alarm. Understanding and utilizing the various methods discussed here will help your organization meet the reliability goals desired. Many types of oil analysis software exist that allow for statistical analysis similar to that mentioned here. Giving the end user the ability and knowledge to create alarms will help everyone involved ensure the most value is received out of the oil analysis program.

The answer to the question posed at the beginning of this session. If alarm levels had been in place based on the methods mentioned here, this

report would have had a better chance of being caught and flagged by the system based on the level of copper and the severe change in additive levels. Having proper alarms in place at the client level resulted in an immediate catch of this issue and understanding of what had happened. Had the client not had the appropriate alarms in place, this report may have been filed away since the comments did not indicate any abnormalities.

References

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Detecting and Controlling Water In Oil

By **MARIANNE DUNCANSON, EXXONMOBIL GLOBAL LUBRICANTS AND PETROLEUM SPECIALTIES**

This paper discusses some of the effects of water in oil, what factors affect demulsibility and how to check for water contamination. It lists major sources of water contamination and offers suggestions on how they can be controlled. Finally it discusses different methods of water separation that can be used if the source of contamination cannot be eliminated.

Effects of Water on Equipment and Lubricants

The effects of water are insidious. Failure due to water contamination may be catastrophic, but it may not be immediate. Many failures blamed on lubricants are truly caused by excess water. The following are some of the effects of water on equipment:

- Shorter component life due to rust and corrosion
- Water etching/erosion and vaporous cavitation
- Hydrogen embrittlement
- Oxidation of bearing babbitt
- Wear caused by loss of oil film or hard water deposits.

Rust and Corrosion

Water attacks iron and steel surfaces to produce iron oxides. Water teams up with acid in the oil and corrodes ferrous and nonferrous metals. Rust particles are abrasive. Abrasion exposes fresh metal which is more easily corroded in the presence of water and acid.

Water Etching

Water etching can be found on bearing surfaces and raceways. It is primarily caused by generation of hydrogen sulfide and sulfuric acid from water-induced lubricant degradation.

Erosion

Erosion occurs when free water flashes onto hot metal surfaces and causes pitting.

Vaporous Cavitation

If the vapor pressure of water is reached in the low-pressure regions of a machine, such as the suction line of a pump, the pre-load region of a journal bearing, etc., the vapor bubbles expand. Should the vapor bubble be subsequently exposed to sudden high pressure, such as in a pump or the load zone of a journal bearing, the water vapor bubbles quickly contract (implode) and simultaneously condense back to the liquid phase. The water droplet impacts a small area of the machine's surface with great force in the form of a needle-like micro-jet, which causes localized surface fatigue and erosion. Water contamination also increases the oil's ability to entrain air, thus increasing gaseous cavitation.

Hydrogen Embrittlement

Hydrogen embrittlement occurs when water invades microscopic cracks in metal surfaces. Under extreme pressure water decomposes into its components and releases hydrogen. This explosive force forces the cracks to become wider and deeper, leading to spalling.

Film Strength Loss

Rolling element bearings and the pitch line of a gear tooth are protected because oil viscosity increases as pressure increases. Water does not possess this property. Its viscosity remains constant (or drops slightly) as pressure increases. As a result, water contamination increases the likelihood of contact fatigue (spalling failure).

The effects on lubricating oil can be equally harmful:

- Water accelerates oxidation of the oil
- Depletes oxidation inhibitors and demulsifiers

- May cause some additives to precipitate
- Causes ZDDP antiwear additive to destabilize over 180°F
- Competes with polar additives for metal surfaces.

Maximum Recommended Water Concentrations

Oil, unless it is dried, contains some dissolved water. The following chart (Figure 1) shows the amount of dissolved water that can be found in ISO 220 paper machine oil and ISO 32 turbine lubricant before it turns cloudy.

Diagnetics Inc. copyrighted a chart, reproduced here (Table 1), that helps determine the relative life of mechanical equipment versus the amount of water in the lubricant. To use the chart, estimate the current moisture level in the system along the y-axis, move toward the right to the target moisture level. The top of the chart gives the estimate of how much the life of the oil is extended. For example, by reducing moisture from 2500 ppm to 156 ppm, machine life is extended by a factor of 5.

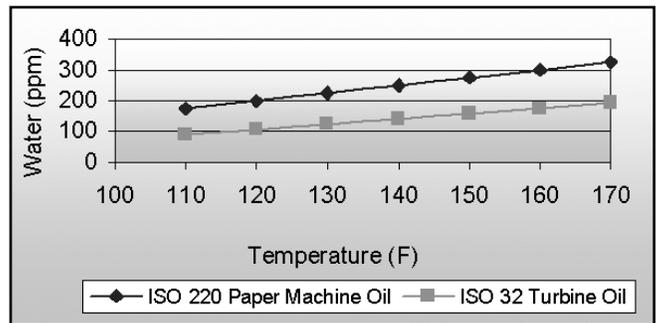


Figure 1. Dissolved Water As a Function of Temperature in Paper Machine Oil and Turbine Oil.

Tests for Water in Oil

The guidelines in Table 1 help only if you know how much water is in the oil. There are several qualitative and quantitative tests. The easiest one to perform is a simple visual test. An ISO 68 turbine lubricant was observed at room temperature with controlled amounts of water. Table 2 shows the results of the test.

Bear in mind that several things can affect the cloudy or hazy appearance of the oil. First, as the oil sits, it will clear up and the oil may become supersaturated. Second, dye and dark color oil can mask cloudiness.

A test that can be performed on sight is the crackle test. It is a quick control test that is performed by heating the oil in a small metal pan using a Bunsen burner or hot plate. It is heated rapidly to 100°C, and the technician listens carefully for the number of pops or crackles. It is not run on hazy oil unless there is a doubt as to whether the haziness is caused by water or some other substance.

Noria has copyrighted the following technique for running a visual crackle test. Here are the instructions from the web site at www.practicingoilanalysis.com.¹

- Maintain surface temperature on a hot plate of 300°F (135°C).
- Violently agitate oil sample (i.e. in a paint shaker) to achieve homogenous suspension of water in oil.
- Using a clean dropper, place a drop of oil on the hot plate.

If no crackling or vapor bubbles are produced after a few seconds, no free or emulsified water is present.

If very small bubbles (0.5 mm) are produced but disappear quickly; approximately 0.05 percent to 0.1 percent water is present.

If bubbles approximately 2 mm are produced, gather to center of oil spot, enlarge to about 4 mm, then disappear, approximately 0.1 percent to 0.2 percent water is present.

For moisture levels above 0.2 percent, bubbles may start out about 2-3 mm then grow to 4 mm, with the process repeating once or twice. For even higher moisture levels violent bubbling and audible crackling may result.

The method is not quantitative. Hot plate temperatures above 300°F induce rapid scintillation that may be undetectable. The method does not measure the presence of chemically dissolved water. Different base stocks, viscosities, and additives will exhibit varying results. Certain synthetics, such as esters, may not produce scintillation. Refrigerants and other low boiling-point suspensions may affect results. False positives are possible with entrained volatile solvents and gases.

Protective eyewear and long sleeves are suggested, and the test should be performed in a well-ventilated area.

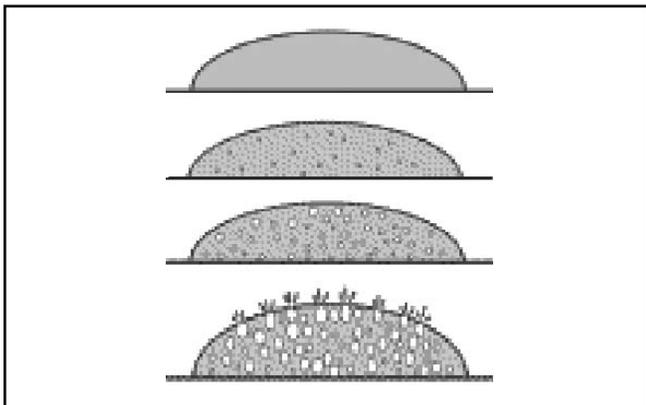


Figure 2. Calcium Hydride Test Kit.

Moisture Life Extension Method										
Life Extension Factor										
Current Moisture Level	2	3	4	5	6	7	8	9	10	
50000	12500	6500	4500	3125	2500	2000	1500	1000	782	
25000	6250	3250	2250	1563	1250	1000	750	500	391	
10000	2500	1300	900	625	500	400	300	200	156	
5000	1250	650	450	313	250	200	150	100	78	
2500	625	325	225	156	125	100	75	50	39	
1000	250	130	90	63	50	40	30	20	16	
500	125	65	45	31	25	20	15	10	8	
250	63	33	23	16	13	10	8	5	4	
100	25	13	9	6	5	4	3	2	2	

Figure 2. Calcium Hydride Test Kit.

A convenient way to determine water concentration in the field is by using a calcium hydride test kit (Figure 2). Water reacts with solid calcium hydride to produce hydrogen gas, which is directly proportional to the amount of water present in the sample. The water content of the sample is measured by the rise in pressure in a sealed container. These test kits are reported to be accurate down to 50 ppm free or emulsified water.

All of the water must come into contact with the calcium hydride. Viscous oils physically prevent water from mixing with calcium hydride whereas polar additives chemically attract water molecules to hold the water in solution.

There are several on-line sensors that measure water while equipment is operating (Figure 3). Some sensors measure the temperature and relative water saturation of petroleum and synthetic fluids and fuels. A probe senses water at a representative point of the system. The devices change capacitance as water concentration increases and decreases. Results are read as percent water saturation. Another technology monitors the humidity in the sump or reservoir headspace (Figure 4). Relative humidity of the headspace air has been found to correlate to lubricant moisture levels.

By monitoring water content below the saturation level, these units allow action to be taken prior to the formation of free water, thus preventing problems such as additive depletion, oil oxidation, corrosion and reduced lubricating film thickness.



Figure 3. On-line Impedance-type Moisture Sensor.

Temperature changes affect saturation. An oil with 200 ppm water may be suitable for use at an operating temperature of 180°F, but if the equipment cools down to 60°F, saturated water can be released as potentially damaging free water. Testing the oil in service and correcting for temperature allows operators to discover and correct water problems before they reach the stage where water drops out.

One drawback of saturation meters is that temperature, additives, contaminants and wear particles affect saturation point. In addition, saturation meters are unable to quantify water content accurately when

water is above the saturation point, typically 200 to 600 ppm for industrial oils. Despite these limitations, saturation meters can be a useful trending tool to determine moisture, provided they are used frequently and routinely.

Another sensor technology is based on the absorption of infrared light (Figure 5). One channel measures the amount of water in the oil while the other is a reference channel. The infrared absorption is determined from the difference between these two channels at the target spectral band for water. This absorption, using a calibration curve, is used to estimate the amount of water in the oil sample as traditionally presented in ppm or percent. According to the manufacturer it will read concentrations to 2 percent water.

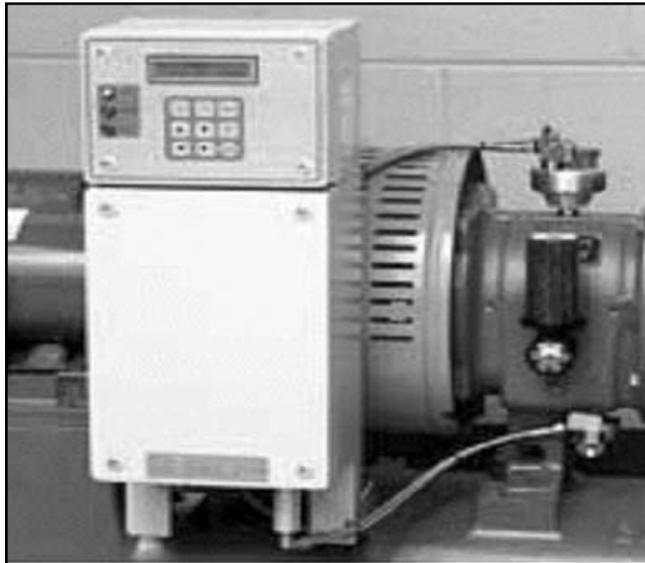


Figure 4. On-line Headspace Moisture Sensor.

Amount of water, ppm	Appearance of oil
0	Bright and clear
100	Trace of translucent haze
200	Slight translucent haze
250	Translucent haze
500	Opaque haze
1000	Opaque haze with slight water drop out

Table 2. Visual Check of Water in Turbine Oil.

Quantitative tests for water include Karl Fischer, water by distillation and FTIR. Karl Fischer (Figure 6) is accurate from 1 ppm to 100 percent and is relatively quick and inexpensive. The oil sample is titrated with a standard Karl Fischer reagent until an end-point is reached. The difference in test methods is based on the amount of sample used for the test and the method used to determine the titration end-point.

ASTM D1744, a volumetric method, is reliable and precise, but there can be reproducibility problems at low water concentrations (200 ppm or less). Soaps, salts from wear debris, and sulfur based additives react with the Karl Fischer and can give a false positive. In fact, a new, clean, dry AW or EP oil may give a reading of as much as 200 to 300 ppm.

ASTM D6304, a coulometric titration method (Figure 6), is more reliable than D1744 at low water concentrations and is less prone to interference effects, although again, AW and EP additized oils can show as much as 100 ppm of water.

The most reliable method is ASTM D6304. The oil sample is heated under a vacuum so that any water present in the sample evaporates. Water vapors are condensed and dissolved into toluene, which is then titrated. Because the additives and other interfering contaminants remain in the oil, the condensed water in the toluene is a true indication of water present in the sample.

Water by distillation measures the amount of water boiled off in a special still (Figure 7). The classic method for determining water-in-oil is the Dean and Stark distillation method (ASTM D95). This test method is fairly cumbersome and requires a comparatively large sample to ensure accuracy, which is why it is rarely used in production-style oil analysis labs today. As the oil is heated, any water present vaporizes. The water vapors are then condensed and collected in a graduated collection tube, such that the volume of water produced by distillation can be measured as a function of the total volume of oil used. It can detect between 500 ppm and 25 percent water.

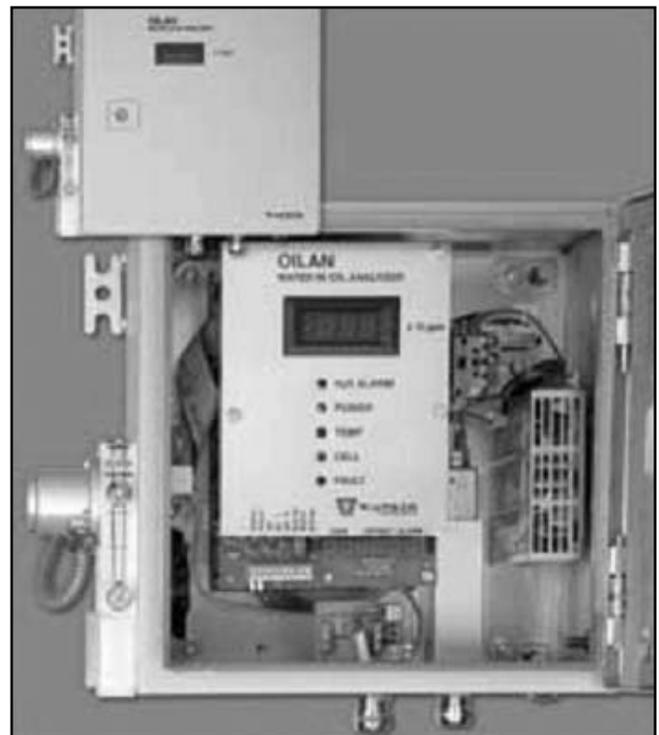


Figure 5. Single-channel Infrared Moisture Sensor.

FTIR can be an effective method for screening samples containing in excess of 1,000 ppm of water, provided a correct new oil baseline is available for spectral subtraction. However, due to its limited precision and comparatively high detection limits, FTIR is not adequate in many situations where precise water concentrations below 1,000 ppm or 0.1 percent are required.

Control of Water Sources

Now that you have determined the amount of water in the oil, how do you control it?

First, control the source of water contamination. Following are common sources of water into lubricating oil and suggestions on how to control them:

- Manage new oil properly.
- Use desiccant breathers or other tank headspace protection.

- Avoid shafts, fill ports and breathers when washing down machines.
- Avoid high-pressure sprays in the areas of seals if possible.
- Maintain steam and heating/cooling water system seals.
- Periodically inspect rotary steam joints for leaks; replace seals and/or correct alignment as appropriate; install flinger flanges to direct steam away from labyrinth seals.
- Repair heat exchanger leaks.
- Prevent wash down water from entering vents and reservoir covers.
- Properly install and seal covers and hatches.
- Watch for condensation caused by cold water lines located close to a hot reservoir.
- Gutter water to divert flow away from reservoir hatches.
- Install secondary seals or v-rings on critical systems.
- Use and maintain high quality shaft and wiper seals.
- Prevent contamination from condensation by using a bladder type breather on vents.
- Install desiccant air breathers on vents (Figure 8).
- Prevent water from entering new oil by storing drums indoors. If they must be stored outdoors, keep them under a shed or tarp, or store them on their sides.
- Install a vapor extractor or fan to remove humidity from large reservoirs.
- Periodically drain water from low points in system.



Figure 6. Coulometric Karl Fischer Titration Analyzer.

Methods of Oil/Water Separation

Once sources of water contamination have been controlled to the extent possible, there are several methods to remove water from oil. Methods that can be used successfully include settling, heat, chemical demulsifiers, filter/coalescers, centrifuges, vacuum dehydrators and headspace dehumidification.

The principal means of water separation is by gravity separation. There are many reservoir designs that can promote settling, but they all work on the same principle. The fluid must have enough residence time to allow the water to settle. This requires a reservoir of sufficient capacity as well as baffling to control fluid flow. Many reservoirs are designed with separate precipitation, filtration and storage compartments. A cone-shaped separating tank improves the effectiveness of gravity separation.

Heating the oil increases molecular motion. The collision frequency of water bubbles increases, and bubble walls bursting due to expansion both promote coalescence. Heating also reduces the viscosity of the lubricant,

and increases the difference between the density of the oil and water. The disadvantage of using heat is that it is expensive and promotes oxidation of the oil.

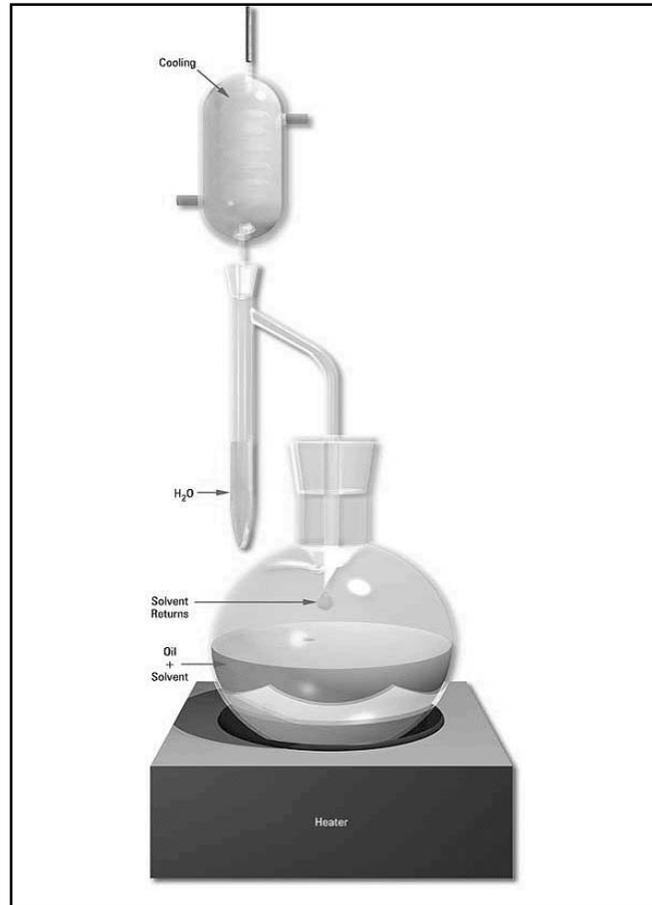


Figure 7. Distillation Method for Determining Moisture Levels..



Figure 8. Desiccant Air Breathers.

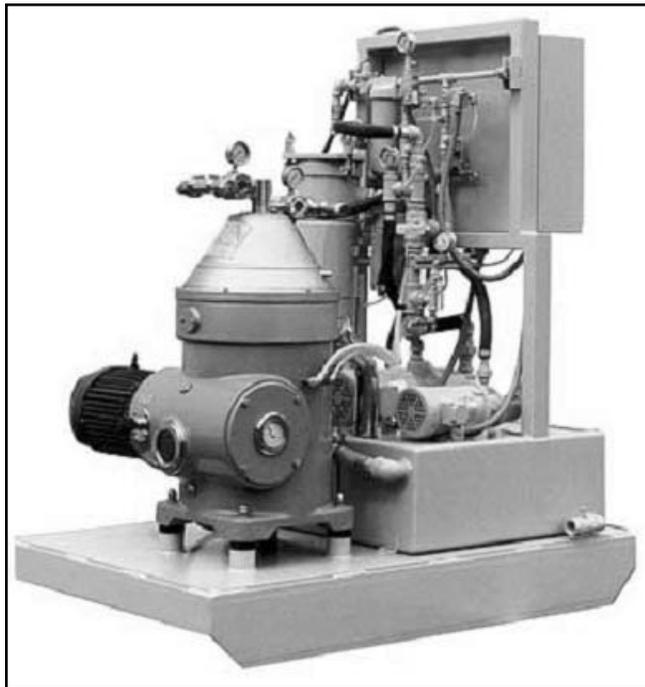


Figure 9. Centrifuged Separator.

Chemical demulsifiers work in two stages. First they flocculate the bubbles by forming a chemical bridge between water droplets. They can also interact with demulsifier molecules that are already absorbed on the droplet's sheath. The second step is coalescence. Once the chemical bridge has been formed, the demulsifier penetrates the emulsion film and replaces the emulsifier molecules to form an unstable film. Demulsifiers can also penetrate the emulsifier film to form a hydrophilic passage through which water can drain from one droplet to another. Both of these mechanisms allow small, stable bubbles to combine into larger bubbles.

Demulsifier additives should be added sparingly, if at all. It is better to correct the root cause of contamination. If it is necessary to use them, consult with your oil or additive supplier on the proper type. As a general rule of thumb, use a water-soluble demulsifier if the emulsion is primarily water, or if the bubbles are large. If there are a large amount of solids, choose a demulsifier that wets solids. And, it stands to reason; use an oil soluble demulsifier if the product is predominantly oil with a small amount of water contamination.

Coalescers work by allowing oil to pass through wetted membranes while keeping water out. The media is commonly fiberglass type material that has a very high surface area and fairly dense pores. Coalescing separators help small droplets of water combine to form large ones so they will drop out of the oil more easily. Coalescing separators are more effective when the oil's viscosity is low, making them an ideal solution for removing water from fuel. Coalescers effectively remove free water, but cannot remove dissolved water.

Free and emulsified water is collected by super absorbent polymers impregnated in the media of certain filters. The water causes the polymer to swell and traps it in the filter media. Superabsorbent filters remove only a limited volume of water before causing the filter to go into pressure-drop induced bypass. They do not remove large volumes of water, but they maintain dry conditions in systems that don't ingest a lot of water.

Centrifuges are one of the most traditional methods of separating oil and water (Figure 9). They use the same principle of density differences that

allow water to sink to the bottom of a reservoir, but they speed up the process by using centrifugal force. Water is thrown to the outside of a spinning element. Stacked conical plates capture the water and direct it downward to the outside of the unit. Clean oil flows through holes in the cones and upward to the top center of the cone stack, where it is collected. Centrifuges are 6,000 to 10,000 times faster than settling.

Separator Type	Water Type Removed		
	Free	Emulsified	Dissolved
Gravity	Yes	Some	No
Centrifuge	Yes	Some	No
Coalescing	Yes	Some	No
Absorbent Polymer	Yes	Yes	No
Vacuum Distillation	Yes	Yes	Yes
Headspace Dehumidification	Yes	Yes	Yes

Water Separation Techniques

Table 3.

Vacuum dehydration can remove dissolved water below its solubility point and can break stabilized emulsions. Oil should be filtered before it enters the dehydrator to minimize contamination of the elements. Each pass removes 1 percent to 1.5 percent of free, emulsified and dissolved water, so it is important to monitor the oil out of the dehydrator to make sure that it is bright and clear. If the oil is still cloudy, it should be recycled through the unit.

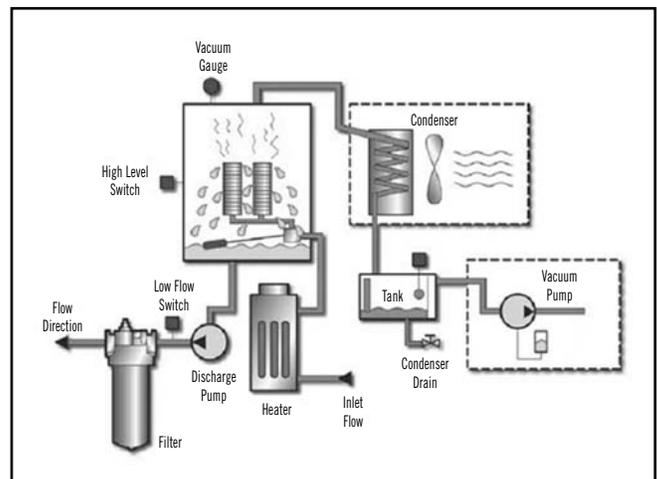


Figure 10. Vacuum Dehydrator.

Vacuum dehydrators are typically run up to 160°F with a vacuum up to 28 inches Hg. At 25 inches Hg, water boils at approximately 133°F (56°C). It is one of the most effective means of removing water, has few moving parts, but tends to take up a significant amount of space and can be relatively slow compared to centrifuges. There is some risk of additive vaporization with this technique.

In dehydrating and reclaiming used lubricants and hydraulic fluids, vacuum distillation equipment is applied in one of three process configurations:

- The first is simply the transfer, in a single pass, through the vacuum distillation unit from one tank to another.
- The second recirculates (multi-passes) oil through the vacuum distillation unit from a static tank.
- The third involves online recirculation through a vacuum distillation unit on an operating fluid system. Such applications may not require the addition of heat to the fluid, as operating temperatures may be adequate to achieve distillation.

Headspace dehumidification units operate by removing air from the headspace of a sump, dehumidifying it then sending an equal volume (or a boosted volume, in some cases) of air back to the reservoir to maintain pressure. If the oil contains water contamination, it will migrate to the dry air, which is eventually sent to the dehumidifier for removal. The great advantage of this technique is that it never contacts the oil. This technique will remove free, emulsified and dissolved water.

Table 3 provides a general rating of the ability of each technology to remove free, emulsified and dissolved water.

CONCLUSIONS

Reducing the level of water in oil can dramatically extend component life. It is important to establish a system to detect the presence of water. Once water is identified, search out possible sources of contamination, and control them as well as possible. Use one of the methods suggested in this paper to treat contaminated lubricating oil in order to maintain acceptable water levels.

Reference

1. Troyer, D. (1998, September-October), The Visual Crackle - A New Twist to an Old Technique. Practicing Oil Analysis.

How to Select Machine-Specific Oil Analysis Tests

By Ashley Mayer, NORIA CORPORATION

An important aspect of oil analysis is being able to produce machine-by-machine test slates which serve the performance requirements of the assets under the user's control. There is no single oil analysis test slate which can serve all the needs of all the different types of oil-lubricated assets on a plant. An understanding of what oil analysis can provide is invaluable in determining test slates for various different types of equipment. It is also essential to determine the type of maintenance profile suitable for the machine. Armed with this information one is in a position to determine a test slate which is effective both in costs and performance.

This paper examines the typical classes of oil-lubricated industrial machinery, and the tests that are most commonly available to be matched to them. A range of tests is examined, from simple field tests, through onsite laboratory tests, to those tests only feasible in commercial oil analysis laboratories. Ultimately the goal is for the user to be able to confidently match the tests to their machines' reliability profiles.

INTRODUCTION

There are a couple of different perceptions of oil analysis. One view is that oil analysis is there to provide warning of imminent breakdown. This is the predictive maintenance approach. Another view is that oil analysis is a metric of the overall health of a machine, the proactive approach. And oil analysis can fulfill both of these roles admirably, if used correctly. By used correctly is meant that the correct tests are chosen for the machine to serve its reliability profile. As an example: an iron mine, as much as they claimed differently, and as much as they wanted to believe differently, were practicing rudimentary preventive maintenance. This company was owned by a large international mining house which demanded their subsidiaries carry out particle counts on all their oil-lubricated assets. It was asserted, and rightly so, that particle counts are an important part of a proactive maintenance program. But as this mine was not practicing any type of contamination control the laboratory they were using was seldom able to produce a meaningful particle count due to the severe dirt and wear metal contamination in the samples. The results: oil analysis data which was meaningless for the mine's operation, loss of faith in the tool, undetected failures, and an overall bad taste in the mouth for anything to do with lubrication. Had this mine been able to acknowledge their maintenance abilities, been able to choose tests more suited to their existing maintenance procedures they would have been able to detect more impending failures and act on them, rebuff the oil analysis skeptics, and use the proven savings to justify improvements to their lubrication program.

Trying to determine the correct test slate for an oil-lubricated piece of machinery can be daunting. There are so many tests available, some appropriate for the application, others not. Having an idea about what the various tests are, what they can accomplish, and taking into account the maintenance philosophy being practiced, test slates to accomplish the desired results can be easily drawn up.

This paper begins with a brief overview of some of the commonly available tests. Next it examines common test classes one might find in industry, and provides some example test slates, depending on the needs, for each of the test classes.

The Tests

Eleven commonly performed tests are being considered, and are listed in Table 1. These tests are not all the tests that can be performed, but do include all the most common ones. The table also indicates whether this test can be reasonably done as at an onsite laboratory, or whether they are more likely to be performed in a commercial oil analysis laboratory. Onsite laboratories range from very simple to very complex, and the third column in Table 1 represents an industry average of what might be found in an onsite laboratory.

It is worth noting that test packages can be purchased from most

laboratories at a price substantially cheaper than the sum of the individual tests purchased separately. Where possible these test packages should be used, and complimented with extra tests if desired.

Item	Test	Onsite Laboratory	Commercial Laboratory
1	Particle Counting	✓	✓
2	Water (crackle test)	✓	✓
3	Water (Karl Fischer)		✓
4	Viscosity	✓	✓
5	Ferrous Density		✓
6	Analytical Ferrography		✓
7	Filter Analysis	✓	✓
8	Acid Number	✓	✓
9	FTIR (oxidation)		✓
10	Patch Test	✓	✓
11	Elemental Analysis		✓

Table 1. Common Oil Analysis Tests.

Oil analysis can be broadly divided into three different categories: fluid condition; contamination; and wear. In discussing the tests outlined in Table 1 reference is made to which aspect, or aspects, are covered.

Particle Counting

The particle counter produces a count, in different size ranges, of particles per 1 ml of oil. It is concerned primarily with contamination, but as some of this contamination may be internally generated the wear aspect of oil analysis is also addressed. With most particle counters differentiating between internal and external wear is impossible, but there are new technologies available which are addressing this.

A particle counter produces a number for each of the different size ranges. A typical result may look something like Table 2. Various different types of machines are used to generate these counts, and different reporting structures are used, but Table 2 probably represents the most common one.

4	6	10	14	20	50	75	100	4 / 6 / 14
1,752	517	144	55	25	1.3	0.27	0.08	18 / 16 / 13

Table 2. A typical particle count.

Each column, except the last, reports the number of particles bigger than a certain size in microns per 1 ml of fluid. Because trying to absorb all the information presented at once is not that easy, a summary of the particle count is presented in the last column. This summary reports an index related to the number of particles in each of the following different size ranges: larger than 4 microns; larger than 6 microns, and larger than 14

microns. Increasing numbers as evaluated on a trend basis indicate the fluid is getting dirtier, and decreasing numbers indicate the fluid is becoming cleaner.

It is worth mentioning that there are interferences that can cause anomalies in the results; these interferences depend on the technology being used, but can include water droplets, air bubbles, and heavily discolored oil. If significant differences in particle counts are noticed the first course of action should be to ensure, as far as possible, interferences have been dealt with in the testing process, and that other significant test results have not changed, such as water contamination.

Particle counters are not inexpensive, but the results they provide are generally seen as being important enough to warrant their inclusion in many onsite oil analysis laboratories.

Water (Crackle Test)

The crackle test is one of the simplest tests that can be performed on an oil sample, and is an absolute must for any onsite laboratory. It addresses the contamination aspect of oil analysis. The test involves heating the oil up to between the boiling point of oil and water – at this temperature water in the oil will boil and produce noticeable bubbles. In practice it involves putting a drop of oil onto a hotplate and watching for the water bubbles in the oil drop. It is accurate to approximately 500 parts per million (ppm), or 0.05%, water content.

Interferences are few, probably the most significant being the presence of contaminants such as refrigerant gas. The crackle test will suffice for most moisture content determination needs: if it passes the crackle test your moisture levels are acceptable.

A failed crackle test should in most cases be followed up by a test to determine the exact water content. Various options are available, the most common being the Karl Fischer test.

Water (Karl Fischer)

The Karl Fischer method is used to determine the exact water content of an oil sample. It reports results as ppm water. It is most commonly used as an exception test generated by the crackle test, but should absolutely be run as a routine test in situations where water content below 1,000 ppm is important, such as electrical transformers. In most industrial applications Karl Fischer as an exception test from the crackle test should suffice.

Viscosity

Viscosity is a fluid's resistance to flow. It is an important indicator of the condition of the oil, and can be negatively affected by contamination too. There are various means of carrying out the viscosity test, and it can be reported at temperatures of 40°C or 100°C. For most industrial applications a viscosity measurement at 40°C is required.

Many onsite laboratory instruments do not carry out the test at 40°C, but rather perform the test at room temperature and then estimate a 40°C measurement. The method used is of secondary importance to consistency in method in performing the test from sample to sample. It is the trend that is ultimately the most important.

Ferrous Density

Ferrous density is a determination of the content of magnetic debris in the oil. As most wear metal is iron-based, this test is, in most cases, a good indicator of the amount of wear debris in the oil. It does not have a particle size bias, as does the elemental analysis test, but generally does not have good sensitivity at very low levels of wear metal contamination. As such, the

nature of this test puts it squarely into the realm of predictive maintenance, rather than being a proactive maintenance tool.

There are several different instruments ranging from portable to desktop units available for performing this test, and each instrument reports its results in a different way. Once again, the particular instrument used to perform the test is of secondary importance compared to consistency of method from sample to sample.

Analytical Ferrography

Analytical ferrography is the visual analysis of solid contaminants removed from the oil sample. As the name suggests it is biased towards contaminants of a ferrous nature, i.e., wear metal, however some non-magnetic debris gets trapped as well. The test uses magnetic fields to separate the ferrous debris into different size ranges on a microscope slide where after the slides are examined under a compound microscope. It is an expensive test to perform, and the results are subjective, so this test is usually only performed as an exception test.

On filtered systems the results of this test may be misleading due to the possibility of abnormal wear particles being filtered out. It certainly can be used on filtered systems, and on systems which are filtered by portable filtration units there may be no choice, but preferably a filter analysis should be carried out such systems.

The high capital outlay for equipment and the complexity of interpretation make it unlikely that analytical ferrography will be found in most onsite laboratories.

Filter Analysis

Filter analysis is a visual analysis of solid contaminants removed from the filter. It involves washing out a piece of the filter membrane, and depositing the contents onto a filter patch for microscopic analysis. The debris can be separated into magnetic and non-magnetic components if desired, but unlike analytical ferrography the particles are not separated according to size. Like ferrography, the test is time-consuming, thus expensive, and subjective. It provides better resolution of non-magnetic debris than analytical ferrography. This test should be carried out on filtered systems as an exception test, possibly generated by an out-of-specification elemental analysis, ferrous density, or particle count.

Filter analysis can be successfully performed in an onsite laboratory however more advanced diagnoses will probably be available from a commercial laboratory.

Acid Number

The acid number (AN) test measures the acid content of a sample. The AN is an indication of how much the fluid has oxidized, or degraded. AN is also used to determine the rate of depletion of the anti-oxidant additive. It is primarily focused on the condition of the oil, although some contaminants can also affect the AN. Units are mg KOH/gram oil. An increasing AN indicates increasing oxidation of the oil. Unlike some conditions, like contamination, which can be reversed, a high AN cannot be.

Acid number can be easily and inexpensively carried out in an onsite laboratory.

FTIR

Fourier-Transform Infra-Red (FTIR) spectroscopy uses infra-red light of varying frequencies to search for the presence of absence of certain compounds in the oil. The scope of the test can range from very simple, thus inexpensive, to very complex and expensive, depending on the results

sought. FTIR examines both the condition and contamination of the sample.

For most industrial applications the simple tests can give sufficient information. The primary property sought here is oxidation.

FTIR is seldom found in onsite laboratories due to its high capital cost and moderate complexity of operation. It is worth noting that prices on the spectrometers are decreasing and as such the feasibility of including one of these devices in an onsite laboratory is increasing.

Patch Test

Like the crackle test, the patch test is one of the easiest and most inexpensive tests to perform and is a must for an onsite laboratory. The test involves filtering oil through a filter patch and examining the filtergram through a microscope. This test focuses on the contamination and wear aspects of oil analysis. If desired, the contents of the oil sample can be separated into magnetic and non-magnetic components and each part examined individually. It is worth attaching a camera to the microscope to record the resulting images on a computer for comparison purposes.

Elemental Analysis

Arguably the most important test in the oil analysis arsenal elemental analysis provides information on all three aspects of oil analysis: the condition of the fluid (levels of some additives); contamination; and machine wear. The commonly used method is inductively-coupled plasma (ICP) spectroscopy which utilizes light in the visible and ultra-violet ranges. It reports results in ppm of various elements.

The major drawback of this test is the size of the particles it can detect. Particles larger than 5 to 8 microns in size are not detected by this test. However in most wear situations there will be an increase in wear particle sizes across the range, so elemental analysis still provides excellent results. An understanding of the metallurgy of the machine is vital in the interpretation of the results. It is also important to employ exception tests when anomalies in the elemental analysis are detected.

Due to the high capital costs and complexity of operation ICP spectrometers are found in none but the most sophisticated of onsite laboratories.

The Profiles

Three commonly encountered industrial test classes are going to be examined: gearboxes; and clean-oil systems.

The test profiles have been divided up into three categories: screening; predictive; and proactive.

A screening test can be run in a few different applications. It might be used on small, non-critical pieces of equipment for which regular full-slate oil analyses are not cost-effective. Screening tests can also be run on any piece of equipment where a problem is suspected. The benefits of a screening test should be low cost and particularly high speed of turnaround. Typically for these reasons a screening test would be performed at an onsite laboratory. A screening test should be seen as an enhancement to a routine oil analysis test slate, rather than a replacement.

The routine oil analyses have been divided into two categories, predictive and proactive. Ideally one wants to be performing proactive maintenance as far as possible, but there are numerous times when performing predictive maintenance is the correct course of action. Such occasions might include low replacement cost or low criticality of particular pieces of equipment, when more complex maintenance strategies are unwarranted. Proactive

maintenance strategies would typically be performed on newer, more expensive equipment, and where criticality of operation makes a high reliability desirable.

In Table 3 and Table 4 the predictive and proactive test profiles have two types of tests indicated, routine and exception. Routine tests are performed each and every time the sample is tested. The screening profile has no exception tests indicated; the exception test for a failed screening test is a full routine analysis.

The profiles presented are designed to serve as guidelines only to help with creating test slates for the most common industrial applications. There are instances when the criticality of operation, cost, safety factors, environmental factors or fluid selection make changes to the suggested test slates desirable. In all instances the previously mentioned factors need to be taken into account in deciding the final test slate. An understanding of what oil analysis can provide in conjunction with the reliability goals is essential when making the final choice.

Gearboxes

Some suggested test profiles for gearboxes are presented in Table 3.

There is more emphasis on abnormal wear in the predictive test slate, and on contamination and oil condition in the proactive one. As an example, whilst ferrous density and patch tests are suggested as routine tests in the former they are only exceptions in the latter. It can also be seen that AN is included in the proactive test slate, here more to monitor abnormal additive depletion rather than oxidation.

Item	Test	Screening	Predictive	Proactive
1	Particle Counting			✓
2	Water (crackle test)	✓	✓	✓
3	Water (Karl Fischer)			E(2)
4	Viscosity	✓	✓	✓
5	Ferrous Density		✓	E(1)
6	Analytical Ferrography		E(5)	E(5,10)
7	Filter Analysis			
8	Acid Number			✓
9	FTIR (oxidation)		✓	✓
10	Patch Test	✓	✓	E(1, 5, 11)
11	Elemental Analysis		✓	✓

Table 3. Gearbox Test Profiles. R = Routine. E = Exception (triggering tests in parentheses).

Clean-oil Systems

Clean-oil systems include machines such as compressors, hydraulics and circulating systems, such as turbines. As can be seen in Table 4 there is more emphasis placed on contamination in clean-oil systems than with gearboxes. Due to the nature of these machines they are generally less tolerant of contamination than gearboxes.

Item	Test	Screening	Predictive	Proactive
1	Particle Counting	✓	✓	✓
2	Water (crackle test)	✓	✓	
3	Water (Karl Fischer)		E(2)	✓
4	Viscosity	✓	✓	✓
5	Ferrous Density			E(1, 11)
6	Analytical Ferrography			
7	Filter Analysis			E(1, 10, 11)
8	Acid Number		✓	✓
9	FTIR (oxidation)		✓	✓
10	Patch Test		E(1)	E(1, 11)
11	Elemental Analysis		✓	✓

Table 4. Clean-oil Systems.

CONCLUSION

Oil analysis can serve many goals including failure prediction and overall health monitoring. But it is only able to do its job when the correct tests are chosen to serve the goals in mind. Before one can choose a test slate for a

machine one needs to take cognizance of both the reliability profile of the machine and have a thorough understanding of the basic tests. Once this has been done the user can confidently select an oil analysis test slate to accomplish the task at hand.

Directing Maintenance Activities with Oil Analysis

BY KEVAN SLATER, SCHEMATIC APPROACH INC.

Oil Analysis is not just a method of determining the condition of the lubricant, but more importantly, a very effective method to assist in evaluating the immediate and future maintenance requirements for lubricated equipment.

Armed with an effective fluid and equipment condition-monitoring program, this case study looks at timely representative oil sampling, equipment specific knowledge, the equipment failure modes and the tests required for identifying them. Basic ISO Particle Counts, laboratory-specific Scanning Electron Microscope (SEM) tests and L10 bearing life factors were utilized to effectively assess and evaluate the optimum maintenance activities required to operate a mission critical pump until scheduled maintenance repairs could be performed.

Condition Based Monitoring (CBM) programs should be more than identifiers of anomalies in equipment; the technologies available should be systematically selected to assist in identifying anomalies, evaluate the cause of a condition, trend degradation and manage a cost-effective process for the repair.

Many organizations have the ability to effectively coordinate these tasks but lack the understanding of the original design conditions/requirements, the internal metallurgy of the components, and the bearing specifications of each piece of equipment in their program. The upfront cost of an Equipment Audit combined with the lack of vision that lubricants and equipment will fail diminishes the ability to perform effective methods to manage this maintenance process. The information required for many of these activities is obtained through this comprehensive information collecting process starting with a visual inspection (walk-down) of the critical equipment. Equipment models and OEM (Original Equipment Manufacturers) specifications reviewed and recorded, internal components identified, and the followed up by setting equipment specific targets and limits that reflect the specific equipment design.

Mature PdM (Predictive Maintenance) teams armed with this information have the ability to assist in identifying the root cause, the effect to the equipment and the maintenance options required to operate safely and cost-effectively.

Background Information

Many plants have critical equipment that has a predetermined duty cycle (mission time) that is required for a process, licensing or more importantly maintaining a safe operating condition. The following case study outlines the series of events, tests and recommendations performed by a trained PdM team. The component/system engineers along with the maintenance management team competently assessed the results and determined the ability of a critical centrifugal pump to perform its required duty cycle based on all information/data collected. Since the data and the results are both shared and used by each of the technologies for evaluation, the following layout appears to be technology specific but is in fact truly a team effort.

Initial Discovery - Oil samples were taken from P1 on March 18, 2004 during the forced outage (tested March 23, 2004). The oil sample for the NDE bearing appeared dark green and opaque. Initial oil analysis determined that the oil was heavily contaminated with wear particles and that viscosity had nearly doubled. These initial results led the PdM team to speculate that the brass slinger ring was wearing as a result of the high viscosity lubricant and that failure of the bearing was imminent. The oil data and work order history indicated that the change in viscosity was possibly caused by the addition of the wrong oil during a recent oil top-up.

Work Orders were put in place to flush housing and fill with the correct lubricant and re-test the oil after a 30-minute runtime. A vibration survey would also be performed to evaluate equipment condition.

Follow-up Testing - The following subsequent vibration, oil and metallurgical analyses were performed in unison to assist in directing maintenance activities for effective assessment of the asset's condition and the possible solutions for correcting the anomaly.

- **Oil analysis:** ISO 4406 particle counts were 15 times the critical alarm levels, while physical properties of the lubricant were within specifications. Ferrography and Patch tests confirm the presence of copper alloy and ferrous wear debris material. This analysis was not sufficient to determine if the bearing and the slinger ring were the source of the wear debris. Thus, a Scanning Electron Microscope (SEM) X-ray spectroscopy was scheduled to determine the metallurgy of the wear particles.
- **Vibration Analysis:** P1 was test run for 12 hours on March 30, 2004. Vibration readings were very low, as is typical with this model of pump. Bearing defect frequencies were essentially undetected, and the bearing has not yet entered into Stage 1 failure. There was no change in vibration during the 12 hour run.
- **Metallurgical analysis:** SEM/EDX analysis determined that the wear particles were primarily leaded brass/bronze and grey cast iron. Materials composition in the P1- NDE bearing housing determined the source of particle generation was the deflector disc (SAE 40) rubbing against the bearing cover (class 30 grey cast iron). Steel particles were not detected, indicating that the bearing (52100, 1050) and oil ring sleeve (1020) were not wearing nor was the shaft (410SS), as Chromium (Cr) was not detected in any significant amount. The important conclusion here is that bearing wear is not detected.

Oil Screening Results

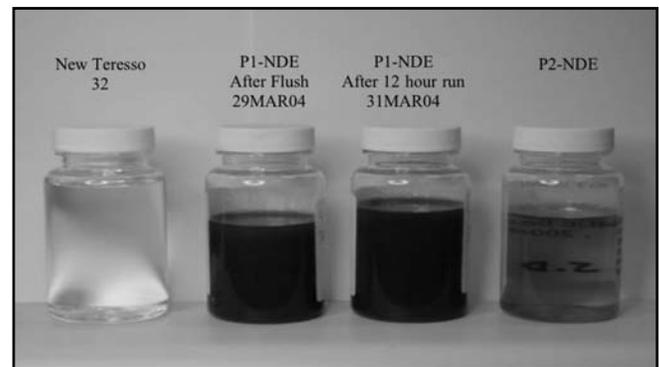


Figure 1.

Visual Comparison of Oils

The darkening of the P1-NDE lubricant is a direct result of the wear debris contained in the sample and not the degradation of the lubricant. Visual inspection shows wear debris particles visible to the naked eye (larger than 60 micron).

Lubricant Screening Data

Sample Location	New Oil Sample, Teresso 32	P1 NDE Bearing Housing	P1 NDE Bearing Housing	P1 NDE Bearing Housing	P1 NDE Bearing Housing	P2 NDE Bearing Housing
		Routine	Routine	30 minute run after Oil Flushing and Change	12 hour run after Oil Flushing and Change	Same pump in different location
Sample Date	06-Feb-04	11-Sep-03	23-Mar-04	29-Mar-04	31-Mar-04	18-Mar-04
Particles > 5 µm	219	5990	21901	261954	60193	4256
Particles > 15 µm	23	639	2341	28006	6434	455
ISO Rating	15/12	20/16	22/18	25/22	23/20	19/16
Total estimated debris mg		3mg	12mg	250mg	30mg	
Viscosity, cSt@40°C	32.0	28.7	58.2	40.8	34.3	33.2
Fe (ppm)	0.1	3.5	35.9	51.5	68.2	12.3
Al (ppm)	0.0	0.0	0.3	0.7	0.6	0.0
Cu (ppm)	0.0	1.2	88.9	226	207	0.4
Pb (ppm)	0.0	9.2	32.1	34.6	40.4	10.0
Sn (ppm)	0.0	0.1	4.8	9.5	9.8	0.2
Cr (ppm)	0.0	0.1	0.4	0.5	0.8	0.1
Si (ppm)	0.0	2.6	2.3	3.3	3.5	16.1
Zn (ppm)	6.6	1.1	7.5	21.4	18.8	1.1
P (ppm)	19.5	3.7	11.9	4.9	0.5	2.2

Table 1.

Wear Debris

Ferrogaphy and Patch Tests confirm the presence of large quantities of copper alloy (brass) debris. They range in size from 2 to 60 microns, but the largest concentration appears to be 15 to 25 microns. Some of the larger brass particles have identifiable striations (sliding wear) and appear to have been subjected to rolling wear conditions. Also present in the ferrogaphy slides are substantial quantities of very small (less than 5 micron) ferrous wear. The wear mechanism could be the direct result of rubbing wear or spalling (roller bearing wear).

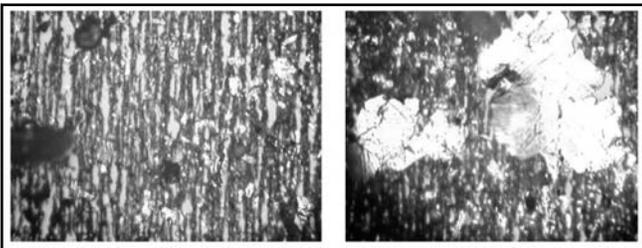


Figure 2.

Oil Analysis Recommendations

After the second flushing of the bearing housing, the viscosity was within specification but the generation of both ferrous wear and copper alloy appeared to be very aggressive. If this wear material is from the slinger ring, the weight and shape of the ring will affect the delivery of lubricant which would result in the rapid deterioration of the bearings. Ferrous debris remains very small (<5 microns) but in very large quantities. Reviewing pump metallurgy data indicates that the ferrous wear material could be from the slinger ring spacer, bearing races and/or the bearing cage. A similar pump application (P2) was tested and the results were reviewed for comparison.

Since vibration data did not indicate any anomalies that would be typical for the amount of wear material being generated, a sample was sent immediately for a SEM (Scanning Electron Microscope) elemental analysis.

Vibration Readings

A series of vibration measurements were taken during the course of a 12 hour test run on a P1- NDE bearing after the oil was changed. The purpose was to determine the degree of bearing degradation through vibration analysis and if the bearing would survive the upcoming outage.

Vibration levels were consistently very low at P1 NDE V bearing on all measurements. Bearing defect frequencies, specific to an SKF 5310AH bearing, were not detected in the velocity spectrum.

Spike energy spectrum showed very low level peaks corresponding to inner and outer race defects. This indicated possible very early stages of bearing failure, i.e. pre-Stage 1 of failure.

Vibration Data

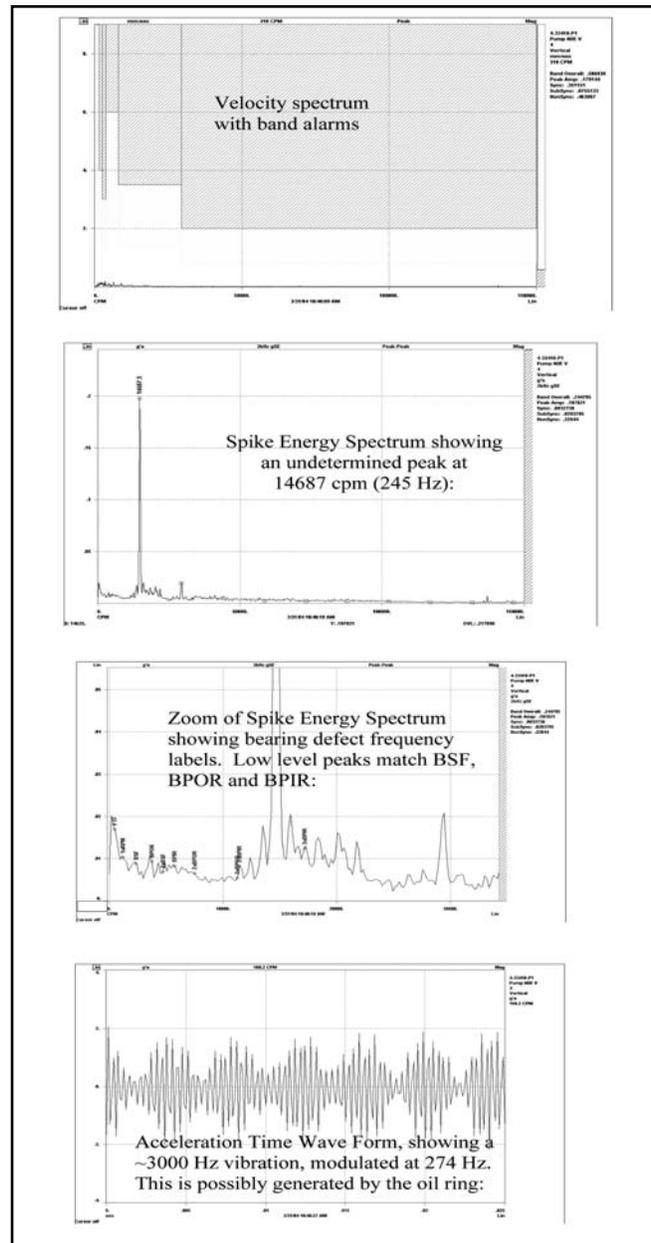


Figure 3.

Vibration Recommendations

Vibration analysis indicates that the P1 NDE bearing is unlikely to fail during the upcoming outage. However, due to very severe particle contamination of the lubricant, abrasive wear of the bearing is probable. The source of the contamination needs to be eliminated and the bearing changed out at first opportunity.

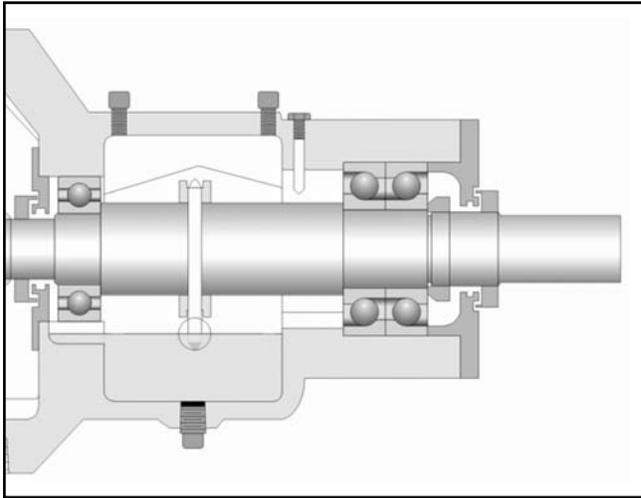


Figure 4. Component Metallurgy

Metallurgy	Oil Ring Spacer SAE 1020	Oil Slinger SAE 62	Deflector SAE 40	Inboard Cover Grey cast A.30	Bearing Cage AISI 1050	Bearing 52100
Fe	99	0.15	0.3	95	98	98
Cu		87	85			
Pb		0.3	5			
Zn		1 - 3	5			
Ni		1.0	1.0			
Sn		10	5			
Cr						1.4
Mn	0.4			1	0.7	0.3
P	0.04	0.05			0.04	0.025
Si	0.05			2	0.05	0.025

Figure 5. Metallurgy of Internal Components

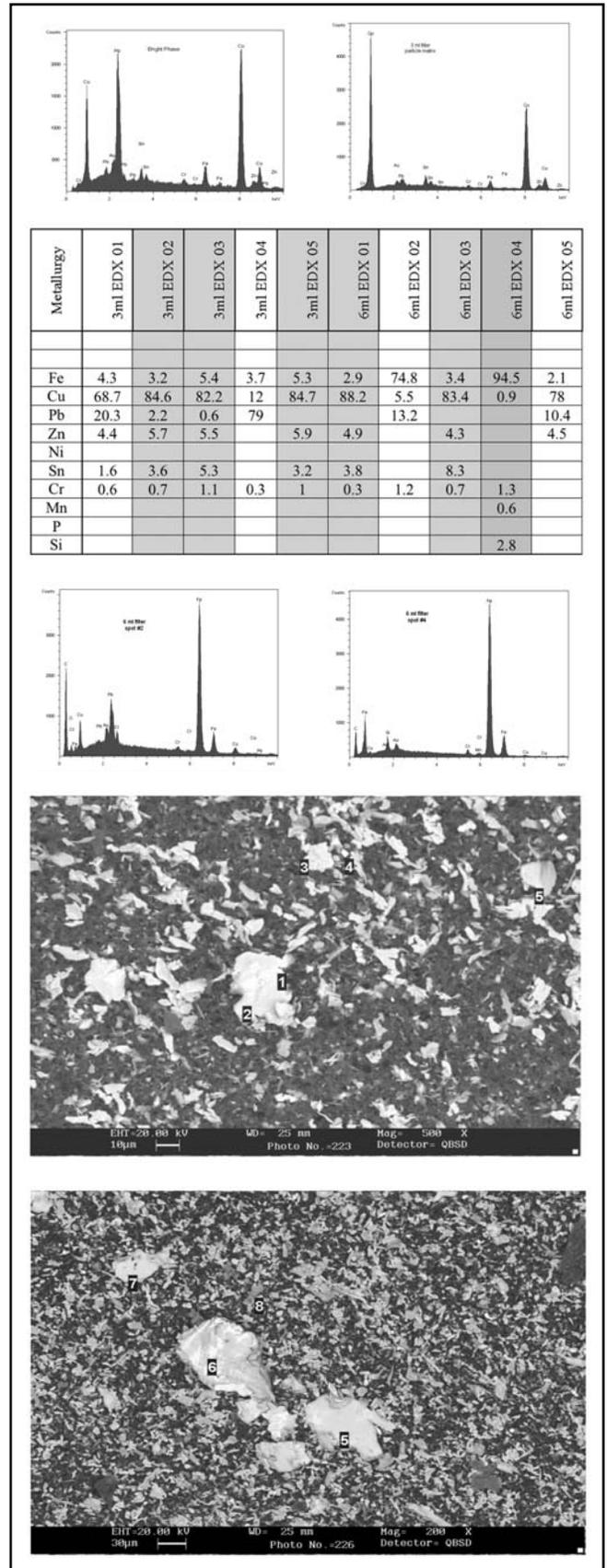


Figure 6. Overview of SEM/EDX Debris Composition Results

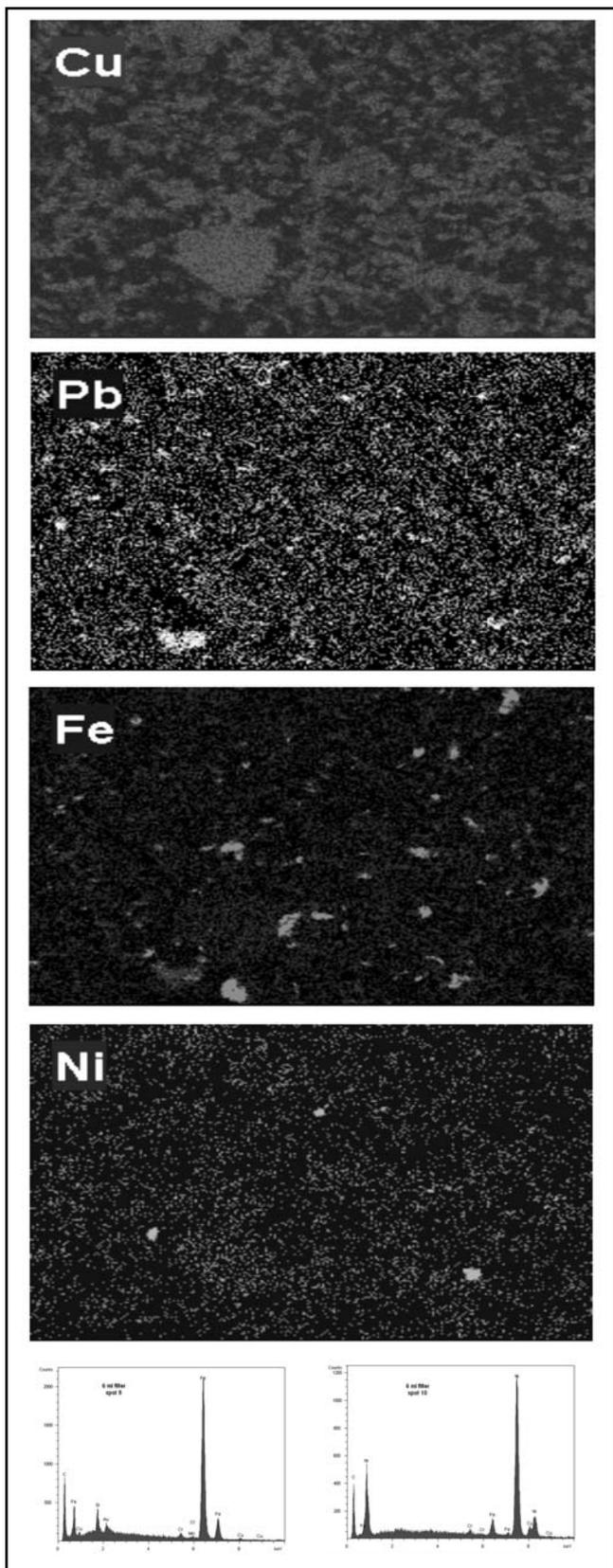


Figure 7. BSE image, EDX X-ray intensity element maps and EDX spectra from particles on 6 ml filter disc (P1-NDE). The maps show the distribution of major elements of interest. Note that the majority of the particles are copper-based, then some iron-based and a few nickel-based are seen.

SEM Results

A majority of the bronze particles were identified as SAE 40 material, which is the composition of the oil deflector disks. The ferrous material was identified as grey cast A30 which is the composition of the inboard cover. This means that the bearing, bearing cage, oil ring and oil ring guide do not appear to be either the cause or have received substantial damage due to the high contamination level in the lubricant.

L10 Bearing Calculations

The SKF rating life calculations were performed using the calculator located on SKF's website, http://skfiec.skf.com/c1_e.htm, with the following assumptions:

- n_c , contamination factor, is 0 for very severe lubricant contamination
 - P , equivalent dynamic bearing load, is 2.2 kN (or 500 lbf)
 - n , rotation speed, is 1180 RPM
 - v , kinematic viscosity, is 50 mm²/s (or cSt), for Teresso 32 at 30 deg C
- L10mh, SKF rating life (at 90% reliability), was calculated to be 96,700 hours. 10% remaining life is, therefore, about 10,000 hours.

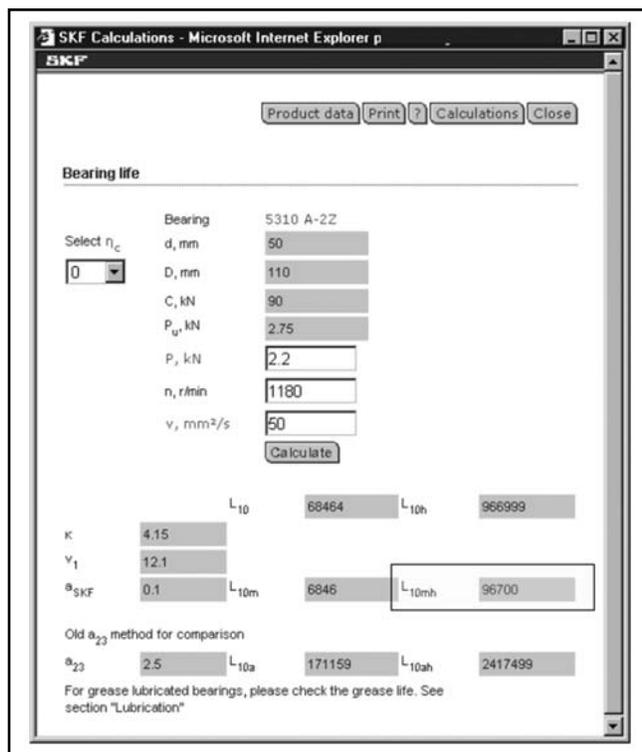


Figure 8.

If the particle generation is eliminated, and lubricant contamination is maintained at normal levels, remaining L10mh life is expected to be about 5,000,000 hours. This high life expectancy is due to the fact that the dynamic load on the bearing is below P_u , the fatigue load limit, of 2.75 kN.

The penalty for very severely contaminated lubricant is a life reduction factor of about 500.

Considering a worst-case scenario, a rolling bearing at Stage 1 failure is expected to have about 10% of L10 life remaining. Even with very severely contaminated lubricant, remaining life was estimated to be about 10,000 hours, per SKF rating life calculation.

Given 10,000 hours of remaining bearing life and a maximum required mission time of 10 days, or 240 hours, there is a safety factor of 40 or more.

Recommendations

Vibration and metallurgical analysis have determined that the P1- NDE bearing is not presently damaged. Oil and metallurgical analysis has determined that there is a severe wear particle generation present and the most likely source is the oil deflector disc rubbing against the bearing cover. Using the SKF Bearing Life calculations, it is estimated that approximately 10,000 hours of useful bearing life remains. With a required mission time of approximately 7 to 10 days (168 to 240 hours), P1 will be available for service during the upcoming outage. The following is a list of recommendations that should be implemented:

- Vibration readings should be taken at least once a day during the outage to detect any early signs or acceleration of bearing damage.
- Schedule P1 tear-down and inspection of the pump bearing housing internals directly after the scheduled outage.
- Ensure all parts are in stock for tear down.

CONCLUSIONS

A successful and comprehensive equipment maintenance management strategy is critical to machinery operation, plant reliability and equipment availability. It spans many diverse functions and responsibilities, ranging from designing maintenance jobs to providing and managing the resources needed to complete the work. PdM activities form one small segment of the entire program but the early fault detection yields benefits in diagnostic time, avoidance of unplanned downtime, elimination of chain reaction failures and improved precision of maintenance actions.

Coordination of a team of trained and dedicated maintenance professionals can produce substantial economic benefits by increasing the awareness of equipment condition and providing vital information for logistical planning and continuous improvement of the equipment.

Reference

Diesel Engine Oil Analysis and Wear Limits

BY STEPHEN PERKINS, LLOYD'S REGISTER OF SHIPPING

INTRODUCTION

Since about 1990, Lloyds Register's Lubricant Quality Scan (LQS) has provided a machinery condition monitoring program through used oil analysis. Lloyd's Register (LR) recognizes the benefits of regular analysis of the in-service lubricant to monitor the health of the associated machine. Over this period, 2274 in-service lubricant samples from large marine two-stroke crosshead diesel engines have been analyzed. The laboratory method employed by LR to measure levels of wear metals in used lubricating oils is the Inductively Coupled Plasma Emission Spectrometer (ICPES). To date, despite the wealth of wear metal data collected by LR, no statistical analysis has been carried out. The objective of this paper is to determine, using statistical analysis, wear limits for the various manufacturer and model types of two-stroke crosshead diesel engines. These wear limits will make future diagnosis of wear metal analysis data for these engine types easier, allowing those engines where undue wear of a system component may be occurring to be quickly identified. The author is confident that by providing wear limits on the routine lubricating oil analysis report, this would offer the vessel operator would have additional confidence that his engine was exhibiting wear metal levels within those expected for a particular engine model type.

Considering the ICPES element data for two-stroke crosshead diesel engines, this paper concentrates only on the manufacturers that exist today. The three current manufacturers of these large marine diesel engines are MAN B&W Diesel, Wartsila (Sulzer) and Mitsubishi. Another point to be considered is that statistical wear limits will only be calculated for those engines where sufficient data is available to LR and for those engine model types that are likely to remain in-service for some time. In other words, there is little value producing wear limits for engine types that are either few in number or where LR has insufficient data for any meaningful statistical analysis.

Where calculated wear limits show variations between different engine manufacturer and model types, it is outside the scope of this paper to explain these differences. The statistical wear limits themselves do not imply that one particular engine model type exhibits more wear than others do. It is important to note that the wear limits produced should only be used as a comparison against future oil analysis results for the same engine manufacturer and model type.

Background

Two-stroke crosshead diesel engines are for the majority of large ocean-going vessels, the preferred choice of engine for providing main propulsion. Two-stroke crosshead diesel engines typically have power outputs ranging from less than 10,000 kW to more than 80,000 kW. The volumes of oil in circulation for these types of engines can be as much as 50 tones for a single engine, but more typically is around 15 tones. The importance of these engine types cannot be over-stressed, and it is for this reason that it was decided to confine the scope of this paper to two-stroke crosshead diesel engines only. There is, of course, no reason why the statistical methods employed in this paper could not be applied to any engine or machinery type. Figure 1 shows an example of a two-stroke crosshead diesel engine.

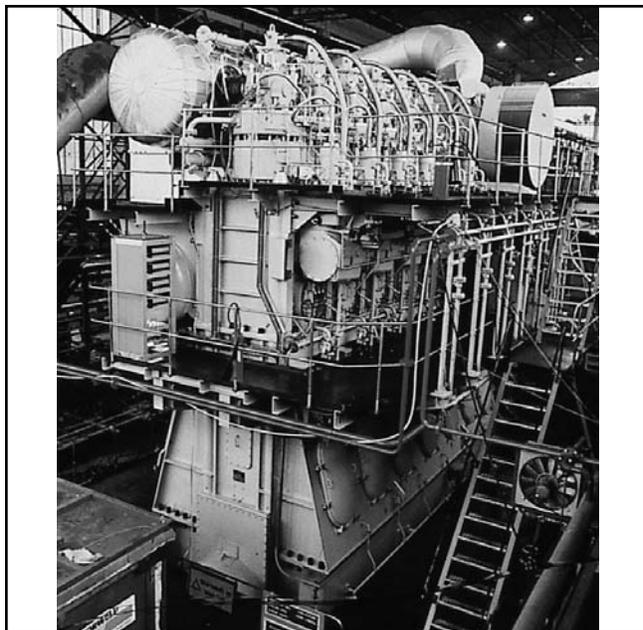


Figure 1. A Two-Stroke Crosshead Diesel Engine.

Although historically there have been a number of manufacturers of these types of engines, in more recent years the number has reduced to three. The current manufacturers of two-stroke crosshead diesel engines are Mitsubishi, Wartsila (Sulzer) and MAN B&W Diesel.

Figure 2 shows how the ICPES analysis data held by LR is divided into the different engine manufacturers. Of the 362 two-stroke crosshead diesel engines monitored by LR, 55% (197) of the engines were manufactured by MAN B&W Diesel, 30% (110) by Warsila (Sulzer) and 11% (41) by Mitsubishi.

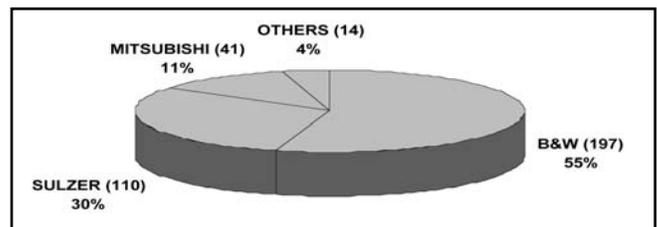


Figure 2. Two-Stroke Crosshead Diesel Engines by Manufacturer (number of engines).

Figures 2,3 and 4 show a breakdown of the different engine manufacturers into their respective model types that LR has accumulated data for. They do not represent the complete product range of two-stroke crosshead diesel engines available for each manufacturer.

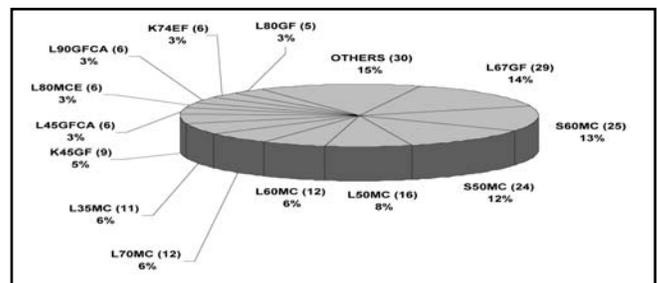


Figure 3. MAN B&W Two-Stroke Crosshead Diesel Engines by Model Type (number of engines).

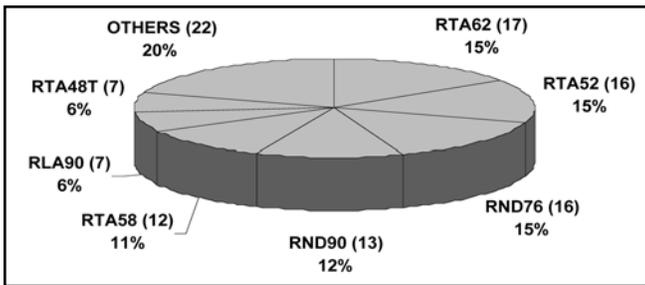


Figure 4. Wartsila (Sulzer) Two-Stroke Crosshead Diesel Engines by Model Type (number of engines).

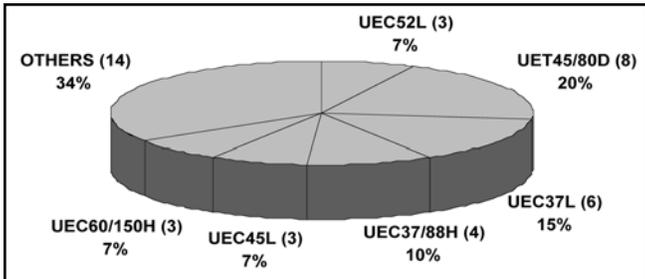


Figure 5. Mitsubishi Two-Stroke Crosshead Diesel Engines by Model Type (number of engines).

Examples of wear element/PQ index trending

The following figures provide examples of graphical trending of the levels of the wear metals iron, copper, lead and tin measured by ICPEs for various engine model types. The PQ index, which was introduced more recently as a lubricant test method, is also shown where results were obtained.

Figure 6 shows the levels of copper, iron, lead, tin and PQ index measured over approximately a ten-year period for a MAN B&W 8L90GB engine. The volume of system oil in circulation in this engine was approximately 18,000 liters. The levels of the wear metals show a relatively stable trend, apart from the period around May 1993. During this period, copper shows a marked rise, reaching a peak of about 70 mg/kg. This is usually evidence that one or more of the piston rod glands requires attention.

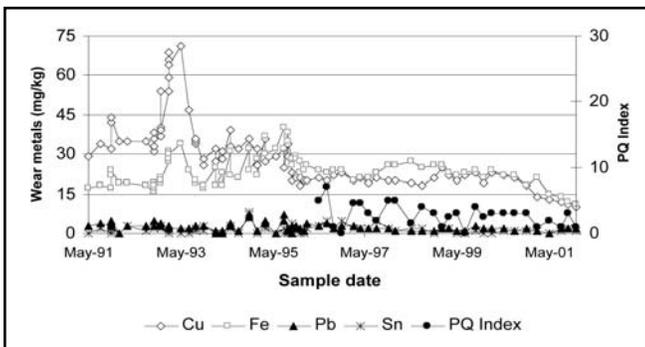


Figure 6. MAN B&W 8L90GB engine.

Figure 7 shows the levels of the wear metals trended over a six-year period for a Mitsubishi 6UEC52LS engine (lubricant volume approximately 17,000 liters). In this example, iron is the most prevalent wear metal present. Since about February 1999, the level of iron has continued to show a downward trend as sampling has progressed. The other wear metals show a relatively stable trend throughout the whole period, indicating that the reduction in the levels of copper is not due to increased make-up.

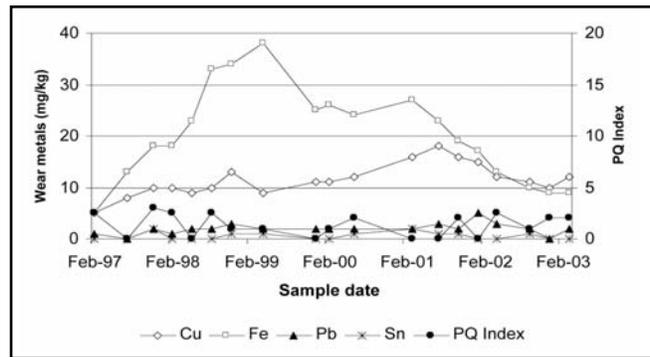


Figure 7. Mitsubishi 6UEC52LS engine.

Figure 8 shows the levels of wear metals trended for just over a ten-year period for a Sulzer 5RTA62 engine (lubricant volume around 12,000 liters). In this example, iron is again present at the highest levels. A notable aspect of the trending is the apparent step change in the level of copper in October 2000. As stated earlier, increasing copper is often attributed to the piston rod glands that may require attention.

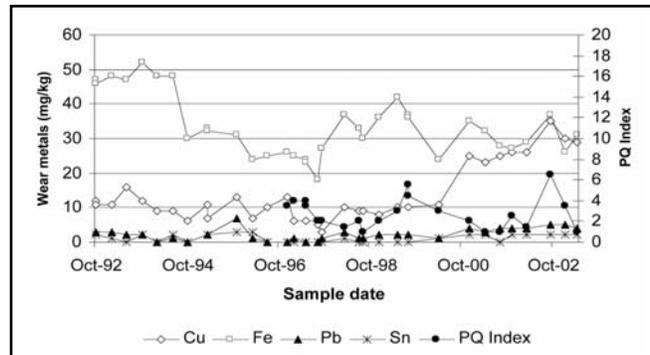


Figure 8. Sulzer 5RTA62 engine.

Figure 9 shows the levels of the wear metals recorded for an eleven-year period in the system oil of a MAN B&W 5K45GFC engine (lubricant volume around 9000 litres). Since about February 1998, there appears to be a relationship between the levels of iron and copper.

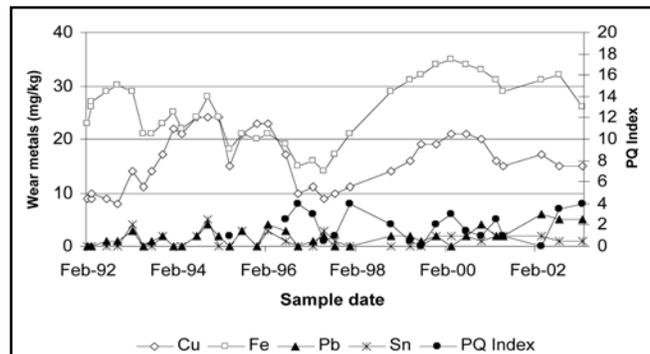


Figure 9. MAN B&W 5K45GFC engine.

Figure 10 shows the levels of wear metals measured in the system lubricant for approximately six years in a MAN B&W 7S50MC engine (lubricant volume 13,000 liters). Note how low the levels of both the wear elements and PQ index remain throughout the period. In fact, this characteristic is typical for this engine model type, as will be shown later in the paper.

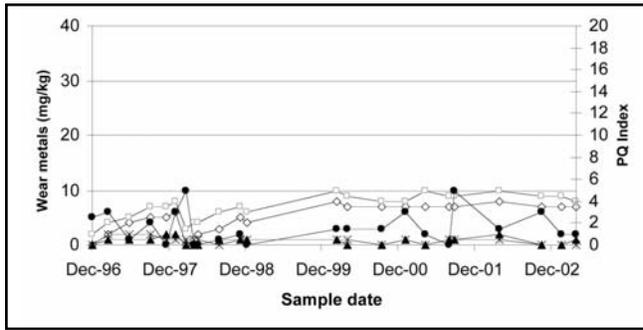


Figure 10. MAN B&W 7S50MC engine.

Figure 11 shows the levels of the wear metals trended over a one-year period only for a MAN B&W 5L35MCE engine (lubricant volume 4500 litres). In this example the increasing trend in the levels of copper and iron accompanied by the marked rise in the level of PQ index is of some concern. An increasing trend in the levels of wear elements measured by ICPES does not necessarily mean that abnormal wear is taking place. However, when an increasing trend in one or more metals is coupled with a high PQ index, this is more indicative that undue wear is taking place. In this example the PQ index has reached a value of more than 35, which is considered very high for the system oil of a two-stroke crosshead diesel engine.

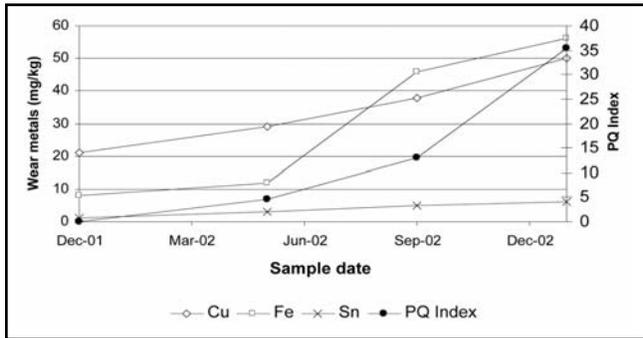


Figure 11. MAN B&W 5L35MCE engine.

In Figure 12 the marked reductions in the levels of the wear metals in about January 2002 suggests that the system oil charge was probably renewed. After this date, however, there is a continued rising trend in the levels of copper and iron, together with an increasing PQ index. A PQ index at this level, around 35-40, is considered of some concern for this Sulzer 5RTA52U engine (lubricant volume 7000 litres).

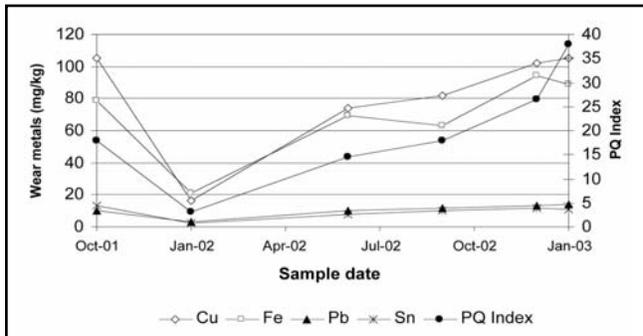


Figure 12. Sulzer 5RTA52U engine.

The relationship between Iron and PQ index

Figure 13 is a graph showing iron plotted against PQ index for 1665 samples. These samples were taken from all manufacturer and model types of two-stroke crosshead diesel engines, where both iron and PQ index were measured. It can be seen that for the majority of samples, iron is in the range 0-50 mg/kg, and PQ index is typically between 0 and 10.

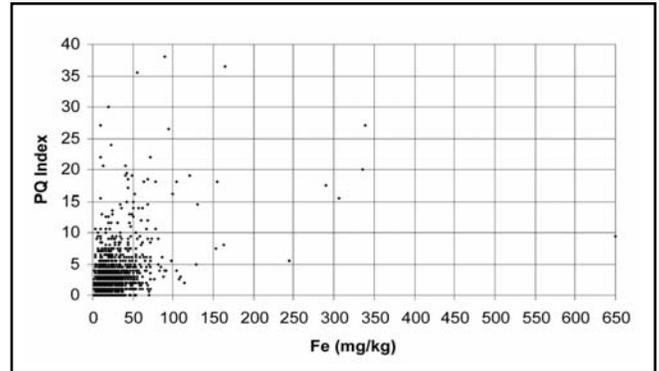


Figure 13. Iron versus PQ index for 1665 samples.

Wear metal distributions for various engine model types

The following histograms show examples of the distributions of the wear metals iron, copper and lead measured in the system oil samples for various engine model types. Figure 14 shows the distribution of iron measured for 205 samples taken from the B&W S50MC engine. Nearly fifty percent of these (100 samples) exhibited iron in the 6-10 mg/kg range. Figure 15 shows the levels of iron recorded for 206 samples from the B&W S60MC engine. In this example, the distribution is much flatter with the most frequent result obtained being in the 21-25 mg/kg range. The main difference between these two engine types is the cylinder bore size, 500 mm for the S50MC engine and 600 mm for the S60MC engine. As stated before, it is not within the scope of this paper to establish why these differences exist, but instead to document that they do.

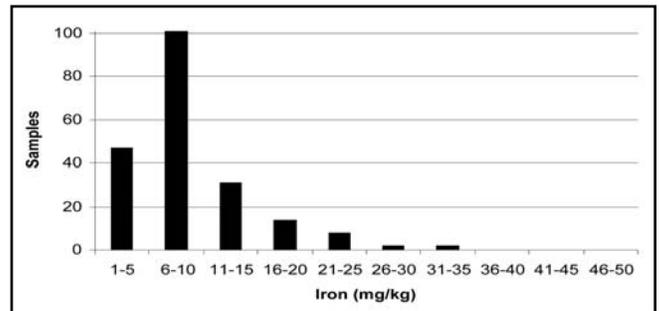


Figure 14. MAN B&W S50MC engine – iron as measured for 205 samples (24 engines).

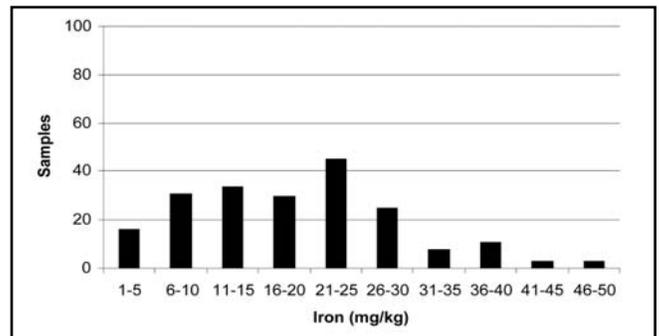


Figure 15. MAN B&W S60MC engine – iron as measured for 206 samples (25 engines).

Figure 16 shows the distribution of iron measured in the system oil for 182 samples from the Sulzer RTA62 engine type. In the case of this engine, iron is typically higher and can be seen at levels of up to 60 mg/kg.

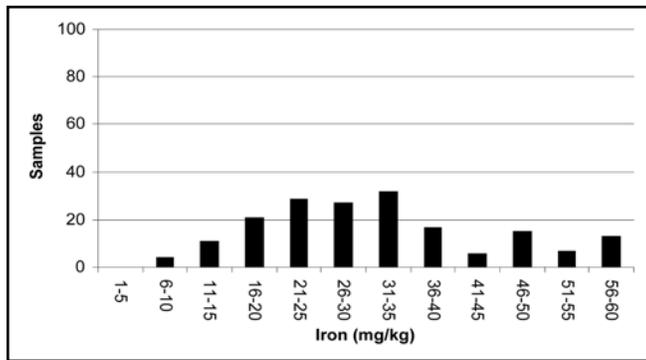


Figure 16. Sulzer RTA62 engine – iron as measured for 182 samples (17 engines).

The distribution of measured iron obtained for the Mitsubishi 6UET45/80D engine is shown in figure 17. It should be noted that this distribution represents fifty-one samples from eight engines only. Nevertheless, the levels of iron recorded for this engine model type are significantly higher than for those previously shown.

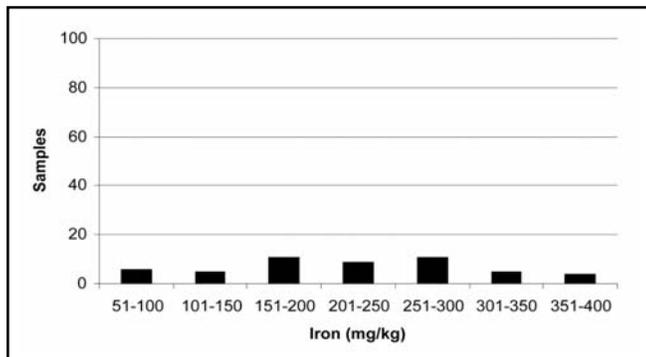


Figure 17. Mitsubishi 6UET45/80D engine – iron as measured for 57 samples (8 engines).

Figure 18 shows the distribution of the levels of copper determined in the system lubricant for a B&W S60MC engine. Of the 208 samples, the most frequently obtained result for copper falls within the range 16-20 mg/kg.

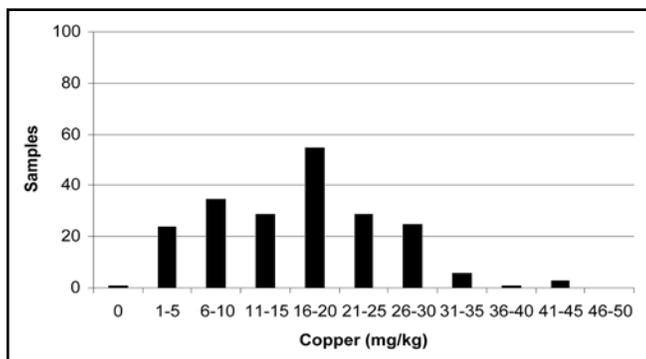


Figure 18. MAN B&W S60MC engine – copper as measured for 208 samples (25 engines).

Figure 19 is a distribution showing the levels of lead measured for the same engine model type as above. Lead is considered to originate from white metal lined bearings which are applicable to main, bottom end and

crosshead duties. These bearings are of the shell type, and can be either thin shell or thick shell depending upon the area of application. Consequently lead is usually present in the system oil of two-stroke crosshead diesel engines at much lower levels than copper and iron. In the case of this engine, 2 mg/kg is the most frequently observed result, with a maximum value recorded of 5 mg/kg only.

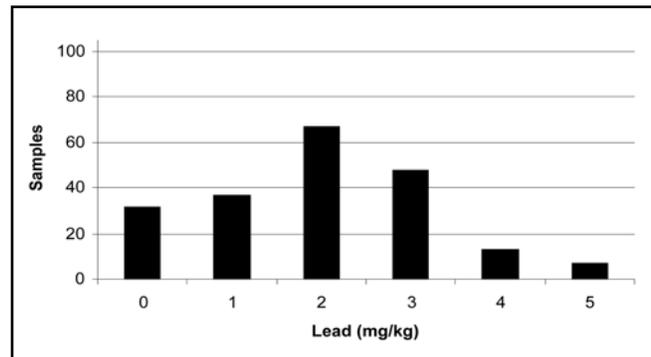


Figure 19. MAN B&W S60MC engine – lead as measured for 204 samples (25 engines).

Statistical Wear Limits

In order to explain how the statistical wear limits for each engine model type are derived, four engine model types have been chosen as examples. Figure 20 below shows the statistical results obtained from the iron data available for the four different engine model types. The results for “average” are calculated from the arithmetic mean of the sample results. The standard deviation (STD) is a measure of how widely values are dispersed from the average value (the mean). In other words, the standard deviation tells us how tightly the results are clustered around the mean in a set of data. In this case, when the iron results are tightly bunched together the standard deviation is small. When the results are spread apart then the standard deviation is relatively large. The standard deviation obtained from the sample data for the Mitsubishi 6UET45/80D engine is significantly larger than for the other three engine types shown. The standard deviation was calculated using the Microsoft Excel function:

=STDEV(P(A1:Z99) "biased" or "n" method.

“Confidence” is calculated using the Microsoft Excel function and returns the confidence interval for a population mean. The confidence interval is a range on either side of a sample mean. For example, the level of iron measured in a system oil sample can be predicted with a particular level of confidence in a range on either side of the sample mean. The maximum and minimum values shown represent the confidence interval for each engine type. The confidence value is dependent on the standard deviation and population size. A large population size and small standard deviation will ultimately give a smaller confidence interval. The 6UET45/80D engine has a relatively small number of samples and a large standard deviation giving a much larger confidence interval compared to the other three engine types.

Engine Model	S50MC	S60MC	RTA62	6UET45/80D
Number of samples	207	214	204	57
Average	10.05	21.22	36.04	264.49
STD	9.30	13.35	18.99	160.34
Confidence	1.27	1.79	2.61	41.62
Min	8.78	19.44	33.43	222.87
Max	11.32	23.01	38.64	306.12

Figure 20. Example of statistical calculations for four engine model types (iron).

By employing the same statistical techniques for the wear metals copper and lead, wear limit tables can be produced for different engine model types for the three two-stroke crosshead diesel engine manufacturers. These wear limit tables are shown in Figures 21, 22 and 23. The lower limit of the confidence interval or minimum value, as shown in Figure 20 above is of little significance. For instance, if an operator decided to renew the entire volume of system oil, the levels of wear metals measured in the lubricant would return to very low levels. A level of iron measured in a system lubricant that is below the confidence interval will never indicate that there could be a problem. The upper limit of the confidence interval is the only value of significance here, and these are shown as the statistical upper wear limits. The tables also include information relating to the number of samples analyzed and the number of individual engines monitored for each engine model type. The importance of this information cannot be overstated, because the wear limits generated from the largest number of engines and samples is of greatest value statistically.

Sulzer	RTA48T	RTA52	RTA62	RND76	RND90
Iron	11	37	39	36	31
Copper	17	51	20	70	55
Lead	4	6	3	14	10
Engines	7	16	17	16	13
Samples	63	98	204	85	53

Figure 21. Sulzer Limits

B&W	L35MC	L45GFCA	L67GF	8L90GB	K45GF	10K90MC	S50MC	S60MC
Iron	13	29	28	22	28	16	11	23
Copper	18	29	21	31	17	23	14	20
Lead	4	4	3	3	3	2	3	3
Engines	11	4	29	3	9	2	24	25
Samples	83	57	59	148	206	62	207	214

Figure 22. MAN B&W Limits

Mitsubishi	6UEC45LA	6UEC52LS	6UET45/80D
Iron	30	19	306
Copper	7	17	25
Lead	2	3	5
Engines	3	3	8
Samples	67	56	57

Figure 23. Mitsubishi Limits

Summary

The success of the study has meant that from statistical predictions of the expected levels of wear metals in the in-service lubricant for a particular engine type we can now observe more readily when an engine is exhibiting wear metal values outside the “normal” expected range. This can alert the engine operator to identify root causes at an early stage to minimize the risk of unforeseen potentially costly breakdowns.

Care must be taken when comparing levels of wear metals in any in-service lubricant with statistically produced wear limit tables. For example in Figure 21, the Sulzer RTA62 engine shows a wear limit for iron of 39 mg/kg. This should never lead one to the conclusion that 39 mg/kg is acceptable and 40 mg/kg indicates a problem. This is a far too simplistic approach... if only machines operated in this idealistic way in the “real” world. Machine wear is dependent on too many factors to allow engineers to be able to determine precisely when a machine is exhibiting abnormal wear from easy to read wear limit tables. The factors that influence levels of wear metals in oil include: load, skill of operation, manufacture, assembly, unit service hours, oil service hours, oil make-up and filtration. Monitoring trends is always the most reliable method of observing changes in wear regimes for a machine.

So, do wear limit tables offer any real benefits? The author believes the answer to this question is most definitely yes! For any machinery system, there will always be times when trending is not available to the diagnostician. On these occasions, the availability of wear limit tables could be used to alert the operator to a possible problem. The cost in terms of time and money of taking further samples and perhaps conducting a visual inspection, must surely be preferential to unknowingly continuing to operate a machine that may be experiencing abnormal wear of a component. Unplanned downtime of any machine will invariably cost more money to rectify. In the paragraph above, skill of operation is included as one factor that can influence abnormal wear in a machinery system. For an engine where abundant trending data is available, is this always sufficient? For instance would an operator necessarily know if a machine was exhibiting component wear more frequently than, say, a similar machine type elsewhere? The answer to this question is that although, in many cases, a competent operator will be aware of the manufacturer’s expected component life, this may not always be the case. In cases where less obvious deviations from an expected component life are observed, these could all too easily be overlooked. Using “wear limit values” as a comparison could benefit an operator in optimizing the operation of a machine. The same can be said for manufacture and assembly. Being able to compare the levels of wear metals measured for a particular machine with statistical wear limit values may alert an operator that a component is deteriorating faster because of a possible flaw in the manufacture or assembly of the machine.

Field Screening Methods for Soot Levels in Used Diesel Engine Oils

By DAVID DOYLE - CTC ANALYTICAL SERVICES

More attention is being paid to soot levels in used diesel engine oil over the past few years due to changes in engine designs to meet exhaust emission standards, which have led to increased soot formation during combustion. Soot levels are expected to continue to increase in diesel engines made after October 2002 with the introduction of cooled EGR systems in engine design.

Even though the chemistry and mechanics of soot formation can be quite complex, soot is basically unburned fuel that develops into carbon particulate during combustion. Excessive soot that enters into engine oil can create a range of operational problems. These can include increased viscosity and poor lubrication, filter plugging, soot related wear and depletion of oil additive dispersant package.

Laboratory oil analysis services for used diesel engine oil will routinely show soot content in a standard test report. But with the increased attention to soot formation in today's engines and its effect on oil and equipment performance, methods for field screening of soot levels in used oil can prove beneficial. Field screening for soot levels in used engine oil can help provide immediate inspection of oil and equipment condition as well as determine if more in-depth laboratory analysis is required.

There are several methods for soot screening that can be conducted on-site or in the field. Methods vary from little or no cost to relatively expensive. Quantitative determination can range from relatively ineffective to highly accurate (Table 1).

The simplest determination that some individuals employ is to inspect the color or appearance of the used oil. Though this technique is quick and inexpensive, it is not very effective since soot will darken an oil so quickly that appearance in this matter has little relationship to the actual soot content of an oil. This method is not recommended for a screening process.

A more common and more acceptable screening method is the blotter test. This method can give a general indication of soot levels and oil dispersancy performance. Though there are variations on this method, generally one or two drops of oil sample are placed on chromatography paper and allowed to spread out on the paper and then dry for at least an hour (Figures 1 and 2). In some circumstances a simple business card is used instead of chromatography paper. The sample should be at least at room temperature and shaken thoroughly. Warming the sample to 130°F is helpful. Sometimes the blotter paper is placed in a warm oven to facilitate drying. An oven temperature of 150°F should be sufficient. After the oil blotter samples have dried the appearance of the oil spot is compared to give a general value of soot level in the oil and dispersancy performance. The color and darkness of the oil spot will correlate with the level of insoluble matter within an oil sample, which would be primarily soot in a diesel engine oil sample. Dispersancy performance is evaluated in regard to how uniform the oil spreads out on the blotter paper and if a dark ring forms towards the center on the oil spot.

Very dark oil spots on a blotter test will mean elevated soot which can indicate improper fuel injection or fuel air mixture, restrictive air-intake or excessive idling or lugging. The lack of homogeneous wicking of the oil spot on the blotter paper or dark ring formation towards the center of the oil spot means poor dispersancy performance of the oil. Poor dispersancy can be caused by extended

FIELD TEST		
Type	Cost	Description
Color	Inexpensive	Relatively ineffective.
Blotter	Inexpensive	Semi-quantitative - Test results can be subjective. Hard to distinguish soot levels above 4 percent. Also indicates dispersancy performances left in an oil.
Blotter/Lantos Solvent Extraction	Inexpensive	Semi-quantitative - Test results can be subjective. Also indicates dispersancy performances left in an oil.
Blotter Photometer	High Equipment Cost	Semi-quantitative - Effective up to 4 percent with higher precision. Also indicates dispersancy performances left in an oil.
Blotter/Reflectance Meter	Moderate Equipment Cost	Semi-quantitative - Effective up to 4 percent with less subjectivity than visual blotter.
Infracal Infrared Soot Meter	Relatively Expensive	Quantitative - Very accurate up to 12 percent. Easy to use.
LAB TEST		
Type	Cost	Description
Insolubles, Pentane/Toluene	Relatively Expensive	Quantitatively accurate - Test results included all insoluble material, not just soot.
FTIR (Infrared)	Inexpensive	Quantitatively accurate - Susceptible to instrument interferences.
Soot Meter	Inexpensive	Quantitatively accurate - Very reliable and accurate up to 12 percent.
Total Gravimetric Analysis	Expensive	Highly accurate - Most definitive method, accurate at any concentration.

Table 1

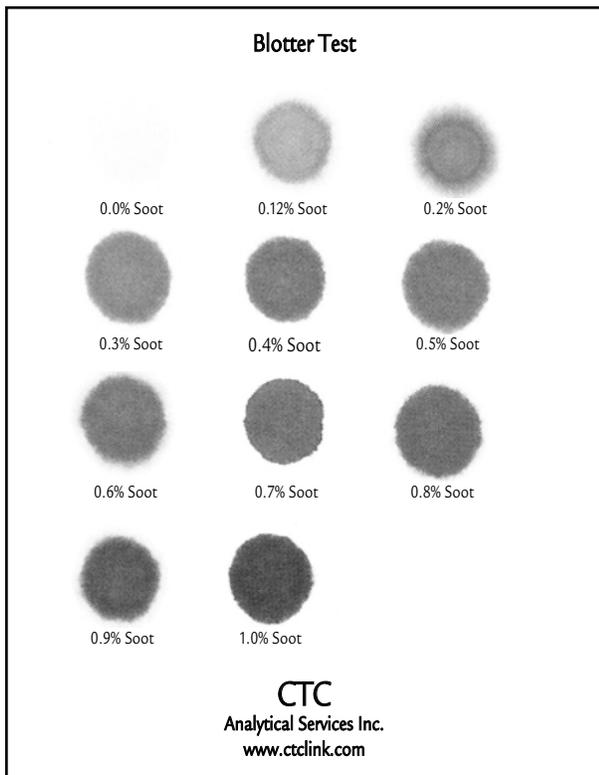


Figure 1

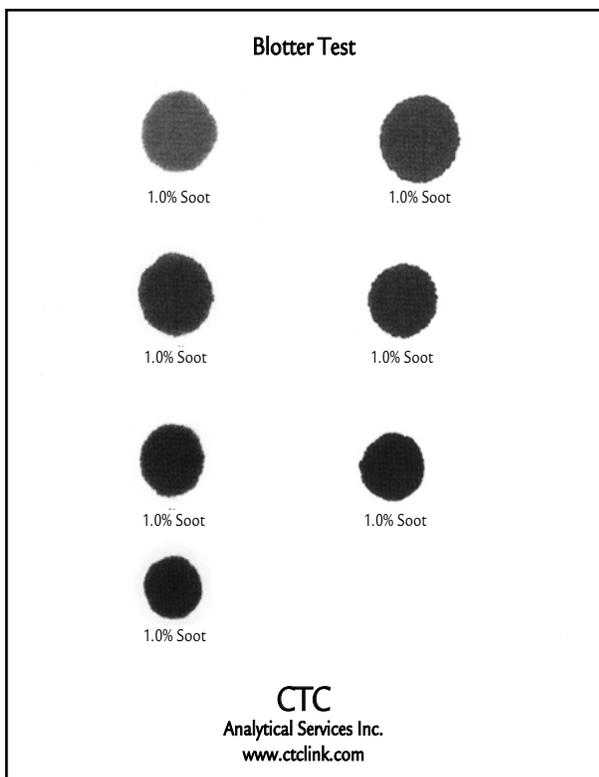


Figure 2

drain interval, contaminants such as water, fuel coolant, or excessive soot buildup.

The biggest drawbacks to using the blotter test as a field test screening method is that soot values above 4 percent are really not distinguishable. Therefore, the test is not effective above this concentration of soot in the oil. Also, interpretation of the test results can be subjective between individuals performing the test. Consistency in application of the method can also be a factor in test result interpretation.

As stated previously, there are variations on the blotter method. Some variations are concerned primarily with sample size, heating, drying time and choice of blotter paper. These are all variations on a basically manual, low cost application. With these types of variations, consistency to applying the method is the key. Anyone using the blotter test to screen for soot level in their engine oils should retain the blotter samples in a binder logged with all relevant information, such as date, time on the oil, engine information, and any laboratory information on the same sample which would include soot but should also include information regarding contaminants such as water, fuel and glycol.

More technical variations on the blotter test that can still be applied to the field may include the investment in some basic equipment. A more technical application can give a higher level of precision for the test results, but with additional expense in material or equipment.

An enhancement to the basic blotter test is referred to as the Lantos Method and is outlined in the July-August 2002 issue of *Practicing Oil Analysis* magazine. The method uses chromatography grade blotter paper that is cut into rectangular strips. A sample of homogenized used engine oil is deposited 20 mm from the end of the test strip and allowed to dry at room temperature (Figures 3 and 4). After drying, the clean 20 mm portion of the blotter test strip is bent at a right angle and placed on a support rack. The rack containing the strip is then placed in a tray containing solvent so that the test strip is supported above the solvent with the bent right angle portion of the strip submerged in the solvent. Two solvents are alternately used which are heptane and toluene. This is a variation on a laboratory method that uses solvent extraction to monitor oil degradation material and contaminants. The test strip soaks up the solvent and soluble material in the oil is extracted from the oil spot and spreads across the remaining portion of the test strip. Solvent extraction by the heptane and then toluene can be performed on the same test strip or on two separate test strips. The insoluble material left behind after heptane and toluene extraction will contain free carbon and indicate general levels of soot in the oil. This method will also indicate oxidation and resinous material due to oil degradation by displaying products that are insoluble in heptane but soluble in toluene. Interpretation of test results can be subjective and consistency in application of the method is important. Finished blotter test strips can be logged with previous test strips for interpretation along with pertinent sample information. The Lantos Method using solvent extracted blotter can be an effective

screening tool for soot that is complemented with actual laboratory analysis.

Another enhancement to the blotter test is to incorporate the use of a photometer to measure light absorption of the blotter spot. The photometer can measure the intensity of the light absorbed by the oil spot and correlate the measurement to soot concentration. This application is detailed in the September-October 2002 issue of *Practicing Oil Analysis* magazine. This method references the heating of an oil sample to 240°C for five minutes in order to stress any oil with a marginal service life. After the sample cools 2 mls of oil are dropped onto blotter paper and allowed to wick in an oven at 80°C for an hour. The *Practicing Oil Analysis* article references the use of a VPH 5G CCD Photometer by ISL, which can optically measure the light absorbance of the insoluble material on the blotter spot. Test results can then determine dipersancy performance and general soot levels as well as lubricant degradation in a used oil sample. The use of a photometer to determine soot measurement with the oil blotter eliminates individual subjectivity in the test result interpretation. This method is still limited to soot levels only up 4 percent but is an effective screening tool, which allows for higher precision. ISL supplies the VHP 5G photometer at a cost of around \$24,000 from Petroleum Analyzer Co.

The cost of the VPH 5G photometer may not be practical for field analysis when compared to the cost of a standard laboratory analysis, but a simple reflectance meter could still be incorporated into the theory of the photometer in order to screen field samples for relative soot levels at a much lower cost. Basically, the percent light reflectance of a blotter sample that is registered by the meter correlates in the same manner as the light absorbed by the photometer. The information obtained in this manner would be much less detailed than with the VPH 5G but would still allow the operator to make a more consistent and less subjective evaluation of the blotter test for soot screening.

As previously mentioned, logging and retaining blotter tests, along with relevant information, will greatly enhance the interpretation of the results for soot levels. This would also include any laboratory test results available on the same oil sample.

A more precise and convenient field method that is different from the variations on the blotter method for soot determination, but also more expensive, uses a portable Infracal soot meter. The soot meter is based on infrared technology and can accurately determine soot levels in used engine oil up to 12 percent. This field instrumentation correlates well to laboratory soot determinations and is easy to use. The instrument uses some simple calibration and quality assurance techniques and the actual analysis takes less than a minute. As with the blotter methods, having a homogeneous sample is important. Test results are displayed on an LED readout. The instrument can also incorporate a remote plug for doing soot determination via the lubrication system using a sensor installed in an engine. The portable Infracal soot meter for field application cost between \$1,000 and \$1,500 and can be obtained through Wilkes Enterprises or Koehler Instrument Co.

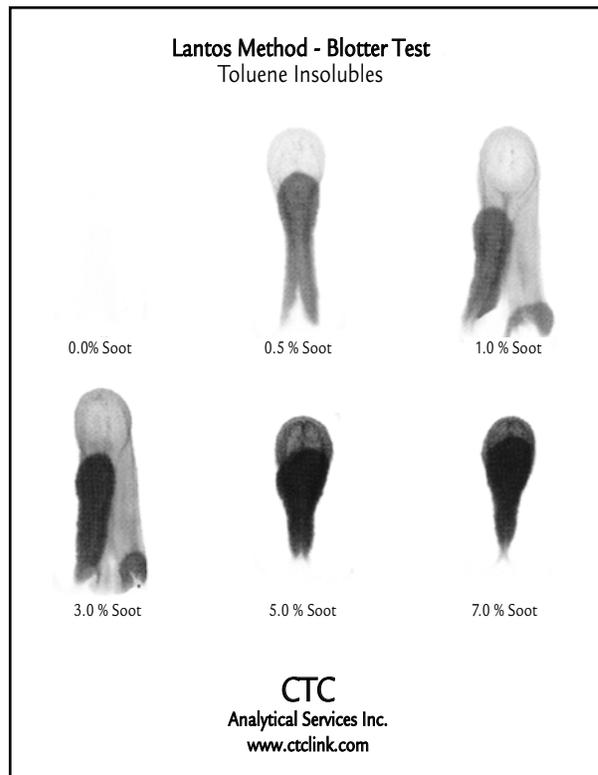


Figure 3

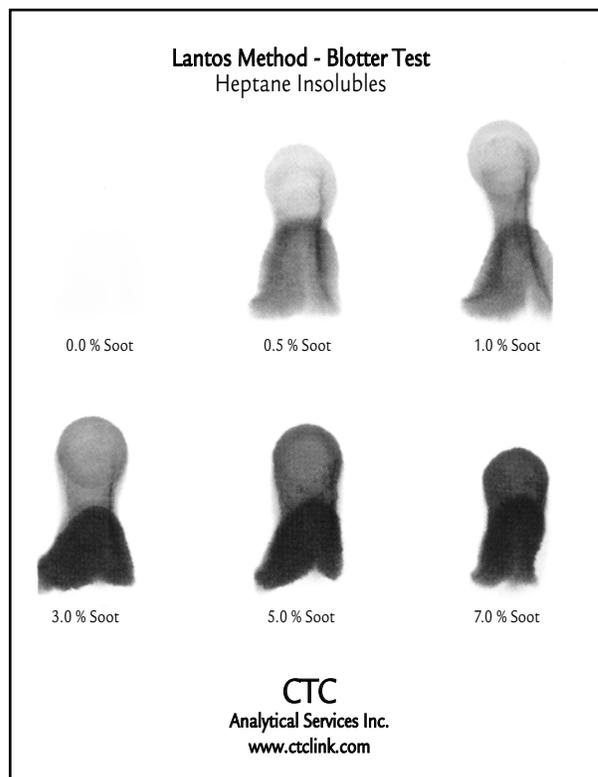


Figure 4

Detecting Thermal Failure and Varnish Potential

By GREG J. LIVINGSTONE - CLARUS TECHNOLOGIES

There are many industrial plants that have established exceptional preventative maintenance programs, utilizing oil analysis as a predictive tool to enhance machine reliability. These plants also employ advanced contamination control devices to ensure that the lubricants are clean and dry. Imagine at one of these plants, an oiler mentions that the filter strainers are plugging on a regular basis with a gooey, sticky substance. Then, there are complaints of sticky valves effecting machine performance. Despite all of the predictive maintenance efforts that have been made, suddenly there is an unexplained, critical machine performance issue. To add to the mystery, the lab results indicate that the fluid is in excellent shape. Varnish has struck again.

Varnish is a widely used term in the lubricant industry; however, little is known about this dangerous form of contamination. Unlike dirt and debris particles, varnish does not cause abrasion distress and unlike water contamination, it does not generate a corrosive environment. Nevertheless, varnish can produce significant lubricant performance issues and maintenance headaches, even in minute quantities.

Much research has been done on the effects of varnish on pistons in high-temperature combustion engines. This has led to the development of advanced detergents and dispersants that control varnish formation in engine operations. However, in industrial machinery, less research has been performed on varnish and its effects. This paper will discuss varnish that occurs as a result of thermal failure in industrial lubricant applications.

Identifying a fluid's potential to produce varnish is challenging. Routine oil analysis does not provide a sufficient warning to alert the lubricant user of varnish potential. This paper highlights a series of six oil analysis tests that, when used in conjunction with each other, can be useful in predicting the formation of varnish due to thermal failure.

Varnish Introduction

Varnish can be defined as a hard, sometimes brittle, veneer-like coating that covers the metallic components inside lubrication systems. Varnish and sludge are terms that are used interchangeably because, for the most part, they are generated from the same degradation processes. To differentiate, sludge is less dense than varnish and often acts as a predecessor to varnish. Sludge can also have high water content, whereas varnish is moisture-free. Over time, elevated temperatures can cure sludge, thereby evaporating moisture and increasing its density, producing varnish. Although both sludge and varnish create perilous lubricant conditions, varnish is a more arduous problem to address. From a performance standpoint, its sticky nature initiates more serious stiction and seizure problems in valves. From a maintenance perspective, it is substantially more difficult to remove because of its strong adhesive qualities.

Varnish has become a more prevalent issue due to a general trend towards smaller reservoir sizes, longer oil drain intervals and higher temperature demands on the fluid. Premature gear failures in paper machine oils, hydraulic control issues in plastic injection machines, and sticking problems in steering systems on marine vessels have all been attributed to varnish formation. Combustion turbines in particular are very sensitive to varnish formation. Miniscule amounts of varnish in a combustion turbine's control valve can have catastrophic effects and have been blamed for unplanned outages.

Oil degradation derivatives make up the principle ingredients of varnish. Its tackiness can also encapsulate wear and debris particles. Varnish has a high molecular weight and a polar nature; two characteristics that allow it to find metallic surfaces a friendlier domicile than the lubricant.

Thermal Failure

Heat is an enemy of lubricants. Higher temperatures impart greater energy into the lubricant and when this energy becomes too great, thermal failure occurs. When a lubricant thermally degrades, the molecular bonds are broken, altering the fluid's properties. The carbon-carbon chain scission then propagates through branching reactions, accelerating the rate of thermal failure. Thermal failure is directly related to temperature. A 10°C rise in temperature has been shown to double the rate of thermal failure.

Thermal failure in a lubricant typically changes the fluid's odor and color. Additionally, changes in viscosity and depletion of additive systems are common. Finally, thermal failure instigates the creation of by-products, which can lead to the formation of sludge and varnish.

When molecular bonds are broken, the by-products produced are of either a higher and/or of a lower molecular weight.

- Low molecular weight by-products are often referred to as low boilers. Low boilers have a low flash point, and in small concentrations, will lower the flash point of the entire lubricant reservoir. This can create a dangerous situation in closed process heating applications where no venting of low boilers is possible. In most applications, evaporation is possible.
- High molecular weight by-products are the pre-cursor to varnish. They are polar in nature and have an inclination to precipitate out of the non-polar lubricant onto dipolar metallic surfaces. They can affect several of the lubricants properties including viscosity, foaming, demulsibility characteristics and cause interference with polar additives such as EP, AW and corrosion inhibitors.

Thermal failure occurs with one or more of the following conditions.

- A hot spot in the system which elevates the lubricant to a very high temperature causing localized thermal failure.
- Pressure-induced thermal failure, which is the rapid adiabatic compression of air bubbles in a system that creates excessive high temperatures, causing thermal failure.
- Pressure-induced dieseling, which is a result of combustion of light end hydrocarbons. This phenomenon creates both extreme pressures and heat and can rapidly cause thermal failure.
- Static electricity that is generated between oil and mechanical filtration, creating high temperatures and free-radical generation.

Lubricants are composed of carefully selected blends of highly refined base fluids and suitable additive systems that among other functions, are designed to resist thermal failure. Various refining techniques produce base oils with different resistances to thermal failure. API Group I basestocks have a lower resistance to thermal failure than Group II and Group III basestocks because they possess a higher level of aromatics and other impurities.

What is the Difference between Thermal Failure and Oxidation?

Thermal failure and oxidation are similar lubricant destructive mechanisms involving free-radical chain proliferation. Thermal failure occurs in the absence of oxygen, whereas the process of oxidation uses an oxygen molecule as a catalyst to the reaction. Both degradation processes generate similar by-products. Analytical methods to measure thermal and oxidative degradation processes are also similar.

Following are some of the differences between thermal failure and oxidation:

- Thermal failure can occur in a lubricant prior to the anti-oxidants being depleted.
- Thermal failure can happen before elevations in acid number.
- Thermal failure can occur in new products from improper storage practices.

Prolonging Thermal Failure and Oxidation

Most lubricants are formulated with antioxidants designed to retard the thermal and oxidative process. Primary antioxidants are free-radicals scavengers, bringing an abrupt end to the self-accelerating degradation process. The key types of primary anti-oxidants are hindered phenols and aromatic amines. Secondary antioxidants decompose hydroperoxides, another by-product in oxidation. Finally, oils are formulated with metal deactivators that render metallic oxidation catalysts inert.

How is Varnish Created through Thermal failure?

Chain propagation and branching reactions in thermal failure produce organic, soluble compounds. The process continues until

insoluble species are generated forming polymers and other compounds of high molecular weight. These insolubles have a sticky characteristic and easily bond to particles, depleted additives and water.

Varnish forms when the solubility limit for the high molecular weight insolubles is exceeded. Temperature is a key factor in the solvency of a lubricant, and is a determinant for the creation of varnish. Studies have shown that insoluble compounds are more resistant to dropping out of solution at temperatures above 68°C. This explains why varnish will first start to form in cooler spots in the system, such as strainers and the splash area immediate above the fluid capacity in the reservoir. At extreme temperatures, thermal failure has the potential to produce black carbon particles, which can fall out of solution immediately.

The Varnish Detection Challenge

It is not possible to monitor thermal and oxidative degradation on the molecular level, but it is possible to observe the products formed at the termination of the degradation process. Oil analysis as a tool to monitor thermal and oxidative degradation to predict the formation of varnish can be a powerful addition to a predictive maintenance program. In many applications, routine oil analysis tests such as viscosity and acid number will alert the user of increased levels of thermal failure and oxidation. Measuring a fluid's resistance to oxidation (RPVOT - ASTM D2272) can also assess the health of a lubricant and indicate the fluid's potential to oxidize and produce varnish.

Once acid numbers become elevated, signifying thermal failure and oxidation, there exist sufficient levels of insolubles in the lubricant to justify varnishing concerns. Emptying reservoirs of thermally damaged lubricants will reveal sludge and varnish accumulation. Strainers will be covered in a brown, resinous material and sight-glasses may be hazy.

The challenge with combustion turbine applications and other sensitive applications is that the level at which varnish can cause serious consequences is extremely low. The formation of damaging varnish can happen well before any routine oil analysis will detect signs of degradation. This was documented in the development of ASTM D4378: Practice for In-Service Monitoring of Mineral Turbine Oils for Steam and Gas Turbines. "Unfortunately, there are no direct methods to measure and monitor the concentration of these sludge precursors" (Robertson, R.S., American Society for Testing and Materials, 1989).

Ideally, detection of a fluid's varnish potential would occur when the thermal and oxidative degradation process initiates the production of soluble and quasi-soluble contaminants, well prior to the creation of varnish. Unfortunately, there are no known analytical procedures that are sensitive enough to measure these minute organic compounds in this state. However, there are several oil analysis tests that have the ability to detect varnish precursors and are suitable to be part of a predictive maintenance program. These tests can help the user:

- Trend the increase of insolubles, even at small levels,
- Indicate early detection of thermal failure or oxidation,

- Provide a potential root cause for the formation of varnish pre-cursors, and
- Monitor the depletion of primary antioxidants.

The combination of these test results provide valuable information that positively correlates to the fluid's potential to produce varnish.

Detecting Thermal Failure and Varnish Potential

There are several tests that have been used to measure the sludging or coking tendencies of lubricants. Some of these include:

- ASTM D4310: Determination of the Sludging and Corrosion Tendencies of Inhibited Mineral Oils.
- ASTM D943: Test Method for Oxidation Characteristics of Inhibited Mineral Oils (TOST).
- ASTM D4871: Standard Guide for Universal Oxidation/Thermal Stability Test Apparatus (UOT).
- IP280: CIGRE Oxidation.
- FTMS 591C5308.6: Thermo-oxidative stability.
- IP48: Oxidation.
- USS 3462-T: Panel Coker Test.
- ASTM D189: Carbon Residue Test.
- ASTM D2070: Cincinnati Milicron Test.

Many of these testing procedures are designed to test new products and are not appropriate for a preventative maintenance program due to the time it takes to perform the test or the cost involved. More importantly, there is low correlation between the above tests, limiting their values as a predictive tool.

There are several tests that are useful in monitoring thermal failure, and which can be used as effective preventative maintenance tools:

- Colorimetric Analysis.
- Gravimetric Patch.
- Ultra-centrifuge.
- Fourier Transform Infrared (FTIR).
- Interfacial Tension Test (IFT).
- RULER™.

Colorimetric Analysis

Colorimetric Analysis determines the degree of oxidation by-products that are in a sample. This data can be correlated to show whether a fluid has a high varnish potential or low varnish potential.

This analytical method distinguishes the contaminants in the fluid by evaluating the color of contaminants collected on a filter

membrane. One hundred milliliters of oil sample is diluted with petroleum ether to polarize and coagulate the oxidation by-products. The solution is then filtered through a 0.3 micron patch. This patch is digitized and analyzed using a spectrophotometer which measures the light reflectance of the patch color and shade of the stain. The values produced by the equipment are valuable in determining the amount of insoluble oxidation by-products in the sample. These values are compared to a brand new, clean patch whose value is zero.

The higher the degree of brown in a sample, the more oxidation by-products exist in the product. This is represented in the red and yellow spectrums. This is illustrated in Figure 1.

Gravimetric Patch Test

Research has revealed that in many used lubricants the majority of contaminants are oxidation by-products rather than particulate. A recent study claims that more than 90 percent of contaminants can be oxidation by-products, rather than particles. Since most of these insolubles are less than 2 microns, their presence is not registered through an ISO particle count. By following ASTM D4898, one can measure the total amount of insolubles above a desired filter size. In low varnish tolerance applications, it is recommended that a 0.3-micron or smaller patch be used. A 0.8-micron patch is recommended with fluids with higher amounts of contamination.

High levels of insolubles are evident when the gravimetric patch results reveal high levels of contamination while the particle count of the fluid is low, as can be seen in Figure 2.

A modified version of the gravimetric patch procedure has been used to isolate the organic resinous matter and the organo-metallic matter, which can also provide valuable information in detecting varnish pre-cursors in a fluid (Fitch, J. [1999, May-June]. Using Oil Analysis to Control Varnish and Sludge. *Practicing Oil Analysis*, pp. 25-33).

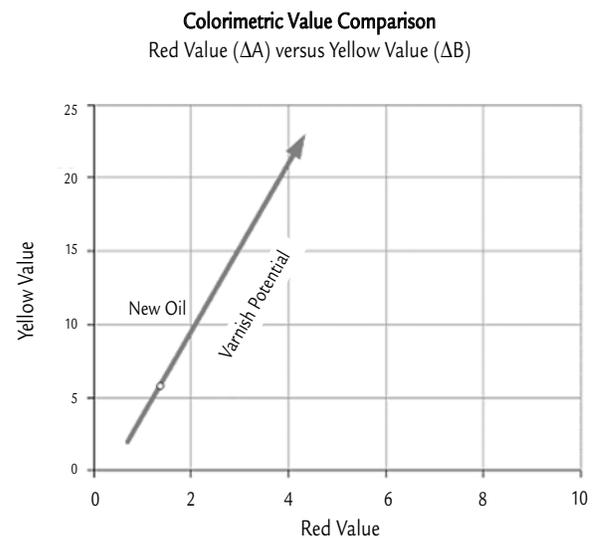


Figure 1. Colorimetric Value Comparison Chart

Ultracentrifuge

Utilizing a centrifuge with the capabilities of spinning in excess of 20,000 rpm, one has the capability to extract sludge and varnish pre-cursors from used lubricants. A visual rating scale is used to determine the degree of sedimentation and degradation by-products. Figure 3 shows the relationship between the Visual Sediment Rating Scale and the varnish potential of the fluid.

Fourier Transform Infrared (FTIR)

FTIR is based on the absorption of infrared light to provide a molecular fingerprint of the lubricant. FTIR analysis can often indicate the presence of oxidation by-products before acid number (AN) runs up because it is measuring several oxidation by-products including ketones, esters, carboxylic acids, carbonates, aldehydes, anhydrides and amines. FTIR can also be useful in determining what degradation method is damaging the fluid as shown in Figure 4. The intense heat generated in pressure-induced thermal failure will cause nitro-oxidation, which is measured in the 1630cm⁻¹ spectrum. Oxidation is typically measured in the 1714cm⁻¹ spectrum.

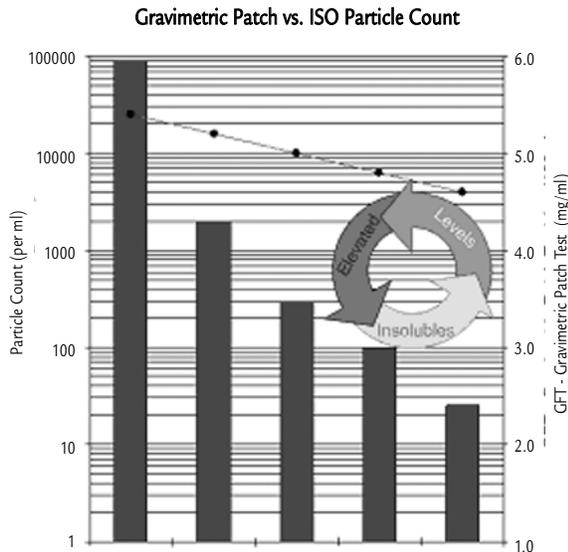


Figure 2. Detecting Elevated Levels of Insolubles by Comparing the Results of the Gravimetric Patch Test and ISO Particle Count

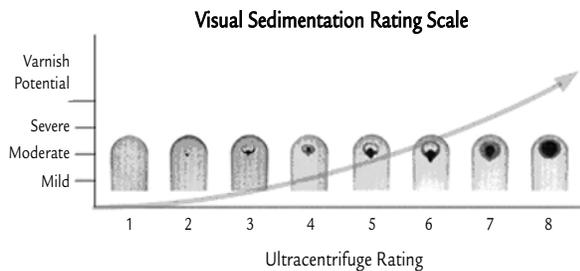


Figure 3. Relationship Between the Visual Sedimentation Rating Scale and the Varnish Potential

Interfacial Tension Test (IFT)

Although interfacial tension (ASTM D971) is primarily employed as an analytical tool in monitoring transformer oils, it can be of value when used with other tests to determine a fluid's potential to produce varnish. Oxidation by-products can immediately affect the surface characteristics of an oil allowing IFT to detect insoluble oxidation by-products at an early stage.

A new lubricant's IFT value is affected by the type of base oil used. Group I basestocks have inherently higher levels of impurities giving it a lower IFT value than Group II or III oils. Therefore, it is advisable to examine a fluid's IFT value in relation to its new value as shown in Figure 5.

RULER™

The RULER™ is a product manufactured by Fluitec International that measures, among other things, the concentrations of primary anti-oxidants. The hand-held device utilizes a patented voltammetric technique. By analyzing the remaining useful life and performance of primary anti-oxidants, one can infer two pieces of valuable information.

1. The oxidation stability of the fluid: There is a strong correlation between the results from the RULER™ and other oxidation stability test procedures such as Rotating Pressure Vessel Oxidation Test (RPVOT), Fourier Transform Infrared (FTIR) and Differential Scanning Calorimetry (DSC).
2. The Root Cause of the varnish formation: Using this test in conjunction with the Colorimetric, Patch, Ultracentrifuge, FTIR and IFT tests can provide a clue at the degradation mechanism. It is accepted that oxidative degradation consumes primary anti-oxidants. Depletion of anti-oxidants will continue throughout the oxidative process until they have been completely used up. During thermal failure, primary anti-oxidants may decrease in concentration but not to a fully depleted state. It is possible to infer from this test that used oil with both a high level of insolubles and remaining primary anti-oxidants may be undergoing thermal failure.

Robert Kauffman, at the University of Dayton Research Institute has developed a technique referred to as COAT (complete oil analysis techniques), based on cyclic voltammetry that measures electro-activity and conductivity. This technique has been successfully employed in testing aircraft engine oil to detect degradation mechanisms. Differentiating between thermal failure and oxidative, allows the lubricant user to detect early-stage engine problems and optimize drain intervals.

Relativity of API Basestock Classification

Solvency, or a fluid's ability to dissolve another substance and create a homogeneous mixture, is related to the level of soluble oxides that oil can hold before precipitation occurs and varnish is formed. Group II and III basestocks have a higher viscosity index

and fewer impurities than Group I basestocks, providing a higher resistance to oxidation and formation of oxidation by-products. Once oxidation by-products form however, their highly polar nature is less stable (soluble) in Group II and III basestocks and are more prone to lay down on metallic surfaces. This may also be due to soluble oxidation by-products becoming insoluble at an earlier stage in Group II basestocks than in Group I. Regardless of the reason, to accurately interpret the laboratory results it is important to understand what kind of basestock was used in the formulation of the lubricant. As a general rule, the higher a fluid's aniline point (a measurement of its solvency), the lower its tolerance for holding insoluble by-products in solution.

Conclusion

Varnish can cause significant performance problems in machinery lubrication, even in small quantities. Thermal failure, a degradation mechanism that breaks a lubricant's molecular bonds due to high temperatures, is one of the causes of varnish formation. Varnish problems can arise long before common analytical procedures used in routine oil analysis, show any abnormal tests. Utilizing six analytical tests, Colorimetric, Gravimetric Patch, Ultracentrifuge, FTIR, IFT and the RULER™ can help predict a fluid's potential to create varnish. These tests quantify the level of insoluble oxidation by-products, provide early detection of thermal failure, measure the fluid's resistance to further degradation mechanisms and monitor the depletion of anti-oxidants. The accumulation of the test results, combined with analytical interpretation experience, will predict a fluid's potential to varnish. For these reasons, the outlined series of tests are ideal for root cause analysis of varnish, and can make a valuable addition to an oil analysis program.

This information is also valuable in determining whether thermal failure is responsible for varnish formation. Understanding the root cause of the varnish allows the lubricant user to make informed predictive maintenance decision, thus increasing machinery reliability.

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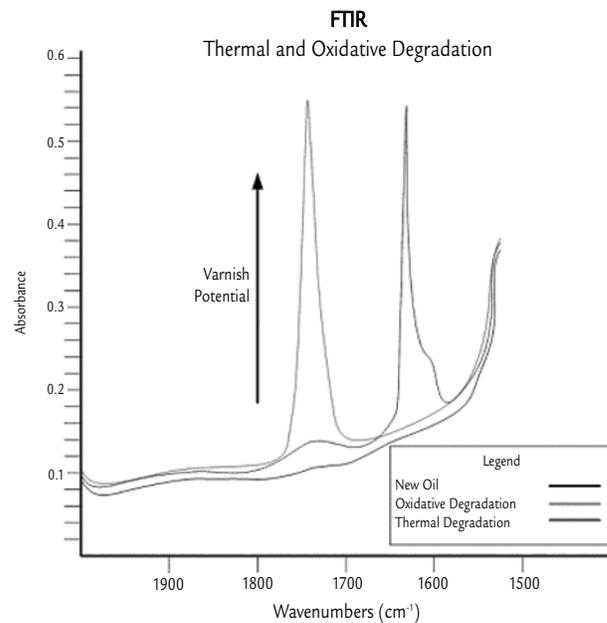


Figure 4. Using FTIR to Determine the Degradation Mechanism

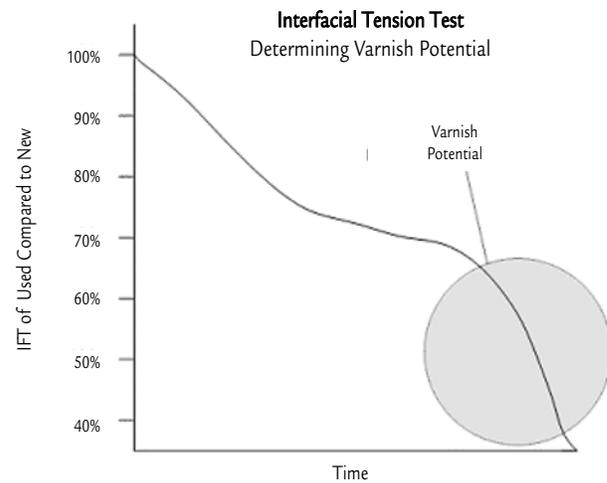


Figure 5. Interfacial Tension Test Used to Predict Varnish Potential

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How to Establish Wear Debris Alarm Limits

By JONATHAN SOWERS

One of the most frequently asked questions addressed to me over the years has been: What are the critical limits for my machines' wear elements? For years, oil analysis labs were reluctant to issue this information; some because they did not have well established wear ranges, and others, because providing this information into the hands of unprepared maintenance supervisors caused a great deal of trouble due to premature tear downs. With today's more sophisticated approach to maintenance, and better-prepared supervisors and engineers, it is easier to explain and justify condemning limits for a variety of machine components. This discussion centers upon how laboratories establish warning limits and how you may establish warning limits specific to your machinery and operational environment. Emphasis will be on use of statistical analysis as a tool for establishing upper and lower limits for machine wear behavior.

Wear Metal Alarm Limits

The use of statistics is one of the more common methods of establishing alarm limits for wear metal concentrations. There are different approaches, but we will concentrate on one that is easy to adapt to commercially available spreadsheet programs as well as many laboratory end user software programs. Primarily, you take each population of elemental concentrations and determine the mean (average, indicated by \bar{x}) and the standard deviation (how far away from the average the spread of the numbers are, indicated by σ). You then decide how many standard deviations from the mean (-3 to +3) you want your alarm limits, based on frequency distribution. In Figure 1, you can see how this distribution might look if 72 percent of the sample population is between -1σ and 1σ , 95 percent between -2σ and 2σ , and 99.9 percent between -3σ and 3σ . The math is as follows:

$$\bar{x} = \sum x_i / n = \text{Average}$$

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n}} = \text{Standard Deviation}$$

x_i = Data Point Values

n = Number of Data Points

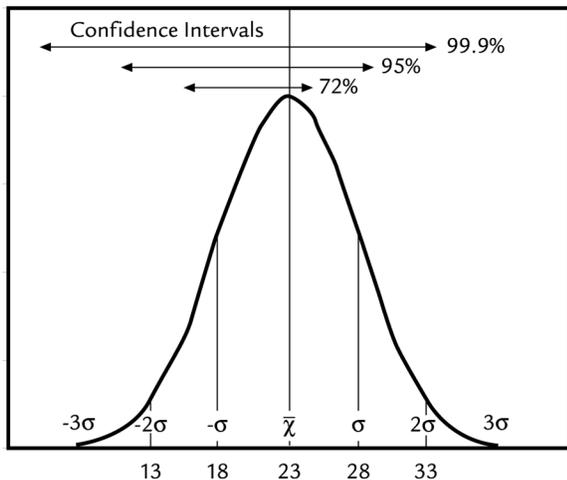


Figure 1. Selected Sample Population Frequency Distribution Curve

Using a spreadsheet or lab supplied software to run a data analysis of the selected sample population will supply you with summarized information such as seen in Figure 2. For each element you could use the formula $(0 + 1\sigma)$ for the first alarm, and $(0 + 2\sigma)$ for criticals, or some variation.

The criteria that form the database that provides this type of summary would be selected from parameters, such as illustrated in Figure 3.

It is important to note that with each change in the selected criteria, you will be looking at a completely different set of samples and the resulting flagging points will change. All of the parameters listed will isolate individually unique sets of wear patterns from your database of component sample histories. It is not enough to simply select gearbox as a unique identifier for a set of data. You will not accomplish the goal of being able to predict when your herringbone

Samples	1	2	3	4	5	6	7	8	9	10
Fe/ppm (x_i)	15	23	21	17	29	31	26	16	22	27
$(x_i - \bar{x})^2$	59.3	0.1	2.9	32.5	39.7	68.9	10.9	44.9	0.5	18.5

$$\begin{aligned} \bar{x} &= 22.7 \\ \sum (x_i - \bar{x})^2 &= 278.2 \\ \sum (x_i - \bar{x})^2 / n &= 27.82 \\ \sigma &= \sqrt{\frac{\sum (x_i - \bar{x})^2}{n}} = 5.3 \end{aligned}$$

Figure 2

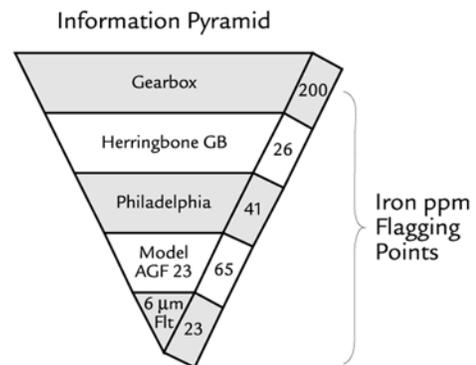


Figure 3

reduction gear test results are indicating an abnormal condition using the generic gearbox identifier. The use of non-specific identifiers will result in flagging points that may use the broadest possible ranges and completely mislead you and the lab evaluator into thinking you are safely within the normal boundaries, when in fact you may be approaching failure. This applies most significantly in the areas of component type, manufacturer, model, sump capacity, application, time on oil and filtration. The previous example clearly illustrates the different flagging points that may be used with more or less information about a given sampling point. These flagging points will be strongly affected by lack of or more complete information on other criteria as well. Check with your laboratory for details as to what kind of information is required.

When you are working with your laboratory, it is essential that you supply it with complete and appropriate information so that it will be able use the most accurate flagging points to evaluate your equipment. You also will not be able to completely take advantage of the tools available to you in determining your own wear patterns and flagging ranges without this information.

Now, having said all that, keep in mind that two identical components sitting next to each other doing the same work will

likely produce different wear patterns. Sometimes, very different wear may be exhibited from one machine to the next, especially in stationary rotating equipment. That is one reason for this paper and discussion, so that you will be able to establish your own flagging points based on data from each component. You may also request your lab to setup unique flagging points for some of your components that do not seem to fall within the typical distribution pattern as the rest the lab's database of similar components.

Another thing to consider is that your components wear behavior may remain below the high range value; yet still indicate to you that there is a problem. By using a factor to flag the percent change in your current sample results as compared to the last sample, and/or the average of the historical test results, you can dramatically see an upward or downward shift in the wear pattern. This is one way to monitor the trend of wear behavior. In both instances, you may want to flag for increases and decreases in the trend, as they are both meaningful indicators. These will show up dramatically when plotted in a chart. Range values for flagging points are very good, if arrived at in a disciplined mathematical manner, but they don't tell the whole story. Monitoring the wear trend is also an invaluable tool for determining normal or abnormal wear.

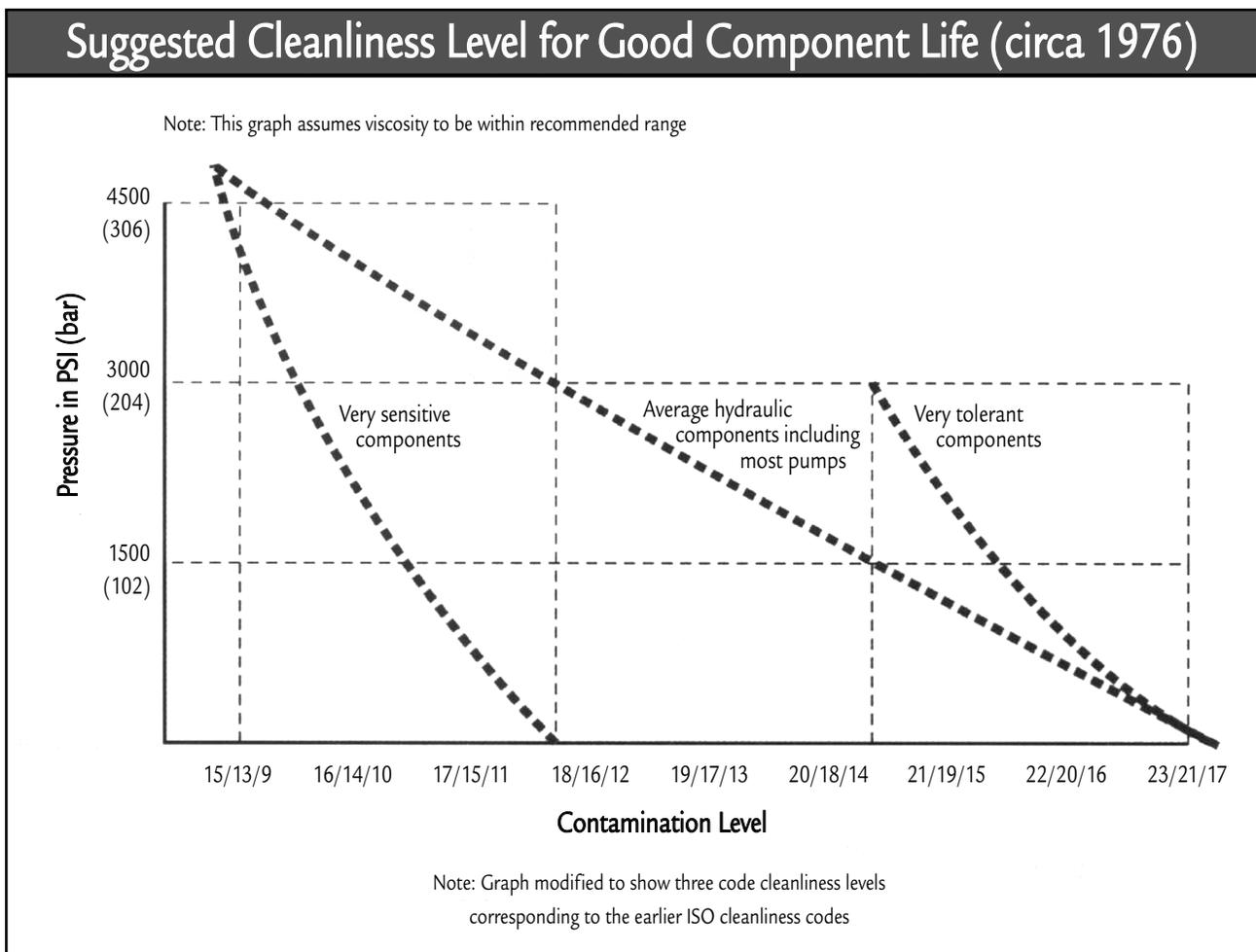


Figure 4. (Courtesy Vickers')

Wear Debris Analysis

When discussing wear debris in lubricating fluids, remember that all of the test methods currently in use have some form of limiting factor as to how much information they can supply. The use of emission spectroscopy mentioned above, is limited by the size of the particles suspended in the oil. The instruments commonly used for elemental concentrations are limited to

observing particulate that do not exceed 5µm to 10µm. To gather information on larger wear debris, the use of other analytical approaches must be employed. There are generally four such analytical approaches currently used by most oil analysis labs: particle counts, direct reading ferrography, gravimetrics and analytical ferrography. This paper will address two methods. Establishing alarm limits for these tests will now be discussed.

Vickers Recommended Cleanliness Code Chart			
PUMPS			
Pressure	<2000	2000–3000	3000+
Fixed Gear	20/18/15	19/17/15	
Fixed Vane	20/18/15	19/17/14	18/16/13
Fixed Piston	19/17/15	18/16/14	17/15/13
Variable Vane	18/16/14	17/15/13	
Variable Piston	18/16/14	17/15/13	16/14/12
VALVES			
Pressure		2000	3000+
Directional (solenoid)		20/18/15	19/17/14
Pressure Control (modulating)		19/17/14	19/17/14
Flow Controls (standard)		19/17/14	19/17/14
Check Valves		20/18/15	20/18/15
Cartridge Valves		18/16/13	17/15/12
Prefill		20/18/15	19/17/14
CMX		18/16/14	17/15/13
H.R.C.		18/16/13	17/15/12
Proportional Directional (throttle valves)		17/15/12	16/14/11*
Proportional Pressure Controls		17/15/12	16/14/11*
Proportional Flow Controls		17/15/13	17/15/13
Proportional Cartridge Valves		17/15/12	16/14/11*
Servo Valves		16/14/11*	15/13/10*
ACTUATORS			
Pressure	1000	2000	3000+
Cylinders	20/18/15	20/18/15	20/18/15
Vane Motors	20/18/15	19/17/14	18/16/13
Axial Piston Motors	19/17/14	18/16/13	17/15/12
Gear Motors	21/19/17	20/18/15	19/17/14
Radial Piston Motors	20/18/14	19/17/13	18/16/13
Cam Wave Motors	18/16/14	17/15/13	16/14/12*
HYDROSTATIC TRANSMISSIONS			
Pressure	2000	3000	4000+
Hydrostatic Transmissions (in-loop fluid)	17/15/13	16/14/12*	16/14/11*
BEARINGS			
Ball Bearing Systems	15/13/11*		
Roller Bearing Systems	16/14/12*		
Journal Bearings (high speed)	17/15/13		
Journal Bearings (low speed)	18/16/14		
General Industrial Gearboxes	17/15/13		

How to Set a Target Cleanliness Level

STEP ONE

Using Vickers Recommended Cleanliness Code Chart, determine the cleanest fluid (lowest code) required by any component in the system. All components that draw fluid from a common reservoir should be considered to be part of the same system even if their operations are independent or sequential (i.e., a central power unit running several different machines). The pressure rating for the system is the maximum system pressure achieved by the machine during a complete cycle of operation.

STEP TWO

For any system where the fluid is not 100% petroleum oil, set the target one Range Code cleaner for each particle size.

Example: If the cleanest code required was an 17/15/13 and water glycol is the system fluid, the target becomes 16/14/12.

STEP THREE

If any two or more of the following conditions are experienced by the machine or system, set the target cleanliness one level lower for each particle size.

- Frequent cold starts at less than 0°F (-18°C)
- Intermittent operation with fluid temperatures over 160°F (71°C)
- High vibration or high shock operation
- Critical dependence on the system as part of a process operation
- Personal safety of the operator or others in the area could be put at risk by a system malfunction

Again, looking at the example above, if this system was expected to cold start in Alaska and a failure could cause personal injury, the target cleanliness would become 15/13/11.

Using this three step procedure the system target cleanliness code for the system is now set.

*Requires precise sampling practices to verify cleanliness levels.

Figure 5. (Courtesy Vickers')

TABLE I HYDRAULIC SYSTEMS: REQUIRED NEW MACHINE CLEANLINESS				
Current Machine Cleanliness (ISO)	Target	Target	Target	Target
28/26/23	25/23/21	25/22/19	23/21/18	22/20/17
27/25/22	25/23/19	23/21/18	22/20/17	21/19/16
26/24/21	23/21/18	22/20/17	21/19/16	21/19/15
25/23/20	22/20/17	21/19/16	20/18/15	19/17/14
25/22/19	21/19/16	20/18/15	19/17/14	18/16/13
23/21/18	20/18/15	19/17/14	18/16/13	17/15/12
22/20/17	19/17/14	18/16/13	17/15/12	16/14/11
21/19/16	18/16/13	17/15/12	16/14/11	15/13/10
20/18/15	17/15/12	16/14/11	15/13/10	14/12/9
19/17/14	16/14/11	15/13/10	14/12/9	14/12/8
18/16/13	15/13/10	14/12/9	13/11/8	-
17/15/12	14/12/9	13/11/8	-	-
16/14/11	13/11/8	-	-	-
15/13/10	13/11/8	-	-	-
14/12/9	13/11/8	-	-	-
Life Extension Factor	2 X	3 X	4 X	5 X

Figure 6. (Courtesy Eaton Fluid Power²)

TABLE II ROLLER CONTACT BEARINGS: REQUIRED NEW MACHINE CLEANLINESS				
Current Machine Cleanliness (ISO)	Target	Target	Target	Target
28/26/23	25/22/19	22/20/17	20/18/15	19/17/14
27/25/22	23/21/18	21/19/16	19/17/14	18/16/13
26/24/21	22/20/17	20/18/15	19/17/14	18/16/13
25/23/20	21/19/16	19/17/14	17/15/12	16/14/11
25/22/19	20/18/15	18/16/13	16/14/11	15/13/10
23/21/18	19/17/14	17/15/12	15/13/10	14/12/9
22/20/17	18/16/13	16/14/11	15/13/10	13/11/8
21/19/16	17/15/12	15/13/10	13/11/8	-
20/18/15	16/14/11	14/12/9	-	-
19/17/14	15/13/10	13/11/8	-	-
18/16/13	14/12/9	-	-	-
17/15/12	13/11/8	-	-	-
16/14/11	13/11/8	-	-	-
15/13/10	13/11/8	-	-	-
14/12/9	13/11/8	-	-	-
Life Extension Factor	2 X	3 X	4 X	5 X

Figure 7. (Courtesy Eaton Fluid Power²)

Particle Counts

For the purposes of this paper we will address only the ISO 4406 (old) or ISO 4406.2 (current) Cleanliness Code as applied to various types of mechanical systems. In setting alarm limits for hydraulic and other lubricated systems, there is assistance from OEMs and filter manufacturers. Both have done extensive research into how various levels of contamination effect system performance and component life and life extension. Laboratories and end users may also use similar statistical methods as described in first section of this paper to assist in determining normal and abnormal contamination levels unique to a specific component or set of components. However, let us look at recommendations from two sources, Eaton Fluid Power (Vickers) and Pall Corporation. Use these tools as guidelines for establishing minimum acceptable cleanliness levels and then go one step beyond to extending component and fluid life expectancy. Both companies have Web sites with extensive help and information resources, which is where the following charts originated. The following information as well as much more is available at Eaton/Vickers Web site:

http://hydraulics.eaton.com/products/filters_fluid_maintenance-pam.htm.

In setting a target cleanliness level, first determine the cleanliness recommended for the most sensitive component in the system, then adjust the code for fluid type, and then adjust the code for external factors that increase stress on the system components (Figure 4).¹

The chart in Figure 5 has been designed to help design and maintenance engineers set a target cleanliness level. These levels are based on engineering evaluations (including materials, critical clearances and machine tolerances) and practical field experiences with Vickers and other brands of hydraulic or load bearing components.¹

It is one thing to set an initial cleanliness target, yet your overall strategy may include extending the fluid and component life. Figures 6 and 7 look at some possibilities in this area.

Field and laboratory testing have led to the publication of life extension charts, such as the charts listed (adapted from Diagnostics of Tulsa, Okla., published Life Extension Factors, 1991.) For the purpose of estimating return on investment, Vickers recommends using the highlighted information in the 2X factor category. This recommendation is based on the fact that there are factors other than contamination that will affect component life. For example, type of fluid, operating temperature and duty cycle.²

For another look at how to target cleanliness levels, check out Pall Corporation's Web site:

http://www.pall.com/applicant/hydraulics/select_guide.asp

Here they will actually calculate the target level for you, as seen in Figures 8 through 11 on the following pages.

Direct Reading Ferrography

Use of DR Ferrography has many useful applications in systems where filtration of the fluid is not practical and the component-metallurgy is primarily ferrous (iron, steel). DR is designed to track particles that are found at the entry point of a ferrogram (where the largest particles are deposited) and 5mm below the entry point (where 1-2 μm sized particles are deposited). These are the areas most sensitive to changing wear conditions. DR provides data concerning large (L) particles ($>5 \mu\text{m}$) and small (S) particles ($<5 \mu\text{m}$). Readings are in empirical units indicating the density of particle deposition at each sensor location.

To set alarm limits for this test it is necessary to first establish a baseline of for the components to be tested. This may be accomplished by sampling one unit several times, or several like units one time.⁴ The values may then be applied to a statistical data analysis similar to establishing wear metal alarms. Use of frequency distribution, mean and standard deviation are a successful approach.

Other ways to utilize this data are through Severity of Wear Index, Cumulative Plots and Wear Particle Concentration (WPC) and Percentage Large.

Severity of Wear Index is determined by the L reading, or the sum of the L + S readings used as an indication of concentration. The difference, L - S, between the readings is used as an indication of size distribution. The product of these terms, either $L(L - S)$ or $(L + S)(L - S) = L^2 - S^2$ may be used as a severity of wear index. If plotted as a function of operating time, it will respond in a more volatile manner than will plotting L or S.

For Cumulative Plots there are two methods:

- **Method 1:** Each new reading is added to the sum of the previous readings - plotted at the same sample interval.
- **Method 2:** Cumulative concentration $\sum (L + S)$, and cumulative size distribution $\sum (L - S)$ are each plotted on the same graph.

Wear Particle Concentration (WPC) is calculated as: $L + S$. The percentage large is calculated as: $(L - S)/(L + S)$. An increase in both WPC and Percentage Large signals an abnormal wear mode.⁴

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Trending Additive Depletion

By DAVE WOOTON - WOOTON-CONSULTING

In order to truly understand used oils, one should also understand the oil formulation that makes up the new oil. This paper describes what goes into an oil formulation, what performance criteria are controlled by the additives used in the formulation, some of the common chemistry of these additives and how one might analyze some of the most important of these formulation-components in the used oil. Two formulation applications (crankcase and gear) were chosen as examples to study the additive's fate.

Introduction

Used oil analysis is the process of studying the chemistry changes of oil in use. Historically, it started with analyzing the metal content of the used oil. This process looked at how much wear metals (iron, chromium, copper, and lead) was produced in the used oil. This process would set limits on the condemnation levels. As time progressed, the program added other chemical changes to the list of analyses. These included:

- Base Number (BN): To control the amount of base reserve,
- Acid Number (AN): To follow the acid production,
- Viscosity: To follow the thickening of the oil,
- Water or Glycol: To know if contamination occurred from the coolant system.

Good used oil programs of today have added:

- Fourier Transform - Infrared (FTIR) analyses: To analyze for oxidation/nitration and zinc dialkyldithiophosphate (ZDDP) depletion,
- Particulate count: To assure oil cleanliness,
- Particulate size determination: To know that the filter cleaning is working properly,
- Soot analyses: To know when the level requires an oil change,
- Filter backpressure: To assure the oil flow is being maintained properly,
- Additive or contamination metals (such as zinc, phosphorous, calcium, magnesium, silicon, boron, aluminum and molybdenum): To add the new metallurgies and assure proper oil blending.

Initially, the thinking was to determine when the oil was bad, so it could be changed. The metal analyses told the user how much of the equipment parts had worn-off into the oil. High iron told the operator that there was a problem with the cylinder liner, camshafts, crankshaft or gears. High copper and lead indicated bearings or bushings wear. And high chromium indicated wearing of the polished metal surfaces like piston ring faces and some pump surfaces. If the copper level got high, the user knew that the bearing was being destroyed. He did not know if this destruction was coming from a wear problem or a corrosion problem. He just knew that this part was being destroyed. If it was being destroyed too much, he knew to change the oil. Although this was a lot better than not knowing anything until the equipment died, it suffered from the problem of not predicting when the oil was going to give problems, or the cause of the oil failure.

Trend plotting of the analyses helped to allow some prediction of the oil life and improved the program greatly. Improvements were also added with the new analyses that looked for the sources of potential troubles. AN and BN analyses informed the operator the state of the used oil's acidity or corrosion potential, while viscosity, soot, and filter back pressure allowed the operator to know the flow properties of the oil. The addition of additive metals (calcium, magnesium, zinc, and phosphorous) and FTIR analyses are starting to allow the operator to see the effects of the formulation.

The more the operator understands about the formulation as well as the used oil chemistry, the better the prediction becomes. If one studies used oil from a chemistry viewpoint, there are three major areas of concern:

1. Contamination: Such as combustion gases or airborne particles,
2. Component formation: Such as polymerization or oxidation,

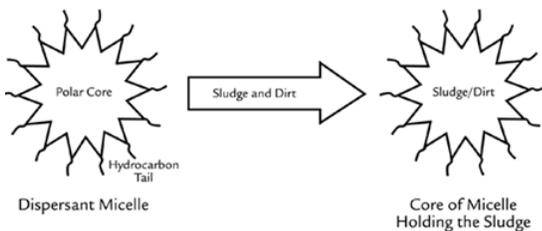


Figure 1. Micelle Action

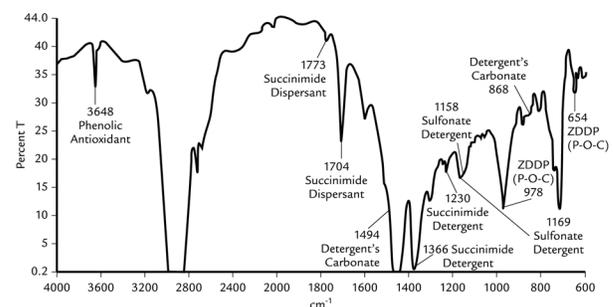


Figure 2. FTIR Spectrum of New Oil

3. Formulation additives depletion: Such as the antiwear, dispersant or detergents.

Many authors have discussed the effects of contamination and oxidation. The emphasis of this paper will be on the fate of the formulation additives.

The New Oil Formulation

A can of oil is basically made up of three groups of components:

1. Base stock,
2. Viscosity index improver,
3. Additive package.

The base oil is the largest component at about 70 percent of the mixture. Its viscosity grade helps to define the overall viscosity or fluid flow properties of the final oil and is based on the ultimate requirement of the application. For example, if one is making diesel engine oils and desiring it to have a viscosity grade of 15W40, he might start off with a mixture of a light viscosity base stock (100 neutral) and a medium viscosity base stock (250 neutral). On the other hand, if the desire is to make gear oil with a viscosity grade of 85W140, then he may want to start off with medium base stock (250 neutral) and a heavier viscosity base stock (600 neutral). These base stocks can be either mineral based (meaning that they come from the petroleum refining operation and not specially manufactured) or synthetic based (which means that they are specially synthesized - like synthetic esters or poly-alpha-olefins).

A viscosity index improver (VII) is added to an oil mixture to stabilize flow properties of the oil with temperature changes. It helps the oil maintain similar flow characteristics at low and higher temperatures. This component is what defines the oil to be a cross-grade (15W30 or 80W140) versus a straight-grade (30 or 90 weight). The VII is in the oil mixture at 5 to 15 percentages for cross- grade applications and not present in straight-grades. The chemistry of a VII varies from

olefin copolymers (such as polyethylene/polypropylenes) to alkyl polyesters (such as alkyl polymethacrylates).

The next major component of a can of oil is the additive package. This component is the most complicated of the mixture. The amount of this component ranges from 8 to 15 percent for crankcase applications, to 1 to 2 percent for hydraulic applications. The additive package consists of many components that are a balanced mixture used to meet the specifications of the application. There can be as many as 15 different components in an additive formulation. For simplicity in this paper, I am going to discuss two application types of formulations: Crankcase (used in a gasoline or diesel engine) and gear (used in an automotive or industrial gear equipment).

Crankcase Formulations: The crankcase formulation is the first to study, since many of the additives present in this type of formulation are also present in other application types as well. This formulation is a combination of about a dozen different components. Each of these components (or additives) is blended into a balanced formulation designed to meet the engine specifications and requirements. Some of these additives are very easy to observe, while others are in low concentrations and much more difficult to observe or study.

The most predominate component in this formulation is the dispersant. This component is present in about 3 to 6 percent. A dispersant is the additive that is designed to suspend sludge and contamination components entering into the oil. It is used to control deposit formation and help bring these contamination components to the oil filter. The chemistry of a dispersant consists of a polar head group with a long hydrocarbon tail. This acts something like laundry soap, trapping the dirt into what is called a micelle (Figure 1).

As the dirt or sludge components enter the oil, they are trapped in the core of the dispersant's micelle. This trapping action prevents the dirt or sludge from depositing on the engine parts and causing premature equipment failures.

The most common chemistry of a dispersant is a polyisobutylene succinimide. The polyisobutylene has a molecular weight of greater than 1000 and forms the hydrocarbon tail. The succinimide portion of the molecule contains a polyamine and forms the polar head. In

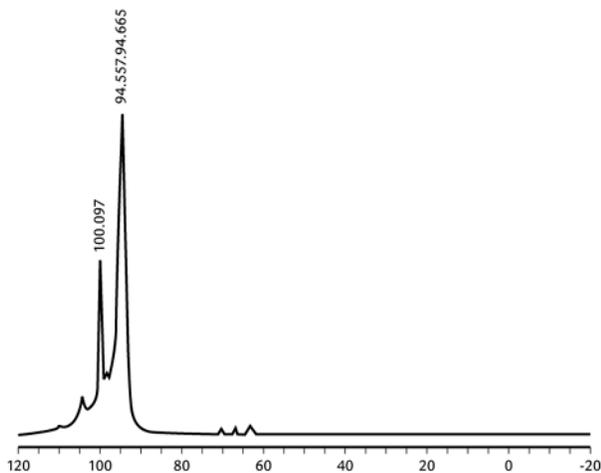


Figure 3. P NMR Spectrum of New Crankcase Oil Showing the ZDDP chemistry

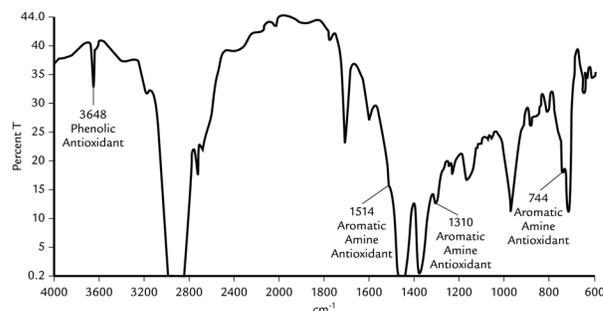


Figure 4. FTIR Spectrum of New Oil with Phenolic and Amine Antioxidants

the new oil this additive can be observed in the FTIR spectrum (Figure 2). This FTIR spectrum allows the analyst to study both the succinimide's carbonyl bands of the polar head-group, as well as the polyisobutylene's hydrocarbon bands of the tail-group. The strong acid BN method (HClO₄ titration - ASTM D2896) allows a study of the amine portion of the polar head-group.¹

The next most predominate additive in this formulation is the detergent. This additive is in the oil at about 2 to 3 percent. The detergent is used primarily to control the acids entering into the oil. However, it does have some ability to wash the metal surfaces of organic deposits. There are several types of detergents that are used in these formulations. The most important of these is the sulfonate. The chemistry of the sulfonate is somewhat similar to the dispersant in that it has a hydrocarbon tail and a polar head. The hydrocarbon tail is much shorter, being only a C-16 to 30-alkyl benzene. The polar head is the salt of a sulfonic acid. The metals used in this salt are typically calcium, magnesium or sodium. In addition to this neutral sulfonate salt, the detergent contains a large excess amount of metal carbonate, incorporated in the center of its micelle. This carbonate contributes much of the oil's BN and is used for the neutralization of any acids that enter the oil during use. This additive's functionality can be observed in the new oil by measuring the oil BN. There are two types of BN that are defined by ASTM: strong acid-BN (HClO₄ - ASTM D2896) 1 and weak acid-BN (HCl - ASTM D4739).² The strong acid-BN method measures both the dispersant and the detergent, while the weak acid-BN method measures primarily the sulfonate's carbonate. These BN methods very effective for following this additive in the used oil. ICP and FTIR can also be used to follow the additive. Inductively Coupled Plasma (ICP) analysis for the metal (calcium, magnesium or sodium) can yield the information about the initial additive concentration. The sulfonate-detergent's S=O bands and its carbonate's CO₃ bands can be observed using FTIR (Figure 2).³

The ZDDP is the next most predominate additive in the formulation and it is in the oil at about 1 percent. The ZDDP is used to control wear and oxidation. The initial concentration of the additive can be determined by ICP metal analyses (zinc and phosphorous). ICP should not be used to monitor the additive, however, since the additive reacts to produce a non-active

phosphorous compound that can remain in the used oil. The chemistry of this additive can be observed and followed by FTIR. There are several infrared stretching vibrations that are clearly observed in the oil (Figure 2). These are the P-O-C bond (seen between 950-1020 cm⁻¹) and P=S (seen between 640-665 cm⁻¹).

The best analytical tool to study the ZDDP and its decomposition is nuclear magnetic resonance spectroscopy, ³¹P NMR (Figure 3).⁴ This analysis measures the chemical environment of the phosphorous, monitoring all the changes in the compound as it is used in the oil's operation. This analytical tool also displays even slight molecular changes associated with the ZDDP.

In addition to the ZDDP, an oil formulation typically contains other antioxidants, such as di-t-butyl phenols and diaryl amines. Antioxidants are used to control the oxidation of the base oil and other additives in the formulation during use. Oxidation is the major cause of viscosity increase and a major source of acid formation. It is a major cause of the loss of VII, pour point depressant and antiwear. The antioxidants are formulated in low concentrations (typically 1 percent or lower) and more difficult to follow by conventional techniques. Both the phenolic and aromatic amine can be observed in the new oil by FTIR (Figure 4). However, as this concentration decreases due to use, they become increasingly difficult to observe and making it necessary to utilize methods like gas chromatography (GC), high performance liquid chromatography (HPLC) or gas chromatography-mass spectroscopy (GC-MS).

Other additives in this formulation are low concentration and become more difficult to study without some additional sample preparation. The linking of a separation technique - like gas chromatography or size exclusion chromatography (SEC) with an identification/quantitation - like mass spectroscopy or FTIR can allow one to study the concentrations to 10-ppm levels. For example, the pour point depressant is added in a level of about 0.1 percent. This additive is formulated to disrupt the wax crystals that form in the oil at temperatures below about -15°C. Most pour point depressants are polymethacrylates with approximately 30,000-molecular weight. They can be observed in the new oil by the strong C=O vibration at 1734 cm⁻¹; however, they can be hidden under the VII (if it is also a polymethacrylates) or lost under the oxidation chemistry as the oil deteriorates. The concentration

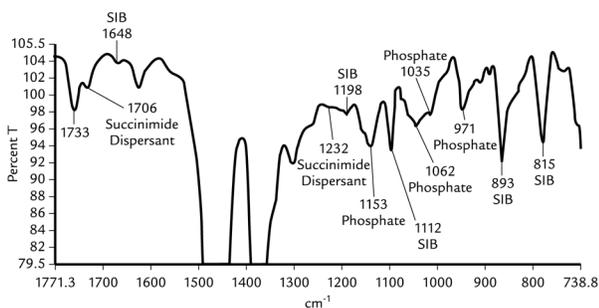


Figure 5. FTIR Spectrum of New Gear Oil

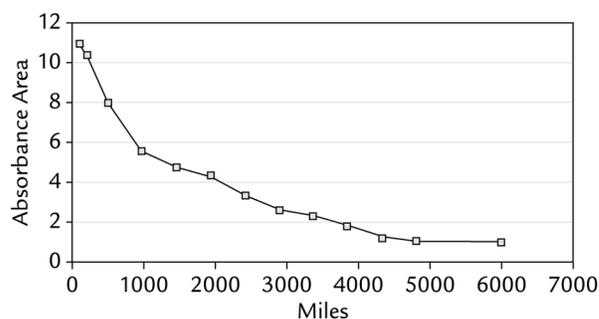


Figure 6. Crankcase ZDDP Depletion

of this additive can be studied if the researcher utilizes size exclusion chromatography or other molecular size-separating techniques as a sample preparation technique. Linking these separation techniques with the FTIR spectra, identification and quantitation becomes achievable of the low concentration components.

Gear Formulations

The chemistry of gear oil and that of crankcase oil are considerably different. The crankcase oil is designed to handle low pressure moving wear and large amounts of acids and contamination. Without the combustion products to contend with, the gear oil is designed to handle very high pressure scuffing wear and much lower amounts of contaminations. Friction modification and extreme pressure wear protection become the most important functions of gear oils. In the modern formulation, control of sludge and deposits is also a function of this oil. The additives used in the gear oil reflect this change in application.⁵

The most important component of a gear oil formulation is the extreme pressure/antiwear additives. These additives form a sacrificial chemical bond or film with the metal surface that inhibits welding and reduces friction between the metal surfaces. There are several additives in the formulation that achieve this functionality. The most important is an organic polysulfide that is chemically - sulfurized isobutylene (SIB) or t-butyl-polysulfide. It is typically used in concentration ranges between 40 percent and 75 percent in the additive package (or 2 to 5 percent of the oil). Other additives that perform this functionality are the alkyl phosphites and phosphate esters. These phosphorous additives are formulated at 15-25 percent of the additive package (or 0.8 to 1.5 percent of the oil). The presence of these two additives is why gear oils are often referred to having sulfur-phosphorous chemistries. Their concentrations are measured by sulfur or phosphorous elemental analyses. Both of these additives can also be seen in the new oil by FTIR (Figure 5). When more chemical information is desired about the phosphorous chemistry, ³¹P NMR is the technique of choice.

Recent gear oils have been claiming "clean gear" properties of the oil. These formulations contain dispersants similar to those used in crankcase formulations. The objective of this additive is to suspend

(through the same micelle action - Figure 1) the oxidation and sludge products in the used oil. There is far less of these sludge-producing materials in gear oils than crankcase oils, but a gear oil lubrication system often does not contain any filtration. Since these dispersants contain polyamines, they can add to the strong acid-TBN (ASTM D2869) of the oil. Like the crankcase example, the dispersant additive in gear oil can also be analyzed by FTIR (Figure 5).

Fate of the Formulation

The traditional approach to studying used oils is to look at what is being formed, such as oxidation or nitration. These components are important as well when studying what happens to the formulation additives. The compounds that are formed are usually reactive to the formulation additives and cannot be ignored. Some of them necessitate modifying the analyses procedures for the formulation additives.

Oxidation/Nitration

Oxidation is the primary source of the oil formulation degradation. All the formulation components are affected by this reaction chemistry. Those components that are affected the most are the antioxidants, since they are added to prevent oxidation and react first. These additives effectively disappear from the oil. However, they actually form nitroso amines and quinines, which harder to observe and further react to produce nitro-benzene derivatives and carboxylic acids. The alkyl-phosphates, both dithio-phosphates (ZDDP and trialkyl-thio-phosphates) and the oxy-phosphates (dialkyl-phosphates, trialkyl-phosphate and phosphate acid salts), are the next to react. The formulation objective is to protect these phosphorous-containing additives as long as possible, since they are also major antiwear additives. The oxidation of these alkyl-phosphates generates inorganic phosphate (such as zinc phosphate) and pyrophosphate (such as zinc pyrophosphate). The inorganic phosphate salts become insoluble or sludge producers in the oil that needs to be suspended or filtered to protect the application.

Everything else within the formulation is subject to the same oxidation as the antioxidants. The others just react slower, being

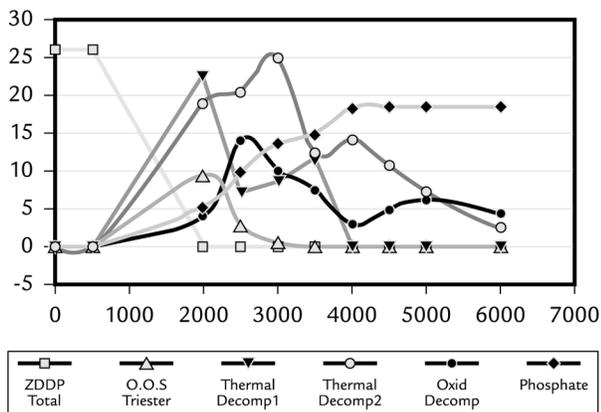


Figure 7. P NMR Data for ZDDP's Depletion

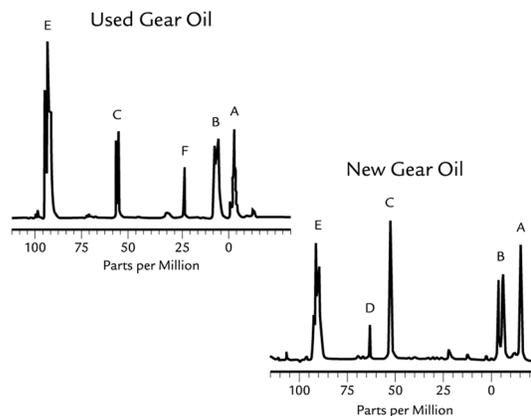


Figure 8. P NMR Spectra of New and Used Gear Oils

protected to some extent until the antioxidant is exhausted. The base oil, being the most abundant component, shows its oxidation first. The dispersant has a very inert succinimide core with unstable amines and hydrocarbon tail. The amine head group reaction can be seen from the loss in strong acid-TBN, especially in formulations that do not contain any overbased-detergents. The dispersant's hydrocarbon-tail is a prime oxidation site similar to the base oil. This tail can react to produce the same by-products as the base oil. In doing so, the dispersant will not only lose its dispersant properties, but will also become a sludge source in itself.

In gear formulations, the sulfur extreme pressure additive (organic polysulfide or SIB) behaves like an antioxidant. The cleavage of the S-S bonds by the oxidation and the formation of sulfates is a typical reaction pathway. The organic polysulfide eventually oxidized to form sulfates, which are a major constituent of the sludge for this application.

Thermal Decomposition

As the temperature of the oil increases, it reaches the thermal decomposition temperature of some of the additives. The additive that has one of the lowest decomposition temperatures is the ZDDP. This additive starts to decompose at just over 100°C. The advantage of this is that in many applications the first decomposition products are as effective as an antiwear or antioxidant agent as the original additive. In some applications, the thermal decomposition mechanism causes the additive to deposit onto the metal surface. Thus, increasing its antiwear properties.

Organic polysulfides also possess poor thermal stabilities. In this case, the low thermal stability helps this additive perform its job. The decomposition of the sulfur-sulfur bond in the presence of a metal surface will promote sulfur-iron complex formation and a better metal surface coverage. Actually, the most predominate location for thermal decomposition is at the hot metal surface of the gear application.

The sulfurized olefins are used for friction modifiers and can suffer from thermal decomposition like the organic polysulfide.

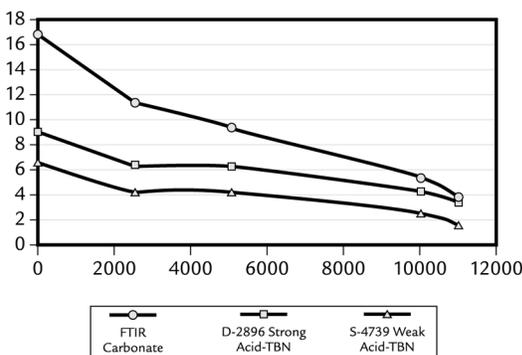


Figure 9. FTIR Measured Carbonate, Weak Acid-BN (D4739) and Strong Acid-BN (D2896) depletions.

Since there are less sulfur-sulfur bonds the decomposition mechanism is the carbon-sulfur bond, requiring slightly higher temperatures. Like the organic polysulfide, these additives can gain activity if the decomposition occurs near the metal surface. When this is not the case, the additive's decomposition can be a source of sludge formation.

Thermal decomposition of the hydrocarbons, such as the VII and base oil takes considerable higher temperature. Instead of thermally decomposing, most of the base oil that encounters high temperatures will evaporate instead of decomposing. If an analyst is studying used oil that does not show sludging problems, the amount of base oil volatilization can be measured by analyzing the calcium or magnesium content of the used oil. As the oil evaporates, the concentration of the non-volatile metal will increase. It is not uncommon to observe 10-percent or more concentration increase in metals between the new and used oils.⁶

Contamination

Contamination is another predominate cause of oil degradation. Oil can be contaminated with:

- Fuel: that enters through lose fitting rings, bad valve seals or leaking injectors
- Airborne particles: such as dust or sand
- Metal particles: from the wearing process or a mechanical component failure
- Soot: from the diesel combustion process
- Water: from the coolant or combustion gases
- Combustion acids: from unburned or partially burned fuel and nitrates
- Sludge: formed from the oxidation mechanisms

The results of these contaminations are well known to cause mechanical failures. There are additives formulated in the oil to protect the equipment for these potential sources of mechanical

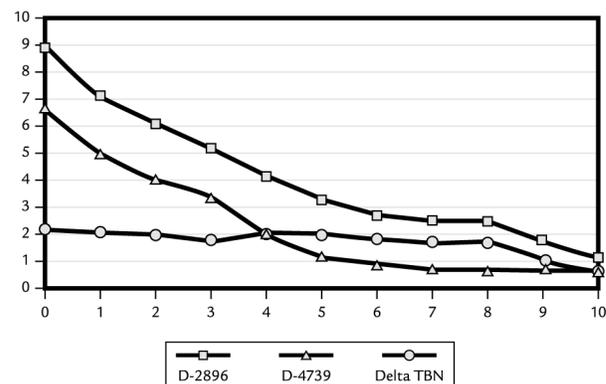


Figure 10. Dispersant Head-Group Concentration via Delta BN

failures. However, the additives can be used up as a result of the contamination. The dispersant is a prime example. This additive acts like a bucket to hold the contamination. If the contamination can be left in the filter, it usually takes the dispersant with it. For example, soot produced in a diesel engine is a small particle that is not trapped in the filter. As the soot is collected by the dispersant, its collective size will grow enough to be trapped in the filter and removed from the oil. A soot particle also has absorption properties that will attract additives. The ZDDP is an example of one of these polar additives that can be absorbed by the soot and removed from the oil.⁷

Oxidation by-products can be a very common source of contamination. As oil oxidizes, it will form carboxylic acids. These carboxylic acids are neutralized by the reserve-BN in the formulation to form calcium or magnesium salts. Most calcium or magnesium salts are insoluble in hydrocarbons. Therefore, these oxidation by-products are a major source of the sludges formed in used oils. Because the dispersant is used to help suspend these materials, when the dispersant becomes overloaded with sludge it can precipitate with the sludge. This association of the dispersant with the sludge, along with the increased amount of sludge in the oil, is a cause of dispersant failures of used oils that one observes in the Blotter Spot test.⁸

Analysis Examples

Used oil analysis methods today often include characterizing several infrared spectroscopic frequencies. One of these is the P-O-C absorption for the ZDDP or phosphorous antiwear. It is observed in the region 1025 to 960 cm^{-1} . In a crankcase lubricant, whether the oil is from a passenger car or heavy-duty diesel engine, this additive component tells a great deal about the life expectancy of the lubricant. It is depleting from both antioxidant and antiwear pathways. Thus, its concentration reflects both of the lubricant functions. Figure 6 shows an example to this additive depletion rate. The oil in this example has been used beyond the useful lifetime of this additive. As a result, there were significant increases in the wear metals observed during the last few miles of the application.

The chemistry of the phosphorous additives is very complex. Some of this complexity cannot be observed in its infrared spectrum. As discussed earlier in this paper, ^{31}P NMR spectrum of the sample

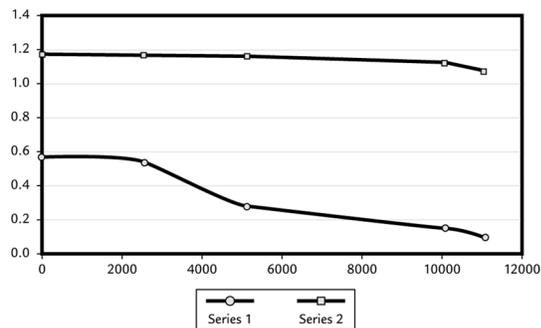


Figure 11. Dispersant Hydrocarbon Tail

is a better tool for this analysis. Figure 7 is a graph plotting of several of the by-products associated with the depletion of a ZDDP in a crankcase application.

One can see that The ZDDP itself depletes reasonably early in this application; however, there are still several intermediate components that are formed which last well into the oil lifetime. Some of the thermal and oxidative decomposition by-products still exhibit the antiwear or antioxidant properties of the original additive. The final decomposition product, phosphate, starts to appear in this used oil about one-third into the lifecycle. It was shown to grow to a steady state concentration through the remainder of the oil lifecycle.

As with the ZDDP chemistry, the phosphorous chemistry of gear oil is also best analyzed by ^{31}P NMR (Figure 8). This figure shows two spectra, one of the new oil and one of the used oil. Between the two samples, new and used, there are phosphorous additives that have depleted (components E, D and C), while there are components that have change or been added to (component B and F). Quantitation of these changes in additive concentration can be related to the performance of the oil.

Base number, or BN, of the used oil can provide the analyst with information about the detergent and dispersant. As discussed earlier, the detergent contains reserve-carbonate to react with the acids being introduced into the oil. The BN from this carbonate is a direct measure of the concentration of this carbonate - the base reserve of the oil. The carbonate can also be measured from the FTIR spectrum (Figures 2 and 9).

Depending upon the analyst, there has always been some disagreement in whether one should analyze used oils with the strong acid-BN (ASTM D2896) or the weak acid-BN (ASTM D4739) method. The reason for the disagreement is that the strong acid-BN method measures both the carbonate from the detergent and a portion of the dispersant's polar head-group, while the weak acid-BN method only measures the carbonate. This difference in the methods is of value to the analyst wanting to measure the concentration of this dispersant head-group itself. Since the carbonate reacts equally with both the strong acid-BN method and the weak acid-BN method, the difference between these methods can be a measure of the dispersant head-group concentration. Like with the infrared response, if one knows the BN response to the different methods - an absolute concentration can be measured. Otherwise, a

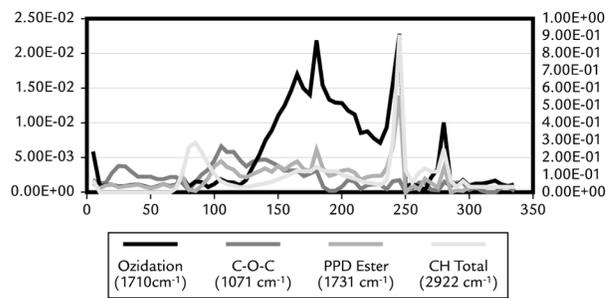


Figure 12. LC-IR Reconstructed SEC Chromatogram

trending change will give the analyst a determination of a change in the dispersant head-group concentration with use of the lubricant (Figure 10). This example shows that the dispersant's head-group was lowered near the end of this oil's lifecycle.

In addition to the head-group, the dispersant's hydrocarbon helps to determine how effective it is in suspending contamination products. If this tail is oxidized to a shorter chain length, the same concentration of dispersant will not suspend as much material. If used oil exhibits sludging due to overloading of the dispersant system, the concentration of the dispersant is lowered by entrapment in the sludge - compounding the problem. Figure 11 shows the results from two-used oil - one of the used oils (series-1) exhibited loss in dispersant tail from oxidation starting just after about 2000 miles and continued to decrease throughout the oil's lifecycle. The other (series-2) had no significant dispersant tail group reduction problems until a small decrease was observed at the end of the lifecycle. One will note that the significant lowering of dispersant concentration caused sludging problems in series-1. Series-1 was an extreme duty-cycle gasoline engine, while series-2 was a mild duty-cycle diesel engine.

The hydrocarbon chains on VI improver (VII), pour point depressant and base oils all have similar infrared spectral features. To analyze these components, one needs to consider the use of a chromatographic separation technique linked to the infrared analyses. An effective interface between a SEC separation system and an infrared spectrometer is provided by the LC-Transform®. The LC-Transform® is a two-part system: a sample deposition system interfaced to the chromatograph and a sample measurement stage that interfaces to the FTIR. In the chromatograph, the system deposits the effluent from the chromatographic column directly on an infrared optical medium - a germanium disk. Within the LC-Transform®, the column effluent is sprayed on a rotating sample collection disk. The solvent is evaporated at the point of deposition. The rotation speed of this disk is critically controlled as a function of angle. This permits a known correlation between the chromatogram's retention time and the disk rotation angle, expressed in degrees. The disk is then located on the measurement stage and an infrared spectrum is recorded for every degree of

disk rotation. This allows an infrared spectral reconstruction of the SEC chromatogram to be performed for any defined infrared frequency (Figure 12).

These reconstructed chromatograms can in turn be correlated to specific chemical functionalities within the separated species. For the example in Figure 12, four different infrared absorption bands were plotted. From the reconstructed chromatogram, one can determine the molecular weight distribution as a function of the infrared spectral peaks studied. The chromatogram is plotted from high molecular weight on the left to low molecular weight on the right. Studying this particular example indicates that a high molecular weight, un-functionalized hydrocarbon component is eluted with the molecular size corresponding to about 80-degrees of disk rotation . . . this sample correlates to the molecular weight of the viscosity index improver. Figure 13 shows an overlay of this area for both the new and used oils.

In this figure, the top spectrum is from the new oil and the bottom spectrum is from the used oil. One can observe that both spectra are of an un-functionalized olefin copolymer (OCP) viscosity index improver (VII). By comparison of the peak intensities, one can also observe that the concentration of the VII in the used oil is less than that in the new oil and can be quantitated from these spectra.

Continuing the study of the chromatograms featured in Figure 12, one can observe an ester carbonyl compound that elutes at about a 105-degree rotation. This is the molecular weight region for the pour point depressant. The spectra from this fraction, Figure 14, indicate the presence of a non-dispersant polymethacrylate pour point depressant.

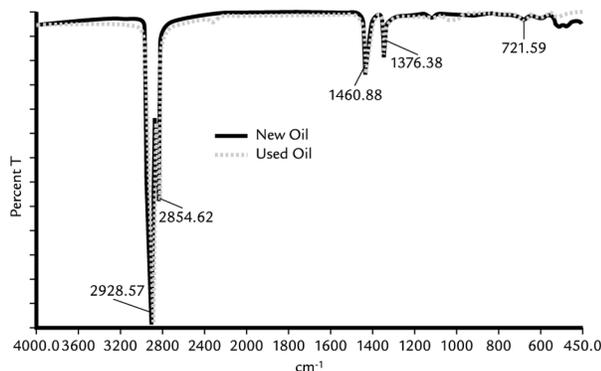


Figure 13. LC-IR 80-Degree Rotation Spectrum - New and Used Oils

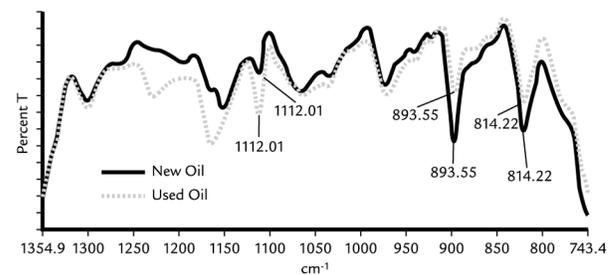


Figure 15. FTIR Spectra of New and Used Gear Oil Samples

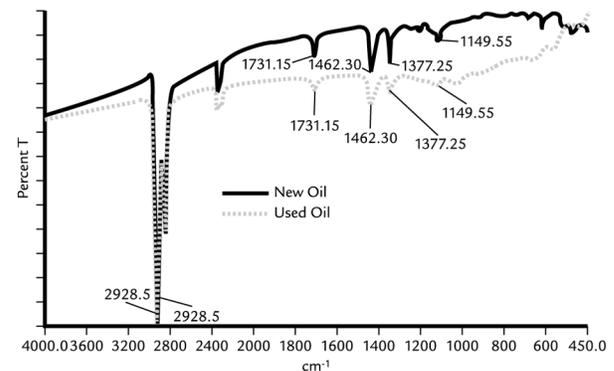


Figure 14. LC-IR 105-Degree Rotation Spectrum - New and Used Oils

Again, in this figure the new oil spectrum is presented as the top spectrum. The lowering in spectral intensity of the used oil indicates the decrease in component concentration in the used oil.

Putting these two pieces of information together can tell the engine operator that there was indeed shear-down of both the VI improver and the pour point depressant during use. If the oil's viscosity had decreased, the additive's stability would be the probable cause. If it had increased, that increase would be compounded by a reduction in the effective performance of the VI improver, making the problem more severe. If the oil were having low temperature gelation problems, this would be correlated to the reduction in concentration of the pour point depressant.

As a final example, one can study the infrared spectra of new and used gear oil (Figure 15). The changes in the phosphorous chemistry are very hard to observe in the infrared spectra. Most gear oils do not exhibit large oxidation degradation. However, there are significant observable changes in the extreme-pressure/antiwear additive (sulfurized isobutylene).

The infrared absorption bands associated with sulfurized isobutylene (1112, 893, and 814 cm^{-1}) are identified for the new and used oil in the figure. The concentration of this important additive is shown to decrease during the gear oil's use and can be quantitated through this approach. A decrease in SIB concentration can relate to product failure.

Conclusions

In conclusion, the used oil chemistry is very extensive. There are many reactions occurring to both produce new components as well as destroy the formulation additives. Some of the new used oil

components are a result of the depletion reactions of the formulation additives, while others help to destroy the additives. Knowing this information, the analyst has the ability to extend or modify the analysis scheme to study the formulation additives. This extension is the next step in understanding the interaction between the lubricant and the equipment it is designed to protect

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Lubricants 101 - Fundamentals of Lubrication

By DAVID COMO - DOW CORNING CORPORATION

Billions of dollars are spent each year to repair damage from mechanical wear in U.S. factories caused by surface degradation, including mechanical wear and fatigue. In this paper, which is focused primarily on grease and oil lubrication, you will learn the fundamentals to help increase equipment uptime, reduce mechanical wear and equipment failures and apply maintenance budgets more effectively for prolonged equipment life. Included are a discussion of tribology (the study friction, wear and lubrication), types of lubricating conditions, forms and types of lubricants and additives and their comparative properties.

Introduction

Proper lubrication is critical to a machine component's function and longevity. Understanding of lubrication fundamentals, application details and available lubricant types are key to success in specifying and using lubricants. Simply crossing over lubricants, substituting one supplier's product for a similar one from another supplier, can be a recipe for disaster. Instead, the specification of the right lubricant for a given application should be based on a long, hard look at both the surfaces to be lubricated; how and why they might be affected by improper lubrication; and the range of lubricants appropriate for them.

The need to carefully match the lubricant to the application is a serious one. It was estimated by Ernest Rabinowicz of the Massachusetts Institute of Technology (MIT) that damage due to mechanical wear amounts to six to seven percent of the U.S. gross national product in repair costs on an annual basis. The cost is in the billions of dollars when combined with the costs related to friction both in the industrial and consumer segments. Overall, the cost of friction is slowing the wheels of industry.

LET'S Solve the Lubrication Problem

When addressing a lubrication problem or specifying a lubricant for a given application, it is important to know as much as possible about the conditions of the application and, as a minimum, the approximate load, environment, temperature and speed (LETS) of the components to be lubricated. Even if these values are approximations, there must be consideration given to each area. These factors are easily remembered by recalling the mnemonic, "LET'S solve the lubrication problem." And it cannot be stressed enough to avoid simply crossing over to a product from another supplier if possible. It may well be that the original material was not properly specified to begin with, so a fresh look can save a great deal of time and money.

Lubricant Functionality

The basic functionality of lubricants includes the following:

- Reduce wear
- Reduce or control friction
- Carry away heat
- Transmit power

- Seal out dirt and contaminants
- Prevent oxidation and corrosion.

The first two, reduction of wear and friction, are what most people consider the primary job of lubricants, but the other functions have important applications in most industries.

Tribology

Tribology helps focus the LETS factor by bringing to bear the physics, dynamics, statics, fluid power and chemistry at work in a given application. All are melded together to express and predict the effects of friction, wear and lubrication, and how they interrelate to affect the world we live in.

Dynamic applications that we take for granted in every day life are affected in some way by their inherent or induced tribological characteristics - from the cars we drive, to the processing of the food we eat, to the sports we enjoy. For example, there would be a profound change in performance if the air drag on a golf ball or the friction coefficient between the ice and a hockey player's skate blade were to be reduced by even 10 percent.

At the heart of the equation is lubrication, defined as the use of any material between contact surfaces of moving parts to reduce friction. Contact surfaces abound, even on the most polished of mating interfaces. Under a microscope, an apparently perfectly smooth finish resembles jagged peaks and valleys (Figure1).

Figure 1 captures the essence of what we seek from the ideal lubricating medium. The lubricant, completely separate from the interacting surfaces, eliminates the interaction between the asperities

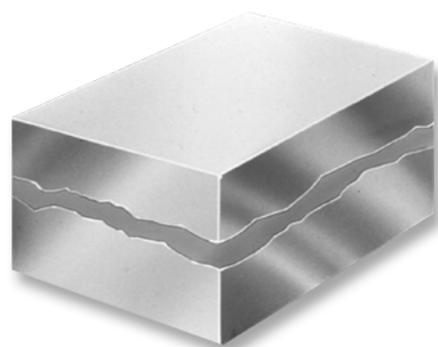


Figure 1. Section of Two Contact Surfaces at High Magnification - Note Peaks and Valleys Separated by Lubricant

of one surface from the other and controls the friction. These could be the surfaces of a ball and race in a moving element or journal bearing, a disc on an air hockey table, or the tires of a car separated from the road surface by a film of water as it hydroplanes without the help of friction to regain control and slow down. The last example illustrates that the total elimination of friction is not always the objective. Sometimes the purpose of lubrication is actually to maintain friction control.

Reduction of friction directly reduces potential heat, wear and power requirements. Without lubrication, contact surfaces greatly accelerate the effects of Newton's third law - For every action, there is an equal and opposite reaction, or simply put, as long as there is motion, there will be forces working to counter that motion. Friction is one of those reactions.

Lubricating Materials Take Many Forms

Not all lubricating mediums are necessarily conventional greases and oils. An abbreviated list is as follows:

- Gases
 - Air
 - Nitrogen
- Solids
 - Graphite
 - TFE, PTFE (Teflon®)
 - Molybdenum disulfide (MoS_2 , "Moly")

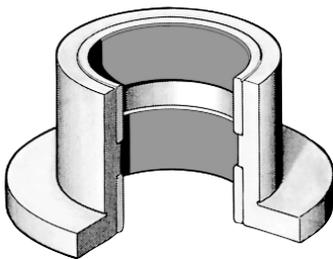


Figure 2. Sleeve Bearing Presents a Hydrodynamic Condition to the Shaft Running In It; A Film of Lubrication Separates the Shaft From the Bearing Surface - At Speed

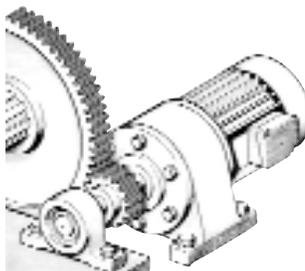


Figure 3. Boundary Conditions Predominate on Low Speed Open Gears

- Liquids
 - Water
 - Oils (petroleum)
 - Fluids (synthetics).

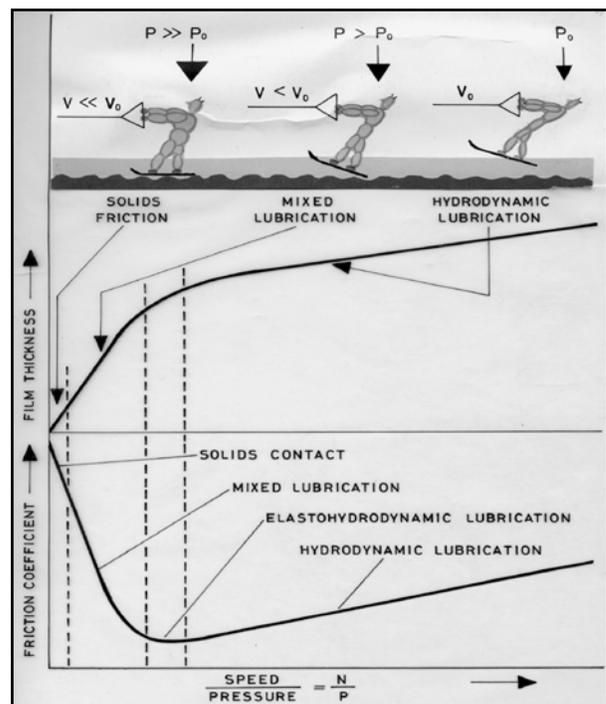
Though invisible and not very intuitive, gases are common lubricating materials, in applications ranging from air hockey tables and gas bearings to equipment-moving air pads and, perhaps, even hovercraft. Likewise, many solids act as lubricants. In fact, in certain cases, even sand can act as a lubricant, as on a shuffleboard table or under a motorcyclist's front tire in a high-speed turn. The liquid form of lubricating material includes just about anything from water to various petroleum-based oils and synthetic fluids. There is further discussion on these later.

Lubrication Conditions

There are three common conditions of lubrication, as follows:

- Hydrodynamic: Surfaces are separated by an oil film, typically occurring at high speed and/or low load;
- Boundary: Surfaces interact with little or no oil film separation, typically occurring at low speed and high load; and
- Elastohydrodynamic: Both boundary and hydrodynamic conditions coincide.

The elastohydrodynamic or mixed condition commonly occurs in rolling element bearings.



Top: Model of Water Skier / Middle: Film Thickness / Bottom: Friction Coefficient (Stribeck Curve)

Figure 4. Model of Lubrication Regimes Depending on Speed and Pressure

Hydrodynamic Condition

Hydrodynamic lubrication is an ideal lubricating condition in which the interacting parts are separated by a lubricating film that keeps nearly all asperity interaction from taking place (Figure 2). Under this condition, there is minimal generation of wear particles. Hydrodynamic lubrication typically occurs at higher speeds and/or lower loads and shows a minimal amount of wear. An example is the journal bearings on the crankshaft of an automobile that has reached a steady-state rotational speed or the conditions that exist between the tires and the road surface of the vehicle mentioned earlier, out of control in the rain and headed for a ditch.

Boundary Conditions

Boundary conditions, in contrast, occur at high loads and/or low speeds. In this condition, the surface asperities of the mating parts will collide without specialized lubrication designed for extreme pressure (EP) conditions. In automotive terms, this condition can occur in high-contact pressure areas in an engine, such as at the valve-cam or pushrod interface, particularly during cold starts. Other examples: low-speed open gearing (Figure 3) or a highly loaded drive chain.

Elastohydrodynamic Condition

Elastohydrodynamic or mixed conditions are in a realm between those previously mentioned. These are the conditions at the micro contact area between a rolling bearing element and a race. The race

surface or element is elastically deformed as the element passes, and the resulting increased surface area allows a pressure wave of lubricant to form that (though very thin) is sufficient to separate the moving parts. Depending on the specific parameters of the application, elastohydrodynamic conditions can result in low wear. These lubricating regimes are illustrated in Figure 4 by a familiar application - that of a water skier - and the associated film thickness and Stribeck curve conditions. As velocity increases, the lifting hydrodynamic force exceeds the load, the figure is lifted off the lake bed.

Putting the Conditions Together

Table 1 captures the key parameters of the three conditions outlined above.

Lubricant Product Forms and Materials

Lubricants of various states (in this case, from solids to liquids) are supplied commercially as greases, compounds, pastes, dry film lubricants, and oils or dispersions.

Greases

The function of the oil or fluid in a grease is to provide the primary lubricating agent. The thickener system forms the grease, giving it body to enable it to stay in place and to tie up or hold the fluid portion in suspension. Additives are used in the formulation to impart specific properties, such as oxidation or corrosion resistance, acid inhibition, wear reduction, friction modification, extreme pressure or load-carrying capacity, color and the like.

Condition	Examples	Characteristics	Oil Film Thickness	Wear (In Steady Operation)
Hydrodynamic	Journal Bearings, Engine Rod and Main Bearings	Surfaces Separated by Oil Film	0.001 - 0.003 in. (0.00254 - 0.0762 mm)	Nil
Boundary	Heavily-loaded Gears, Engine Valve Train	Surfaces Separated by Films of Molecular Dimensions	0.08 - 0.4 micro in. (0.000002 - 0.00001 mm)	High During Run-In, Moderate to Low Thereafter
Elastohydrodynamic	Ball Bearings, Lightly-loaded Gears	Surfaces Separated by a Thin Oil Film, Contacting Surfaces Elastically Deformed	10 - 50 micro in. (0.00001 - 0.00127 mm)	For Properly Lubed and Finished Surfaces; Very Low

Table 1. Key Parameters of the Three Conditions of Lubrication

Type	Water Resistance	Mechanical	Temperature Properties	Temperature Limit, (°C)	Oxidation Stability	Relative Cost
Calcium Soap	High	Superior for Extreme Pressure (EP)	Low = Fair, High = Very Poor/Unstable	175	Poor	\$
Sodium Soap	Very Poor (Equal to Hand Soap)	Fair	Low = Poor, High = Good	135	Good	\$
Lithium Soap	Good	Good	Low = Good High = Good	175	Good	\$\$
Barium Soap	Fair	Fair	Low = Poor High = Good	120	Poor	\$\$
Complex Soaps	Excellent	Fair to Excellent	Low = Varies, High = Varies	Varies (Typically adding 5° - 10°C)	Excellent (Except Barium-Based)	\$\$\$

Table 2. Comparison of the Most Common Thickening Agents in Greases

The fluid or oil is typically the key temperature-limiting factor in the grease formulation, as its maximum temperature is usually reached before that of the thickener or additives. The thickener is usually a secondary temperature-limiting factor, as most thickeners liquefy above a certain temperature (the drop point is discussed below) and thus, no longer provide body or suspension properties.

Thickening Agents

The thickening agents typically used to form greases deserve their own scrutiny, because they affect such properties as water resistance, pressure capabilities and temperature performance. Table 2 summarizes the most common types.

Note that the barium soaps, while they provide superior heat and water resistance, tend to harden with age, are hard to pump (limiting their use in automated systems) and bring heavy-metal health and environmental concerns.

In Table 2, complexing agents such as short-chain organic acids or inorganic salts are added to base soaps to bolster one or many properties, such as heat or water resistance.

There are also nonsoap thickeners, with temperature limits well above soap types - upward of 500° F (260°C). Each nonsoap thickener has its own unique advantages and disadvantages. The most common are the following:

- Clays
- Polytetrafluoroethylene (PTFE)
- Polyurea
- Silica
- Carbon Black.

In addition, there are rarely used thickeners that are beyond the scope of this paper, as they are not commonly found in industrial grade greases.



Figure 5. Grease is Very Useful for High Pressure Applications Such As This Large Pump Bushing

Base Oils and Fluids

Table 3 compares the primary factors of the most common types of lubricating oils and fluids.

Note the following about Table 3:

- Additive acceptance is defined as the ability to solubilize or otherwise synergistically perform with additive packages.
- Viscosity index (VI) is a measure of how little a given fluid's viscosity is affected by temperature (so that if a fluid has a rating of excellent, it means that the fluid's viscosity change is comparatively minimal).
- The compatibility of lubricating oils and fluids with engineered plastics and elastomers and rubbers is increasingly important, because these materials are increasingly specified for a variety of machine and engine components.
- Ballpark pricing is meant for comparative purposes only.
- The high end of the PFPE range includes ultra-pure linear materials that provide lubrication at extremes of temperature, vacuum or oxidizer exposure. With a density nearly twice that of the other materials, a drum can cost tens of thousands of dollars.

Synthetics are especially suited for applications with temperature extremes (Figure 6).

Oil Formulations and Dispersions

Oil formulations typically include a base oil of appropriate viscosity and viscosity index (VI), flash point/evaporative and pour point properties, along with synergistic additives. These additives enhance the properties of the base oil, such as oxidation, corrosion or wear resistance, extreme pressure behavior, viscometrics and so on. Dispersions add solid materials to the equation, typically solid lubricants. The dispersion holds the solid and liquid components in a suspension or solution that is generally tuned to a specific



Figure 6. When Temperatures Are Extreme, Synthetic Formulations Work Best

application. These include applications that require the fluid to carry the solids to penetrate into the machine component, to aid in coating the lubricant on a surface, or to help disperse it in another lubricating medium as an oil additive carrier.

Lubricating Solids

The most common lubricating solids are the following:

- Graphite
- Polytetrafluoroethylene (PTFE)
- Molybdenum Disulfide (MoS₂ or Moly)
- Others:
 - Waxes
 - Phosphates (White solids)
 - Metals (zinc, nickel, copper, etc.)
 - Organic Moly.

Each lubrication solid has its own specific advantages and disadvantages. For example, while molybdenum disulfide has the highest load-carrying capacity, it sublimates around 450°C. Graphite also has a good capacity for load and goes to greater temperatures (higher than 500°C); however, it needs moisture to lubricate effectively and therefore has problems in high vacuums. PTFE has great frictional properties but is not good at extreme loads - and, of course, is comparatively expensive.

Pastes

Pastes are like greases, but are designed for different applications. Unlike greases, in which the base oil is the principal lubricating agent and the thickener serves to keep it in place, the opposite is true in pastes. That is, the solids are the primary lubricating agent and the oil is there to keep the solids in place. A solid lubricant is

not effective in lubricating interacting surfaces if it drops onto the floor under the machine or blows away. Consequently, the fluid portion of the lubricating paste is needed to deliver the solid lubricant to the contact area and to keep it there until it is burnished into the surface or until extreme temperatures have driven off the fluid (some solids can go 1200°C or higher). Typically, mineral oils are used as the fluid component, but synthetics are not unusual for some applications.

Formulations for pastes vary, but usually consist of 50 percent or more solid lubricant content. The solid components are typically MoS₂, PTFE, metals and the like. Pastes may also contain conventional thickeners as well as additive packages; in this way, they are again similar to greases.

Pastes are used in applications that present extremely high loads and/or temperatures at low or no speed. Specific applications include run-in of equipment, assembly aids for operations such as press fitting and - very extensively - for lubricating threaded connections (Figure 7). Pastes can also be used in valve packings, seats and stems; on flanges, studs, ways and guides; chains, open gearing, automotive brakes and hubs; or anywhere that calls for help in assembly or future disassembly or slow speed, high-load applications.

Silicone Compounds

We refer to dimethyl silicone materials typically thickened with silica as silicone compounds, so named to prevent confusion with and application as lubricating greases. Silicone compounds can be thought of as noncuring sealants or room-temperature vulcanizing materials (RTVs) because that's basically what they are, minus the crosslinking chemistry that turns RTVs into rubber. Silicone compounds are great lubricants, sealants and dressings for plastic and elastomeric O-rings, seals, gaskets and belts (Figure 8). However, they are not meant for use as lubricants for metal-to-metal contact. They can also cause softening and property loss when applied to silicone elastomers as they act as diluents for the elastomers.

Type	Temperature Range °F (°C)	Additive Acceptance	Viscosity Index	Compatibility With Plastic and Rubber	Ballpark Price Point \$/Pound
Mineral	-31° to 302° (-35° to 150°)	Excellent	Fair	Fair	< 5
Polyalkylene Glycols (PAG)	-49° to 347° (-45° to 175°)	Excellent	Good	Good	< 5
Polyalpha Olefins (PAO)	-76° to 392° (-60° to 200°)	Good	Good	Very Good	5 - 10
Ester	-49° to 392° (-45° to 200°)	Good	Good	Fair	10 - 20
Silicone	-103° to 392° (-75° to 200°)	Poor	Excellent	Very Good	10 - 20
Fluorosilicone	-40° to 482° (-40° to 250°)	Poor	Very Good	Excellent	50 - 75
Perfluoronated Polyether (PFPE)	-76° to 572° (-60° to 300°)	Poor	Fair	Excellent	75 - ?

Table 3. Key Factors of Base Oils

Many silicone compounds comply with U.S. Food and Drug Administration (FDA), U.S. Department of Agriculture (USDA) and/or National Sanitation Foundation (NSF) specifications for food and potable water applications, reflecting the fact that they are considered safe for sensitive uses. They also tend to have excellent dielectric properties that suit silicone compounds for use in a wide range of power generation, automotive and electronic applications.

Antifriction Coatings

Antifriction (A-F) coatings are suspensions of solid lubricants (for example, MoS₂, graphite, PTFE and the like) with very small particle size resin binders, such as epoxy, phenolic and the like. When cured, A-F coatings form dry, paint-like films that lubricate and provide corrosion protection where the use of a wet oil-based lubricant is impractical. Also known as bonded lubricants or dry film lubricants, antifriction coatings are formulated to act as lubricating paints. A-F coatings are also used with conventional lubricants where run-in protection, friction and/or noise reduction, or where increased EP or start-up protection is desired. Typical applications include exposed gearing and chains (Figure 9), low-speed bearings, automotive pistons and valve trains, farming and excavating equipment, power tools and tooling. These are generally characterized by low speeds and high loads; dirty or dusty environments; oscillating movement (to prevent fretting or galling); and long-term corrosion protection. A-F coatings are increasingly specified where heavy-metal coatings such as cadmium plating were used in the past, as on threaded fasteners.

Depending on the application requirements, a variety of resin binders can be used, including organic or inorganic types. An inorganic material might be selected for use in corrosive or highly oxygenated environments. A polyamide may be preferred when oil or chemical resistance is required or polyurethane where flexibility is a concern. Synergistic solid lubricants and additive packages - such as anticorrosion components, viscosity modifiers, or colorants - are also critical for many applications, as is a solvent base that is acceptable for the application equipment, its operators and the application environment.

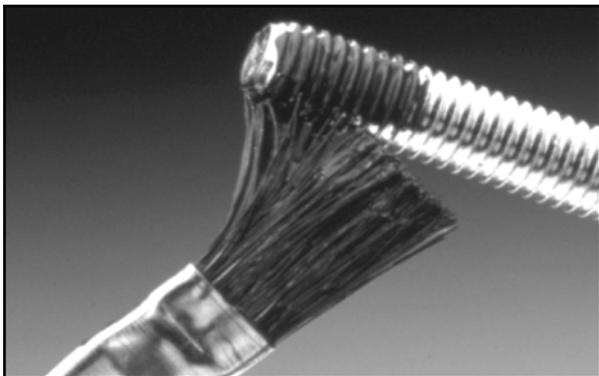


Figure 7. Pastes Are Useful For Assembling Threaded Connections to Prevent Galling or Seizing

Lubricant Properties and Terms

There are a number of lubricant properties that play important roles in the LETS (load, environment, temperature and speed) equation discussed at the beginning of this paper. Following is a glossary of key properties to be found on lubricant data sheets. Most focus on one or two of the LETS factors. Several of the properties occur in pairs; these are designated with brackets. Each property or pair of properties is followed by a brief discussion.

- Flash Point (Temperature; Safety): The lowest temperature at which a fluid gives off vapors that will ignite when exposed to an ignition source.
- Fire Point (Temperature; Safety): The lowest temperature at which the fluid's vapors will ignite and continue to burn for at least five seconds.

The basic difference between these first two is that, while flash point indicates when, as you raise its temperature, a fluid's vapors will ignite instantaneously, fire point indicates how hot the fluid needs to be before it will support a flame on an ongoing basis. In North America, the line between flammable and combustible fluids is drawn at 100°F (37.7°C), an important threshold to consider if you are specifying a penetrating oil or carrier fluid for a lubricant and have flammability or shipping concerns.

- Viscosity (All LETS Factors): The physical property of an oil or fluid that produces internal resistance to flow.
 - Kinematic viscosity: Measured as the time required for a given amount of fluid to flow through a certified capillary while a pressure head is allowed to drop (expressed as centistokes, cm²/sec).
 - Absolute viscosity: Measured as the time required for a given amount of fluid to flow through a certified orifice under a constant pressure head; can also be measured by a shear disk viscometer (expressed as centipoises, dyne-s/cm²).
 - Saybolt Universal (SUS, SFS) method: Similar to the absolute method without the constant pressure head.

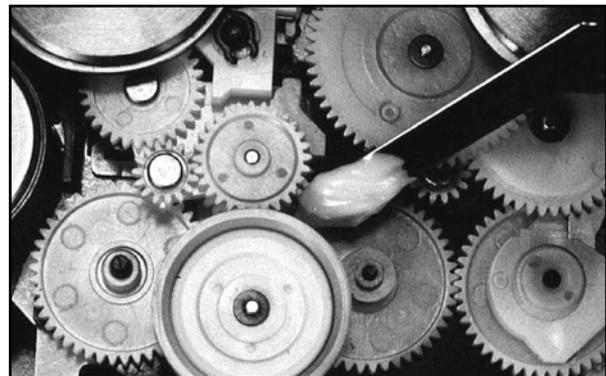


Figure 8. Silicone Compounds Are Ideal For Lubricating Plastic Gear Trains

The trend is toward kinematic and absolute measures expressed in SI units, though the Saybolt method is still popular in the petroleum industry. The Saybolt method is almost a cross between the kinematic and absolute methods in that it is run at atmospheric conditions similar to the kinematic, but incorporates an orifice like the absolute. It is important to note that test values are derived at temperatures specific to their method - the Saybolt method is almost always run at 100°F and 210°F, while the other methods can be run and reported at various temperatures, but typically (in SI) at 25°C, 40°C and 100°C. A couple of degrees either way can make a noticeable difference in the results, so be sure that the values for the lubricants under comparison are the results of tests using the same basis.

Specifying the right lubricant is a balancing act between sufficiently heavy viscosity to keep a lubricant boundary in readiness for a cold start on one hand and sufficient fluidity to avoid viscous drag or frictional losses once equipment is up to speed.

- **Viscosity Index (All LETS Factors):** The VI indicates the rate of change of a fluid's viscosity with temperature.

Viscosity index is a critical property to consider in a lubricating fluid if the application has temperature extremes, because VI indicates how sensitive the fluid is to viscosity changes with temperature - both high and low. While mineral oils exhibit rather low VIs (less than 100), some silicones exhibit VIs as high as 400. A high VI value indicates that the fluid has less tendency to thin with increasing temperature or thicken with cold.

- **Bleed (Temperature and Environment):** In a grease or solid compound, the separation of oil from thickener.
- **Evaporation (Temperature and Environment):** That portion of the lubricant that volatilizes at a specified time and temperature.

Bleed is used to describe the tendency of the lubricating oil to separate from a grease or compound. Some separations are necessary in a lubricating grease, because the oil performs the lubrication, the thickener being there simply to keep the grease in place in the application.

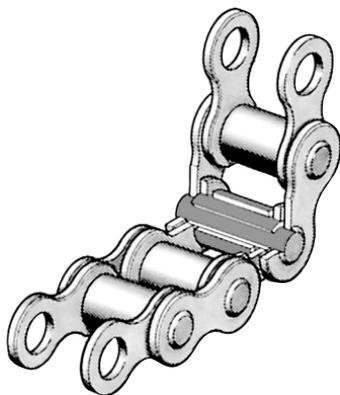


Figure 9. Chains Benefit From Antifriction (A-F) Coatings

Bleed is described in terms of percent and is measured at various temperatures - depending on the base oil type. The downside of bleed in a lubricating grease is that the oil may migrate in the application, which may not be desirable. Plus, if the compound is stored improperly, the oil may separate leaving puddles in the grease that will need to be stirred back in prior to use.

The rate of evaporation of the base oil gives an indication of the temperature capability of that base oil and its probable longevity at higher temperatures.

Bleed and Evaps, as the tests are known, are conducted anywhere from 100°C to 200°C, typically over 24 hours and are expressed in percentages.

- **Pour Point (Temperature):** Lowest temperature at which a fluid will pour from a container.
- **Freeze Point (Melt Point) (Temperature):** Lowest temperature at which the fluid begins to transform from a solid to a liquid phase.

Pour point and freeze point are similar properties, coming from opposite directions on the temperature scale. Typically, they show different values. Pour point is of most common interest in helping to determine the ability of a lubricating oil or fluid to withstand low temperatures without solidifying.

- **Dn Value (Speed):** The product of the bore size (root diameter outside the Americas) of the bearing (mm) times the rotational speed (rpm); Dn value is an estimate of the speed capability of a grease.

Example: If a 2-inch ID bearing runs at 5000 rpm:

$$Dn = 50.8\text{mm (2 in.)} \times 5000 \text{ rpm} = 254,000$$

The Dn value takes into account the size of the components involved. A 10-inch shaft and bearing in an application will have a different effect on a lubricant than a micro bearing. Dn values for greases are typically both estimated and dimensionless, but are nevertheless useful for gauging the performance of the lubricant at its application speeds and dimensions.

NLGI Number	ASTM Worked Penetration (mm/10 @ 25°C) ASTM D-217
000	445 - 475
00	400 - 430
0	355 - 385
1	310 - 340
2	265 - 295
3	220 - 250
4	175 - 205
5	130 - 160
6	85 - 115

Table 4. NLGI Numbers Expressed as ASTM Worked Penetration Values

- Dropping Point (Temperature): The temperature at which a drop of material falls from the orifice of a test apparatus under exposure to rising temperature.
- Channeling (Temperature): The tendency of a grease to form a channel in a high-speed bearing, leaving shoulders of grease on the sides to act as lubricant reservoirs and as a seal.

The dropping point of grease is an indication of the temperature capability of the thickener - the point at which it melts and releases the base oil from the thickening matrix. It is measured in a thimble-like cup with an orifice at the bottom that is gradually brought up in temperature until a drop of oil falls from the cup. This value is NOT the high-temperature capacity of the grease (as many suppliers will allude) - that capacity is primarily determined by the base oil itself.

The channeling of a lubricating grease is important if the grease is to be used in a high-speed application where it is important that the grease vacate the flight path of the moving elements of the bearing, but still provide adequate lubrication to those elements. Excessive tenacity of a grease and its presence in the bearing race in these applications can cause enough friction and heat from viscosity and/or particles to prevent effective high-speed operation and could lead to failure from overheating.

- Penetration (Temperature and Environment): The depth, in tenths of a millimeter, that a standard cone sinks into a material under prescribed conditions of weight, time and temperature.

Penetration is usually expressed as National Lubricating Grease Institute (NLGI) numbers. Although it is a rather archaic test, it remains the standard for the industry for measuring the consistency or thickness of a grease.

Most common greases fall into the midrange of the table and are listed as NLGI 1 (310 to 340 mm/10), NLGI 2 (265 to 295 mm/10), or NLGI 3 (220 to 250 mm/10) greases, and many penetration specifications cross over these ranges.

Conclusion

This paper has surveyed the world of lubrication on the premise that careful specification of lubricants, in what is often a wide-ranging array of applications for even a modest industrial setting, will save money in the long run. To understand proper lubrication specification and application, one must start with an understanding of tribological fundamentals. Nothing replaces the thorough understanding of the application in terms of load, environment, temperature and speed for proper lubrication specification. Familiarization with the types of lubricants and how they are designed gives greater depth to the specification and use of the best lubricant for the application. Above all, keep in mind that the specification or use of an improper lubricant will lead to premature component failure - and take the time to specify the right material for the purpose.

Reference

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Selecting a General Purpose Grease Without Compromising Performance

By MIKE JOHNSON – NORIA CORPORATION

Large production facilities have a variety of grease-lubricated equipment, ranging from steady-state applications to applications that vary significantly in speed and load, and operate in aggressive (wet or dusty) environments. If machine designers address equipment lubrication needs based strictly on a dynamic loading requirement, they might have to specify a wide variety of greases to meet the many existing needs. In this approach, the added system complexity would likely increase the cost and the risk of failure due to misapplication and cross-contamination.

To maximize grease lubrication effectiveness, minimize cost and minimize risk of application-induced failure, lubricant manufacturers have made an effort to formulate greases that cover a variety of applications. These greases range from slow to high speeds, and from low to high loads, in an effort to provide a single product to meet a multitude of requirements. The result is general purpose grease.

What is General Purpose Grease?

A general purpose (GP) grease is designed to meet a broad range of requirements. It is grease manufactured to medium consistency with a medium viscosity base oil and medium wear, washout and oxidation resistance properties. Essentially, it is a product designed to fit the largest possible cross-section of grease lubricated components in an operation.

If the demand on the lubricated components in a plant could be rated on a curve according to speed, load and environment/application severity, the resulting curve would likely resemble a Pareto chart. The typical application in most plants does not severely challenge a GP grease. Some applications would be considered tough, and may or may not be suitable for a GP grease. A few extreme applications will require a grease with one or more special qualities. The proportion of typical, tough and extreme applications might vary considerably.

This distribution has no correlation to the criticality of the mission of the grease-lubricated machines. Many of the tough and most of the extreme applications will require a

thorough technical review to determine what special lubricant properties might be required. Lubricant criteria are fairly narrow at the extremes of load and speed, and therefore may require products that do not suit the vast majority of lubricated components.

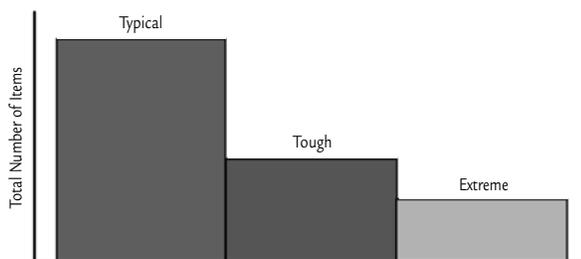
However, it is advisable to cover as many of the lubricated components as possible with as few products as possible. With this in mind, begin by examining the lubricated components for an average requirement and work selectively toward extremes in load and speed.

Equipment Properties to Consider

Given the wide range of characteristics that may exist in the greases at any given plant, it is best to first characterize the equipment and plant conditions, then select a grease to meet the conditions.

Equipment Condition Considerations

Keeping the objective in mind, a general purpose (GP) grease is used as a multi-application grease in a production



- Typical - These machines/components are average. Usually, most machines fall into this category and are good candidates for GP grease.
- Tough - These machines/components are challenged by the environment but are probably good candidates for a GP grease. These machines deserve some thought and investigation to ensure that a GP grease will work. Special attention should be paid to the application method and frequency.
- Extreme - These machines significantly challenge the lube. GP products may not fit the bill. Specialty lubricants may be required to deal with the specific extremes of the application.

Figure 1. Typical Distribution Curve

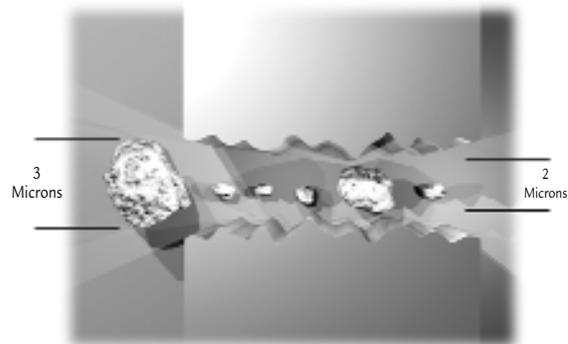


Figure 2

process to reduce complexity and the potential for component failure due to misapplication. Consider the following operational characteristics when selecting the GP grease.

Size and Type

Ball screws, cables, linear bearings, plain bearings, rolling element bearings, slide-ways and seals are just a few of the many different component types that are grease lubricated. If sliding friction is the dominant contact type, then there may be a greater reliance on heavy viscosity oils, polymers and solid additives to support the load and provide lubricating film protection. If rolling friction is the dominant contact type, then greases with lighter viscosity base oils and minimal use of polymers, solids and antiwear (AW) and extreme pressure (EP) additives can be effectively used.

Load

As the load increases, the grease's base oil viscosity must also increase to support the load. If the majority of the components in the mill/plant environment are heavily loaded, it may make sense to use high-viscosity base oils for a general purpose product. This might be the case in a cement, steel or paper mill environment. It is not uncommon to find GP greases made from 460 cSt (40°C) and heavier oils in these types of environments.

Speed

As the speed increases or the load diminishes, the required base oil viscosity also diminishes. In operations with predominantly moderate to high-speed and lightly to

moderately loaded applications, the grease's oil viscosity would fall to an ISO 46 to 150 range. It is unusual to find highly loaded applications that also operate at high speeds that are lubricated with grease. This type of application would likely warrant special consideration and therefore fall outside this discussion.

Atmosphere

The three atmospheric factors that must be accounted for are temperature, moisture and airborne solid contaminants (particles). Although the influence of atmospheric factors can be significant, these factors are considered after the viscosity selection is complete.

The atmospheric conditions have a greater influence on the heavily loaded components than the high-speed components. Heat causes oxidation and reduces the base oil's viscosity. As the base oil's viscosity decreases, its load-bearing capability is diminished. Heavily loaded components operating at elevated temperature are susceptible to inadequate lubricant film and aggressive wear.

Water can do much the same thing to the oil film because water has very low load-bearing capability. If water is allowed into the bearing in a free or emulsified form, the film may be compromised, leading to corrosive, adhesive, abrasive and hydrogen-induced wear.

A continuous grease purge is sometimes used to prevent water and solid contaminants from entering grease-lubricated components. Because most greased components are not constantly purged, there is potential for moisture and particles to enter the component cavities through seals and fittings.

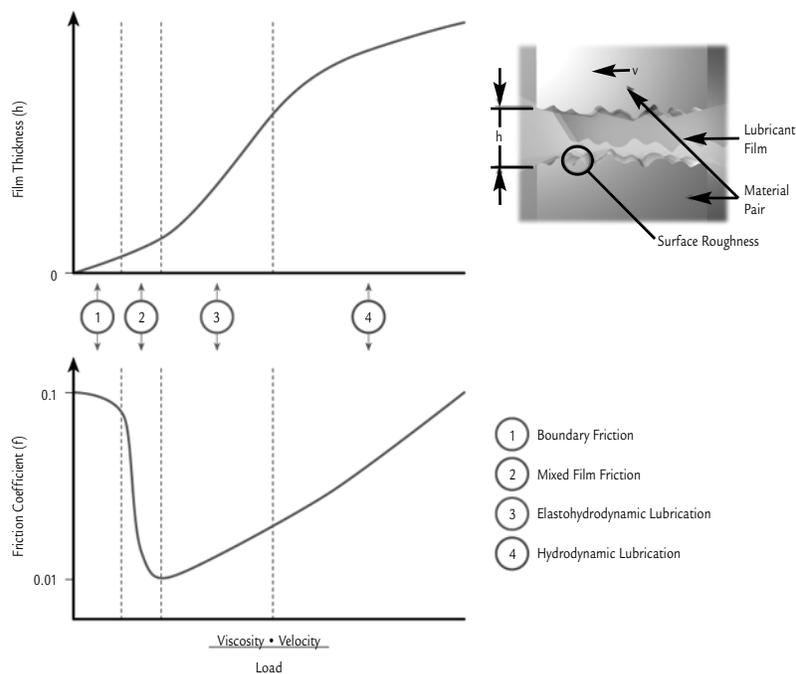


Figure 3. Stribeck Curve Diagram

Silica-laden atmospheric dust and dirt particles that enter into the load zone can scratch and abrade surfaces, generating more abrasive particles (wear debris).

The potential for particles to damage load zone surfaces increases in high-temperature and/or high-moisture applications. The combination of reduced base oil viscosity, free water and particulate at the load zone can be particularly detrimental.

Lubrication Intervals

The method of application combined with the application cycle dictates the rate of application. The rate of relubrication is the amount of lubricant fed into the component in a given time.

Greased components require a constant supply of lubricant at the load zone to sustain the hydrodynamic film much the same as oil lubricated components. The reserve grease contained in the cavity in the housing serves as an oil reservoir that components draw from for lubrication. When grease is resupplied to the housing, the oil reservoir is replenished. The longer the duration between cycles, the greater the likelihood that the reservoir will deplete and the component will run to a semi-dry (mixed film) condition.

The oil in the load zone is squeezed and pushed away over time. If the relubrication volume is insufficient, or the cycle is sporadic (greater risk with manual lubrication), the likelihood that the oil film will dissipate leading to mixed film conditions increases. When these conditions are prevalent, the grease selection must be one that resists the squeezing

action and tendency to dissipate. Greases formulated with heavier viscosity base oils and chemical and mechanical film forming additives can be helpful in these circumstances.

Lubricant Property Considerations

After gaining a thorough understanding of the conditions that the majority of the equipment operates within, consider the lubricant properties that are useful in meeting the equipment requirements.

There are a few lubricant properties that influence lubricant selection, whether GP grease, special purpose grease, oil bath or circulation lubricated applications. Oil viscosity, oxidation resistance, wear resistance and corrosion resistance certainly qualify. Beyond this, the thickener type influences the dropping point and water wash resistance, both of which play a role in the selection of a GP product. Each of these warrants a brief look.

Viscosity

Given the relationship between speed, load and viscosity, and given that the viscosity of the oil in the grease is the primary load-bearing mechanism, just as it is with oil lubrication - the first selection criteria is the grease's base oil viscosity.

Because high-viscosity oil will reduce under load (fluid friction produces heat which locally reduces the base oil's viscosity), then initially defer to the heaviest base oil viscosities the machine can tolerate and move toward

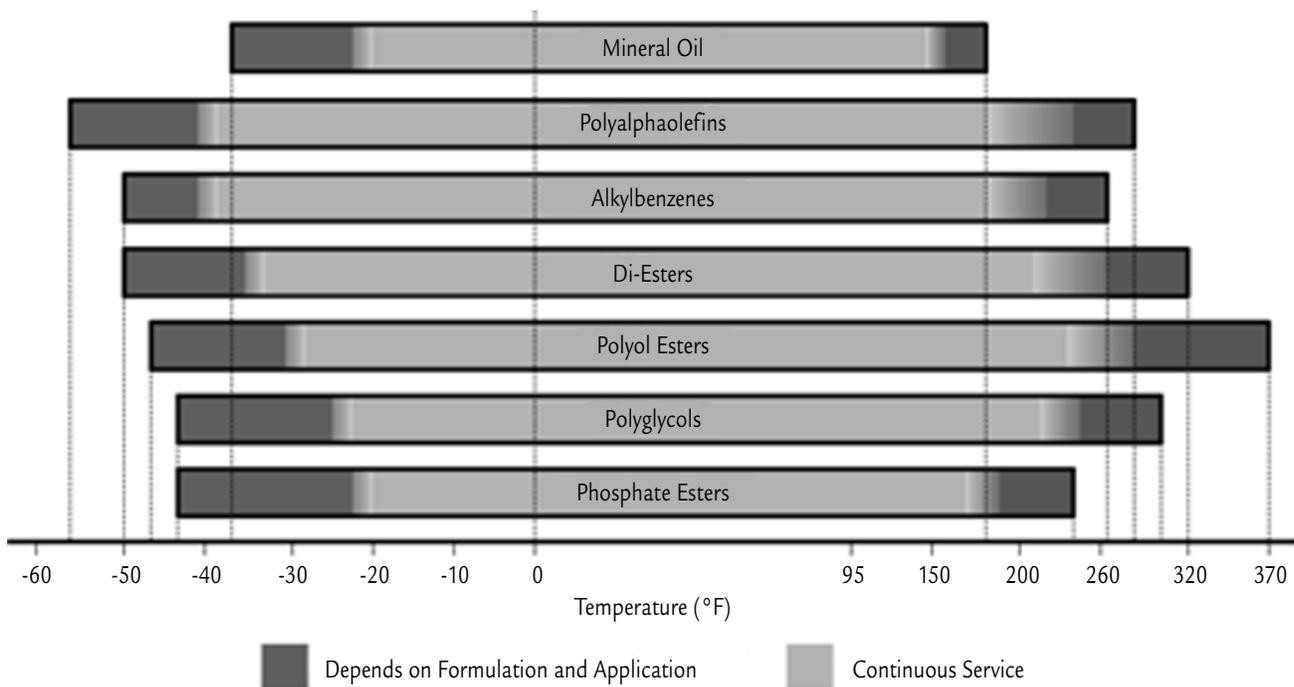


Figure 4

lighter viscosities as high-speed conditions are considered. As noted earlier, general purpose grease base oil viscosities in the ISO 460-plus range may be seen in operations running heavily loaded machinery.

Base Oil Type

If extreme temperatures (high and/or low) are frequently encountered, consider the oil type and the influence of temperature change on the various types available. Synthetics offer a broader range of operating temperatures than petroleum oils, but even within the family of synthetics there are variations. Figure 4 shows common synthetic oils by effective working temperature ranges.

Paraffinic mineral-based oils often have a viscosity index (VI) around 95. With few exceptions, synthetic base oils offer greater flexibility, with VI numbers ranging from 120 to 175. The higher the VI, the broader the temperature range in which the product can effectively operate.

Oxidation Resistance

If the application is one of high temperature and poor machine access, then it is preferable to select a product with a base oil and thickener that can withstand the temperature and resist breakdown over prolonged relubrication intervals. Oxidation resistance is largely a subset of the base oil selection because the base oil type will have a significant influence on oxidation resistance. But thickener and additive system selection also play a role.

Wear Performance

Wear performance is also related to base oil selection, because the viscosity of the base oil at operating temperature is the primary determinant of lubricating condition (hydrodynamic, elastohydrodynamic, mixed film or boundary) that the component will experience.

Where there is a strong likelihood of shock loading and extreme loading, chemical AW and EP additives can be useful in supplementing base oil properties to provide additional protection from wear and seizure. Inorganic additives such as moly, graphite and PTFE are often added to provide mechanical load support in addition to the chemical additives.

Water Resistance¹

Applications where the process employs water-based coolants or process chemicals have multiple problems to address. Water resistance is characterized by the grease's ability to withstand one of four water-related problems, including:

- Washout Resistance: The ability of the lubricant to stay in the bearing while operating partially or fully submerged (ASTM D1264).
- Water Absorption: The ability of the grease to deal with the presence of water by either absorbing or resisting the washing and diluting action of the water. The grease may either absorb a large percentage of ingressed water and then de-gel (lose consistency but retain the water), absorb a lesser amount of water and retain consistency, or resist absorption of water altogether (which leaves water in a separate phase in the component or system).
- Corrosion Resistance: The ability of the grease to prevent corrosion of surfaces when water is present (ASTM D1743).
- Spray Resistance: The ability of the grease to resist displacement from a direct impingement of the water on the greased surface (ASTM D4049).

The thickener, in large part, determines the grease's response to moisture. If the thickener is particularly good at

	Aluminum Complex	Barium	Calcium	Calcium 12 Hydroxy	Calcium Complex	Clay	Lithium	Lithium 12 Hydroxy	Lithium Complex	Polyurea	Sodium	Calcium Sulfonate
Aluminum Complex	-											
Barium		-										
Calcium			-									N/A
Calcium 12-Hydroxy				-								N/A
Calcium Complex					-							
Bentone (Clay)						-						
Lithium							-					
Lithium 12-Hydroxy								-				
Lithium Complex									-			
Polyurea										-		
Sodium (Soda Base)											-	
Calcium Sulfonate			N/A	N/A								-

Borderline Compatibility Compatible Incompatible N/A - Not Available

Table 1. Grease Compatibility

absorbing moisture, such as with sodium soap greases, it may form an emulsion that traps and draws water away from metal surfaces.² The downside to greases which emulsify is that they can be easily washed out.

Rust/Corrosion Resistance

Coupled with water washout resistance, if the typical operating condition is constantly exposed to water, process chemicals or high humidity conditions, then an additional measure of corrosive resistance may be warranted. Some thickeners, such as aluminum, have inherently good corrosion resistance.³

If the thickener resists water, such as lithium or calcium soaps, then rust and corrosion inhibitors will be added to protect surfaces from water.⁴ If the grease is expected to remain in the bearing and prevent corrosion under wet conditions for a prolonged period (between lubrication cycles), then an added anticorrosive capability is highly desirable.

Thickener Type

There are several thickeners available for consideration. Generally, the criteria for selection of the GP grease thickener type will be compatibility with other greases used in a plant and the dropping point (which represents the grease's temperature maximum range) that the thickener imparts to the grease.

Lubricant thickeners are generally compatible with other similarly named thickeners. (Polyureas are an exception.) Lithium thickeners are compatible with other lithium-thickened greases, lithium complex with other lithium complex greases, etc.⁵ Table 1 shows typical compatibility characteristics.

A second rule of thumb is that the complex thickeners can be used to higher temperature ranges, frequently to 400°F (204°C), with frequent relubrication. If the

equipment operates at sustained temperatures above 400°F (204°C) then it probably would not qualify for a general purpose lubricant.

The issue of the thickener type and dropping point is central to this decision because technicians are inclined to use greases when the oil won't stay put. The thickener must remain stable over a sufficiently broad temperature range such that an incidental spike in temperature will not cause the grease to thin and bleed from the application.

Finding an acceptable general purpose (GP) grease requires consideration of many aspects, including lubricant factors such as oil viscosity, oxidation resistance, corrosion resistance, thickener type and water wash resistance properties. There are key operational factors to consider as well, including speed, load, temperature, contaminant type, concentration and relubrication cycles. In food handling and processing plants, toxicity and edibility create a separate set of questions not addressed in this article.

Selecting a grease to meet broad operational requirements requires an understanding of how the equipment runs and how the grease will respond to those operational factors. A well-reasoned and planned consolidation to a general purpose grease can bring dividends through reduced risk of contamination, reduced complexity and improved overall lubrication conditions. However, do not compromise needed machine reliability by force-fitting a general purpose grease into an application for which it is not suited.

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Lubricant Screening

Increasing the Effectiveness of the Maintenance Toolbox

BY KEVAN SLATER - SCHEMATIC APPROACH INC.

Oil analysis programs are in an evolution of change - a change into a method of determining not only the condition of the lubricant, but more importantly, an effective method of assisting in evaluating the immediate and future maintenance requirements for lubricated equipment. This evolution has included the transition of many laboratory-driven oil analysis programs to not only be orchestrated by the maintenance personnel, but also in many cases, the majority of the testing is performed onsite by the same maintenance personnel. Quantitative and qualitative onsite lubricant test equipment has allowed the maintenance professional the opportunity of scheduling, testing, recording and trending various contamination levels along with the physical and chemical conditions of the lubricant. This lubricant screening data naturally integrates with all other precision maintenance activities to effectively assess and evaluate the optimum maintenance activities required for maintenance cost reduction and increased equipment reliability.

Introduction

In today's cost-cutting, globally competitive market, there is perhaps no more critical area in terms of plant profitability as in the successful execution of a balanced maintenance program. Balancing corrective, preventive (scheduled), predictive (failure symptom monitoring) and proactive (failure root cause monitoring) maintenance activities will enable a high degree of equipment availability at a reduced maintenance cost.

A properly executed lubricant screening program provides a natural balance of providing information for all these areas of maintenance. The lubricant screening data can direct corrective maintenance actions to be performed when limits or targets are exceeded. The trending results of collected data can provide direction into optimizing the time frame of preventive maintenance activities while also providing predictive maintenance observations through wear debris analysis. Evaluating and confirming the physical and chemical conditions of new lubricants and monitoring their life cycle combined with root cause degradation mechanisms (particles, water, heat and oxidation conditions) provide an effective proactive method of managing your equipment and lubricant assets.

All diagnostic, predictive and proactive maintenance technologies require intimate knowledge of the equipment, its internal design, the system design, and the present operating and environmental conditions for successful execution. The maintenance professionals are in the best position to understand and integrate this highly complex and equipment specific knowledge. Lubricant screening programs are no different but the maintenance practitioners must realize the importance of laboratory data. Onsite test equipment in some cases does not match up with or compare to laboratory data due to equipment or the various test methods. The key to success is to ensure that clear equipment specific targets and limits for each test parameter are set and that the tests are scheduled and performed to provide a continuous flow of information. Onsite equipment allows for easy adjustment of tests and frequencies for changing conditions or for the various operating conditions of the equipment within a plant.

Once a representative sample is obtained from a system, the sample integrity must be maintained to reflect the lubricant and

the equipment condition throughout all phases of the testing. This paper provides an overview of the testing hierarchy required to maintain sample integrity, but procedural compliance of the original equipment manufacturer (OEM) lubricant test equipment is required to ensure that repeatable trending data is obtained.

** Sem-fluid lubricants (grease) are a critical part of the lubricant management program and the lubricant screening process but will not be covered in this paper.*

Lubricant Screening Process

The following is a sequential method of testing onsite new and used oil samples that have been collected for the purpose of evaluating lubricant and equipment health. This data must include sensory and inspection data along with all other relevant maintenance activities that can provide a clear evaluation of the lubricant, equipment and operating conditions.

Competent training and understanding of the onsite test equipment remains critical as in all diagnostic equipment. Calibrating or verifying calibration must be part of the lubricant testing program to ensure accuracy and repeatability of the tests. Test equipment and methods may be substituted from this paper to reflect the equipment presently in use in your facility as long as the test equipment is quantifiable and qualitative.

Basic Screening Tests

- Operational conditions (temperature/pressure/flow)
- Appearance
- Color
- Particle count
- Water contamination (percent water saturation and/or crackle)
- Viscosity
- Ruler (antioxidants and/or AN)
- Ferrous density/count
- Ferrography
- Debris analysis (patch test)

Trending

A lubricant screening program should control test data in an appropriate software that will allow for the plotting of this data on a continuing graph to establish acceptable trend lines (Figure 1). This graph should have the ability of placing variable caution and critical limits above and below the trend line. Thus, monitoring variations outside the target/limits will be readily noticeable. When targets are broken, retest to verify results, and then access the conditions that can either affect or improve the condition of the alarm.

Flow Path of Lube Sample Screening Tests

After obtaining an oil sample (following an approved procedure), a method of correlating the onsite, laboratory and user-defined tests with the sample date time and location must be utilized. Some lubrication software's refer to this as a sample ID number.

Determine the test requirements for the sample from the lube analysis software. If no screening tests are required, fill out appropriate forms and send to appropriate oil lab for testing. If screening tests are required, refer to the following guidelines.

When performing the screening tests, ensure that the test is required by the schedule frequency. If a specific test is not required, omit the test and continue with the next scheduled test.

By following the attached lubricant-screening template (Figure 2) it will provide a hierarchy method of the testing execution and the text following will provide an overview of the information required.

Operational Conditions

Operating and environmental information varies greatly from machine to machine and from system to system. Recording gauge temperature, pressure, and speed (rpm) will supply information on the running condition of the equipment, while environmental reading such as ambient temperatures, humidity, and apparent airborne contaminants will supply information conditions that can affect or stress the environmental control systems (breathers, cooler, heaters, etc.).

System and/or component designers have a range in which an operating viscosity is recommended. Lubricant viscosity is temperature-dependent, so in most cases the operating temperature of the lubricant must be controlled. Recording the operating temperature will ultimately monitor the temperature control system (heaters/coolers).

Lubricant Appearance

This procedure is a subjective visual/scent method of examining a used oil sample of a lubricant. Training and practice are required to understand the difference between a new oil sample and a lubricant that has gone through various changes during operation. These changes affect both the scent and the visual characteristics of the lubricant. Trending the associated condition by use of the attached severity code number can assist in the evaluation of the lubricant and the triggering of further testing requirements.

Cloudiness

Entrained Air: Immediately after pulling the sample, excessive foaming or entrained air can be viewed. Bubbles foaming on top of the oil can be the result of extreme turbulence in the sample or a system that could be low on fluid. Bubbles or entrained air held in suspension in the oil can be a sign of moisture present due to the polar attraction to air.

By allowing the sample to sit for five minutes, the cloudy effect will disappear if it is directly related to air entrapment.

Emulsions: Water emulsified into oil will result in many different forms and appearances. Any visual indication of the oil becoming hazy or increasing in opacity can be an indication of emulsified water. Allowing the sample to sit for five minutes will aid in determining if the cloudiness is due to water or entrained air. Emulsified water will not usually be separated within a five-minute time period.

Separated Free Water

Free water is the water that has separated or that is not mixed into an emulsified state. Free water usually appears as droplets and

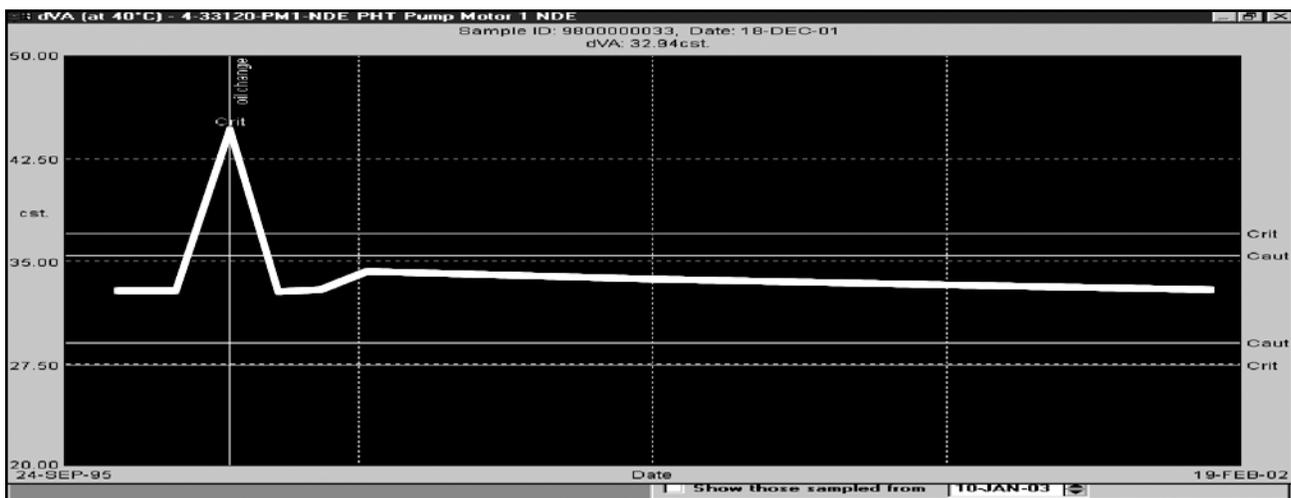


Figure 1

eventually in a puddle-like form on the bottom of mineral-based oils. Allowing the sample to sit undisturbed for one hour tends to allow the water to accumulate and settle to the bottom to allow for a visual indication.

Sediment

Sediment is the visual indication of a highly contaminated lubricant. The visual sediment consists of insoluble materials or sludge formed due to degradation of the lubricant or a high

concentration of contaminants. Large quantities of contaminants will change the colour of the lubricant and will settle out to the bottom of the sample bottle when left for a period of time.

Odor

Changes in oil chemistry or the presence of contaminants will usually alter the odor of a lubricant. The lubricant itself, along with the additives will produce a certain scent. The goal in monitoring odor is to notice a change or condition in the used lubricant.

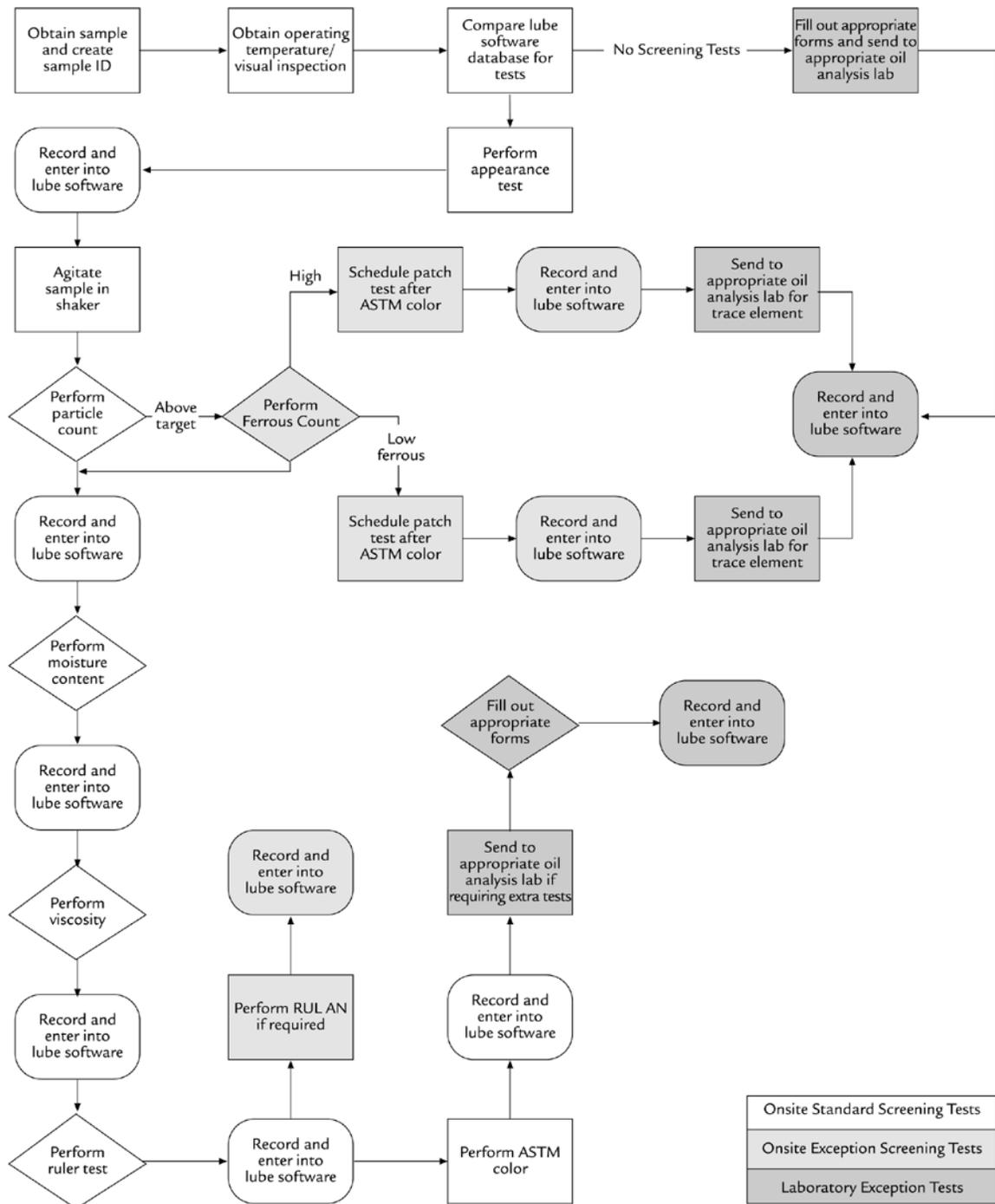


Figure 2. Lube Screening Template

A burnt smell can indicate thermal degradation or operating the lubricant for longer period of time at high temperature. A sour or pungent smell can result in a lubricant that is oxidizing and degrading. A strong stench that resembles decomposing material can indicate the presence of microbial contamination.

Color Change

Changes in color can sometimes reflect contamination, overheating, excessive degradation or the wrong lubricant. A rapid change in color from the original oil sample requires further analysis to identify the source.

ASTM D1500 (Standard Test Method for Petroleum Products) provides colored standards that are used for comparison to the oil sample. Changes can then be recorded with a controlled methodology. The changes of three ASTM Color Standards (Color) should be considered suspicious and further evaluation is required.

ISO Particle Count

The importance of monitoring and controlling the concentration of particle contamination in lubricating oils and hydraulic fluids cannot be overstated. The ISO Solid Contaminant Code (ISO 4406:99) is probably the most widely used method for representing particle counts (number of particles/mL) in lubricating oils and hydraulic fluids. As the range numbers increase by one digit, the associated particle concentration roughly doubles. Particle counts can be obtained manually using a microscope or by an automatic instrument called a particle counter. There are many different types of particle counters in use today and their performance can vary considerably depending on the design and operating principle.

Preparing the sample to represent the system conditions requires agitation to eliminate the possibility of particles settling out. The following guide provides acceptable agitation rates for settled out samples.

- Place sample bottle in oil sample agitator (paint mixer) for the time listed in Table 6 that is based on the ISO Viscosity Grade in cSt.
- Important: Sample agitation may be eliminated if the sample is tested at the equipment or within five minutes of obtaining the sample and continuous hand shaking is performed.
- Enter results of the particle count in the lube analysis software.
- If the count is above the target, action will be listed to perform a ferrous particle count or a ferrous density test.

Ferrous Count/Density

An increase in particle counts can be related to either the ingestion of foreign material to the system lubricant or the direct result of the wearing of the system components. To quantify the amount of the ferrous material present in the sample, a magnetic array is introduced to separate particles from the lubricant between ferrous and nonferrous materials. Depending on the testing equipment and the technology used, the results will be presented in the form of either an ISO particle count of ferrous material or a scaled amount of ferrous material grouped into large, small, and total wear particle concentration. If results are above target outlined in the lube analysis software, perform a ferrography test using the ferrography test instructions after the ASTM Color. If not excessive, perform a patch test using the patch test instructions after the ASTM Color.

Cloudiness	
Severity Code	Appearance
0	Normal
1	Hazy
2	Cloudy
3	Heavy Clouding

Table 1

Free Water	
Severity Code	Appearance
0	No
1	Sight
2	Puddling
3	Layer

Table 2

Sediment	
Severity Code	Appearance
0	No
1	A Few Specs
2	Layer
3	Heavy layer

Table 3

Odor	
Severity Code	Appearance
0	Normal
1	Abnormal
2	Pungent
3	Foul

Table 4

Free Water	
Severity Code	Appearance
0	Normal
1	Slight Darkening
2	Darkening
3	Abnormal

Table 5

ISO Viscosity Grade (cSt)	32cSt or less	46 cSt to 68cSt	100cSt to 220 cSt	220cSt and above
Time (in minutes)	5	10	15	30

Table 6

Moisture Saturation Test and/or Crackle Water “Crackle” Test

This test is performed to quickly identify the presence of abnormal quantities of water. While being subjective in determining the quantity of water in oil, a bubbling and/or crackling of a drop of oil placed on a hot plate (120°C or 250°F) suggests that there is an unacceptable level of water present and corrective actions are required.

Water Saturation

Measuring water content can be expressed in PPM or percent saturation. The percent saturation is a direct measurement of the severity of the water contamination before free water appears. Because temperature can affect the saturation point of a lubricant, the temperature of the lubricant must be recorded along with the percent saturation level. Most saturation instruments produced today record the lubricant temperature and provide a calibration process to ensure accuracy for a quantifiable measurement.

Record moisture saturation and lubricant temperature results in the lube analysis software. If results are above the target outlined in the lube analysis software and alternate confirmation is required, fill out appropriate forms and send to the appropriate oil analysis lab for a Karl Fischer test after all other tests are completed.

Viscosity

Viscosity is a measure of the resistance to flow of an oil and is the single most important property of lubricant analysis. The equipment builder for operating machinery generally specifies oil viscosity and if the viscosity is too high (thick), performance can be sluggish because of increased drag. This also can cause increased temperature, which has an adverse effect on lubricants and sometimes machine life. If viscosity is too low, the oil film might not be able to keep the moving parts separated. In the absence of an antiwear additive, this can result in metal-to-metal contact, contamination with wear debris, and shorter life for both the lubricant and the machine. ASTM D445 method of viscosity measurement is a preferred method for oil measurements.

If the results are out of specifications outlined in the oil analysis software and outside confirmation is required, fill out appropriate forms and send to the appropriate oil analysis lab for a viscosity test after all other tests have been completed. Record results in the lube analysis software.

RULER™

Ruler™ (Remaining Useful Life Evaluation Routine) Instrument (ASTM D 6810) is a technique to measure the antioxidant levels in lubricants. Comparisons of results with those from new lubricants provide a quantitative method of determining the remaining antioxidants or useful life of lubricants. Excessive temperatures, water and/or cleanliness levels of the fluid have a direct relationship to the reduction of antioxidants.

AN (Acid Number)

The acid number test is used to indicate the extent of oxidation. An increase in acid number above the value of the new lubricant indicates the presence of oxidation products or less likely the presence of acidic contamination.

Wear Debris Analysis

A microscopic analysis of debris obtained from the lubricant sample can be used to determine the type and origin of various particles. These particles can consist of normal rubbing wear, severe sliding wear, cutting wear, gear wear or bearing wear along with the presence of red and black oxides and/or contamination particles such as fibers and sand/dirt. Various lubricant degradation products or residue such as sludge, polymers and varnish can also be detected depending on the technology used. The wear debris analysis is split into two categories: patch test for particle evaluation of most types of debris or analytical ferrography that has a natural bias to ferrous materials.

Patch Test

Filtering a measured quantity of lubricant through a fine filter media (patch) separates the particles from the lubricant. A solvent rinse removes the carrier oil residue and examination under a microscope will allow for the identification of the debris.

Analytical Ferrography

This technique involves flowing the diluted oil over a specially prepared microscope slide tilted to provide a known flow rate. A solvent wash removes the carrier oil and a ferrogram is prepared from the dried residue. This is examined through an optical microscope. Magnetism, various colored light and light source location combined with controlled heat treating allows for identification of various solids which include several types of steel, and to a lesser extent, associated copper, lead/tin alloys, friction polymers, moly sulfide, silica, fibers and carbon flakes.

Summary

Onsite lubricant screening is a maintenance-executed fluid and equipment testing condition-monitoring program that utilizes reliable onsite analytical testing instruments and sensors that focus on fluid and equipment failure modes. While integration with a laboratory's specialized analytical instruments is recommended, in many cases this laboratory data is required as the result of specific troubleshooting or lubricant evaluation.

Timely representative samples, equipment specific knowledge, controlled testing methods and system specific targets and limits ensure that the lubricant screening data integrates effectively with all other maintenance activities to assess and evaluate the optimum maintenance activities required for cost reduction and increased equipment reliability.

Proactive 1-Micron Filtration

BY BRUCE ANDERSON - CCECO LAB & FILTRATION

We have all heard the saying, "An ounce of prevention is worth a pound of cure." This paper will discuss how 1-micron filtration, coupled with oil analysis can dramatically reduce bottom line maintenance costs. The term proactive by definition means to determine the root cause and then take immediate action to prevent or delay premature mechanical failure. This is a great idea but where does one start?

The Issue

There is another saying, "You cannot control what you cannot measure." If the goal is to control maintenance costs, one must first be able to identify and then quantitatively measure the source of the problem(s). Okay, so where is and what is the problem?

Whenever one goes to the doctor for our annual physical, one can expect to have a sample of blood drawn. Why? Our blood is our life. This one valuable report tells the doctor the overall condition of our vital organs, our cholesterol, blood sugar, etc. In the very same way lubrication fluids contain the same valuable information about the true health of a hydraulic system. The oil analysis report gives measurable data to determine the need, take action and then monitor progress. Oil analysis is the primary tool used to identify and measure the source of the problem. Once that is determined, the cure, or the medicine of 1-micron filtration is prescribed and administered.

The Problem

The problem-contamination. This serious problem is often overlooked and yet costs the industry billions of dollars annually. The National Research Council of Canada determined that across a number of industries as many as 82 percent of system failures resulted from particle induced failure (such as contamination). To be more specific, contamination occurs in two major categories, dirt and water (Figure 1).

In the world of dirt contamination, not all dirt is created equal - and size does matter. In fact, studies have shown that three and a half

times greater wear occurs from particles less than 10 microns verses larger particles above 10 microns (Figure 2).

This fact initially seems backwards. Look at the design of a today's hydraulic piston pump. Typical flow rates run from 30 to 80 gpm and run pressures up to 5,500 psi. In order to achieve this kind of performance, manufacturers build equipment to tighter dynamic tolerances between moving surfaces than in the past, especially when compared to vane or gear-style pumps. The following illustration will reveal the reason smaller (under 10 micron) particulates cause more damage. The reason is they are small enough to slip in between the critical clearance of the dynamic oil film separating the two moving surfaces. This oil film varies between 0.05 and 10 micron. When this gap is compromised with silt-sized particles, the resulting pressure on these surfaces can

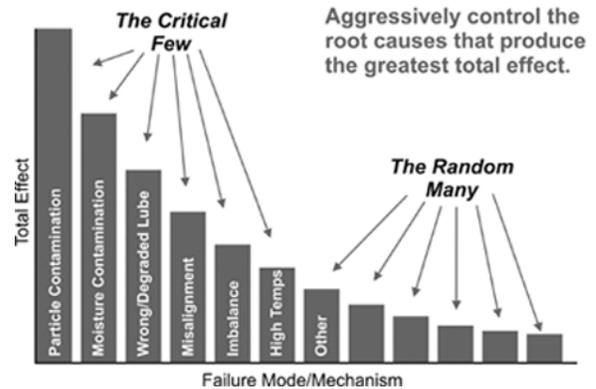


Figure 1. Applying Pareto's Principle (Courtesy of Noria)

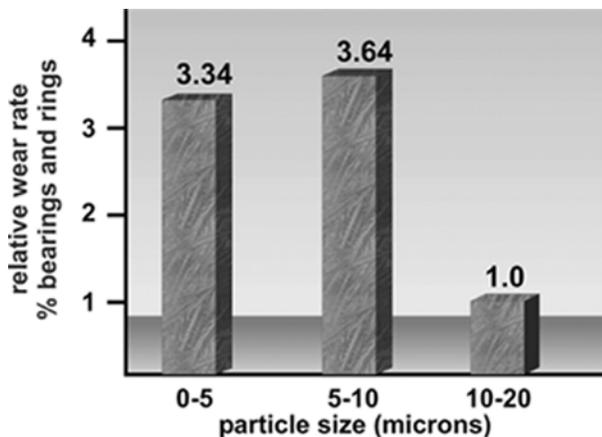
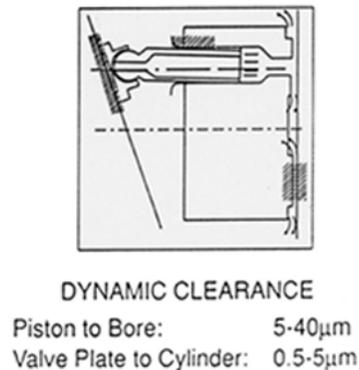


Figure 2



Re: Pall Corp.

Figure 3. Piston Pump

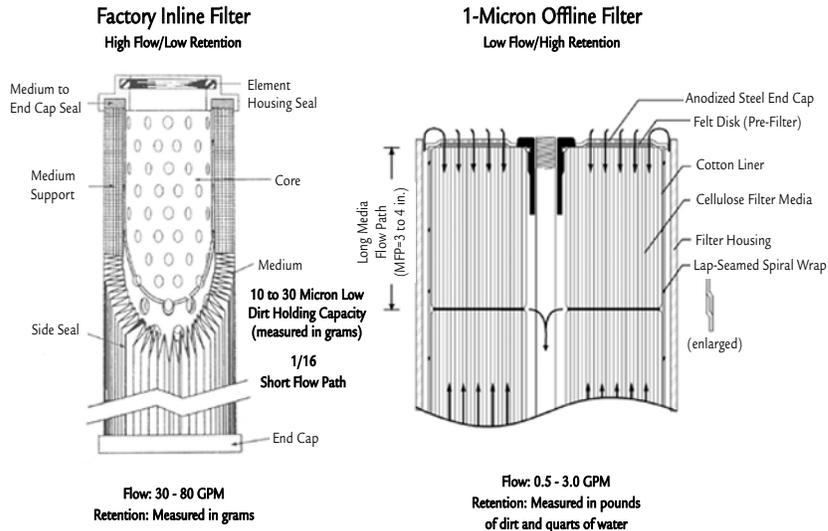


Figure 4

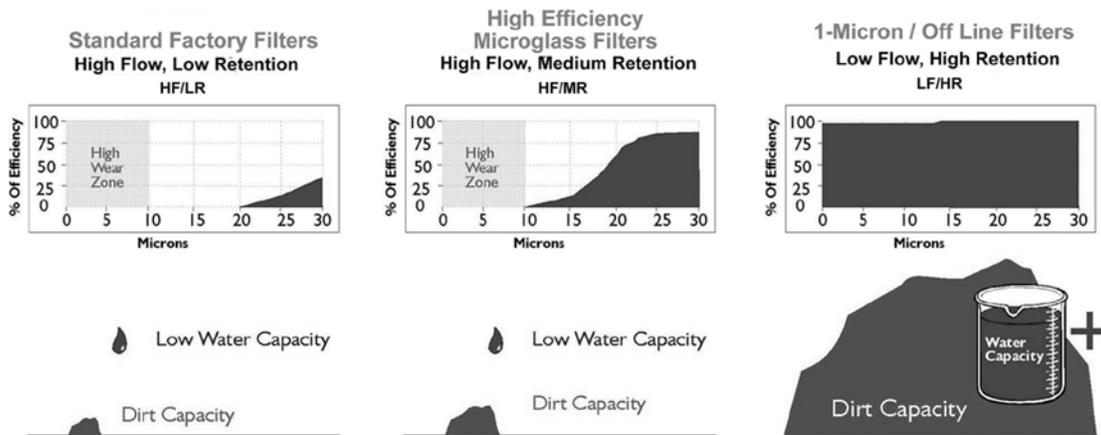


Figure 5

Ave. ISO Code	Ave. Hours Between Breakdowns	Relative Life Factor
24/21	200	0.19
23/20	250	0.24
22/19	325	0.31
21/18	430	0.41
20/17	600	0.57
19/16	800	0.76
18/15	1050	1
17/14	1400	1.33
16/13	1900	1.81
15/12	2600	2.48
14/11	3800	3.62
13/10	5000	4.76
12/9	6500	6.19
11/8	9000	8.57
10/7	20,000	19.05

arbitrary base

- Controlled "field" study of hydraulic machines
- 117 hydraulic machines
 - Injection molding
 - Machine tools
 - Material handling
 - Mobile equipment, e.g., earth moving
 - Marine hydraulics
 - Test stands
- Period: 3 years
- Purpose: Correlate fluid cleanliness to breakdown frequency

Figure 6

exceed 500,000 psi (SAE Paper #881827). Figure 3, is a cut away illustration of a piston pump indicating the high wear zones and the critical clearances that need to be maintained.

The problem has been identified and with oil analysis, the root cause can be measured and quantified. Filtration has historically been the answer to the problem. Today's marketplace now offers the customer two major filtration options: Factory in-line filtration and 1-micron off-line filtration.

The Solution

A. Factory In-Line Filtration

At best, today's typical in-line filtration systems are designed to trap 10 micron-sized contamination or larger. Which means everything under 10 microns (silt) continues to circulate through the system acting much like a lapping compound. The basic function of these filters is to catch the larger particles to prevent catastrophic damage. They are not, however, engineered to address the removal in the silt-sized high-wear zone of under 10 micron-sized particles. The author would characterize factory in-line filtration's function as HF/LR or High flow/Low retention (dirt holding capacity) with flows measured typically between 30 to 80 gpm and dirt retention measured in grams. If the filter media were reduced down to 1-micron, then these elements would plug prematurely. This would require frequent and costly change-outs due to their lack of retention capacity thus making it cost prohibitive for the customer. It should also be noted that these elements typically have little or no moisture removal or retention capacity, which is as critical a root cause of failure as is particle contamination.

B. 1-Micron Off-Line Filtration

Historically, 1-micron filtration systems have been known by any number of names such as depth filter, off-line filter, by-pass filter, fine filter, polishing filter or a kidney-loop filter to name a few. Using the medical analogy of a kidney loop, one can see how the dialysis process for a kidney patient parallels to the 1-micron filtration systems. The kidney dialysis machine independently filters out the toxins that the body's kidneys (filters) are not capable of performing on its own. Figure 4 helps illustrate this point and contrasts the design and performance characteristics of a typical factory in-line filter element to that of a typical 1-micron off-line filter element.

From this illustration, it is easy to see why the 1-micron element is a more efficient filter with extremely high contamination holding capabilities across all micron ranges especially under 10 micron. The oil flow path is typically three to four inches of dense filter media versus a typical pleated media path of 1/16". It is clear that the 1-micron filter element is designed for low flow rates up to 3 gpm versus the factory in-line design that can handle up to 80 gpm.

It is also apparent that these designs were engineered to meet the challenges of two different tasks. The factory in-line filter was designed to primarily prevent catastrophic failure caused by larger particles (above 10 micron). The 1-micron off-line design was designed to address the root cause found in the critical high-wear zone area (under 10 micron). The author characterizes the 1-micron off-line design as LF/HR (Low flow/High retention) with flows measuring typically under 3 gpm and retention measured in pounds of dirt and quarts of water. Speaking of water, an additional and significant benefit of the LF/HR design is that water contamination removal becomes a natural byproduct and function of off-line filtration. Figure 5 will help illustrate this point.

It is important to identify that 1-micron off-line filtration is meant to complement, not compete or replace factory in-line filtration. Now let's look at the direct correlation and relationship of contamination to equipment life longevity. The opportunity is to understand the correlation of how super clean fluids directly translate into longer component life.

Opportunity for Savings

The bottom line is that the cleaner the oil, the longer machinery runs, which results in increased productivity and reduced unscheduled and costly downtimes (Figure 6).

The Benefits

- Extended equipment life (two to three times)
- Optimal oil change intervals (condition-based oil changes)
- Extend in-line filter life
- Reduce environmental impact of disposal of contaminated oil



Figure 7. Four-Step Proactive Program (Courtesy of Noria)

A Case History

The following case history will help illustrate these points effectively. CCECO (Contamination Control Engineering Company) began over 10 years ago as a division of Hydraulic Repair and Design in Kent, WA. HRD is one of the largest repair facilities of its kind in the U.S., repairing over 6,000 hydraulic components annually. Vancouver Mainland Sawmill was one of HRD's largest customers located about three hours north of Seattle. This sawmill was a large operation with over 24 hydraulic power units from 2000-gallon systems down to less than 50 gallons in size. All systems power unit's utilized standard filtration such as suction and return in-line filtration however, suffered the high cost of a premature failures and unscheduled breakdowns. Through oil analysis, it was discovered that many of these systems were highly contaminated with some systems containing water. Starting in early 1993, the mill and HRD began a program of monthly oil analysis and 1-micron filtration installations starting with the largest and most important systems first. The first installation was on the 2,000-gallon power unit and the results were immediate. Once the mill was fully fitted with 1-micron filtration and all remediation work had been completed, routine oil analysis was scaled back to every three months.

The Bottom Line

Prior to the proactive 1-micron filtration the mill spent an average of \$16,000 monthly on hydraulic motor/pump and cylinder repair. Six months after the last 1-micron system was installed, repairs had been reduced to less than \$3,000 a month.

This success along with others, initiated the formation of CCECO Lab & Filtration as a separate corporation. CCECO (Contamination Control Engineering Co.) has continued to expand our product lines and increased services to meet the ever-changing challenges and needs of our customers.

Conclusion

Is your goal to make dramatic reductions to the bottom line of maintenance costs? Then implement a proactive maintenance plan that directly addresses the root cause of premature system failures - contamination. An aggressive 1-micron filtration program that incorporates comprehensive oil analysis will pay impressive financial dividends that go directly to the bottom line each and every year.

Optimizing Oil Change Intervals to Reduce Lubricant Consumption

By JIM FITCH - NORIA CORPORATION

It goes without saying that the optimum oil change interval is one that is as long as reasonably achievable without inducing a reliability or safety risk. However, there are also economic factors to consider. The incremental cost of extending the interval by 100 operating hours for example, may exceed any real benefit gained. After all, the things that extend life are not always free. This is where the word optimum comes in, to balance the benefits of long life to the costs incurred in delivering it.

While maximizing the lubricant's life is one important goal, the second is the efficient timing of the oil change so that it's changed . . . not too soon but also, not too late. This is where oil analysis can deliver in a major way. The lubricant carries with it a database of information about its health and condition. Unless this database is polled regularly, it is difficult to know exactly when to change the oil. In such cases, for fear of harm to machinery, the oil is often changed far too soon.

In the past, many organizations have exclusively used interval-based oil change criteria. The interval was based on an assortment of considerations, such as the calendar, operating hours (meter), fuel consumed, miles/kilometers driven or production/work performed. In many cases, an approaching outage and shutdown have a driving influence on the decision, coming from the desire to avoid unscheduled downtime later or the need to change lubricants on the run. In addition, new equipment under warranty may have OEM-specified lube change-out intervals which can make the matter far less subjective (and optimized).

True Cost of an Oil Change

There are many hidden costs of an oil change that have influenced companies to find a more efficient approach to keeping oil healthy and reliable. A recent study on the subject found that the true cost of an oil change frequently exceeded 40 times the cost of the oil itself.¹ Following are a few of the many factors that contribute to the true cost of an oil change:

Lost Production

Machine downtime and longer outage intervals needed to change oil, flush and prepare equipment to return to service.

Paperwork

Includes maintenance schedules, data entry, manpower planning, inventory management, work orders, documentation, etc.

Labor, Supervision, Benefits

The time required to drain a compartment, transfer lubricant and associated equipment to the machine, flush, fill and prepare the machine for service.

Handling and Storage Costs

For lubricants and associated equipment (filters, funnels, drum pumps, etc.).

Purchasing and Inspection

There are many real costs associated with purchasing lubricants. Also, new lubricant deliveries involve inspection, labeling, stocking and more paperwork. Inspection often involves lab costs.

Disposal Cost

Relates to solid and liquid waste resulting from disposal of oil, sludge, rags and cleaning equipment.

If it Ain't Broke . . . Don't Fix It

Often a lubricant remains serviceable for long periods of time without a drain and new lubricant charge (influenced by makeup rates, operating temperature, fluid volume, cleanliness, etc.). Draining an oil and adding new lubricants into a system presents risks such as:

- Introduction of a wrong oil.
- Introduction of a contaminated oil.
- Introduction of an incompatible oil (with residual oil remaining in the machine).
- Resuspension of settled contaminants in tank/sump floors and inactive zones.
- Human agency failures (dead-heading pumps on restart, cleaning solvents not removed, introduction of contaminants, loosening of machine parts, etc.).

When compiled with real cost and associated risk of an oil change factored in, it is often wise to let the conditions of the oil drive the decision.

Life Factors for In-Service Lubricants

There is an assortment of operating conditions that can reduce the life of a lubricant. Obviously, if possible, these are to be avoided. However, very often nothing can be done as many influencing life factors are associated with machine application and environment.

While the timing of an oil change is highly important, perhaps more important is the strategy to proactively improve conditions that extend oil life. When applied correctly, a proactive maintenance strategy can double or triple lubricant service life. This is achieved by reducing the conditions that stress an oil (cleaner, cooler, dryer, etc.).

The following is a list of factors that influence the life of a lubricant:

Crankcase Lubricants

- **High Fuel Consumption:** Inefficient engines leave behind fuel and combustion by-products, including soot, fuel residuals, sulfur, acids and water. These contaminants distress the quality of the lubricant.
- **Exhaust Gas Recirculation and Retarded Timing:** Engine designs are changing to help protect the environment. While less of the harmful contaminants are emitting into the environment, more are pushed into the crankcase, shortening the life of the lubricant.
- **Blow-by:** Worn engines, timing/injector problems, lugging, incorrect rack settings, excessive exhaust back pressure, excessive idling and cold operating conditions, and high elevations can all contribute to increased blow-by. This adds soot, fuel and an assortment of other contaminants that distress even the most robust lubricants.
- **Coolant Leaks:** Glycol and water sharply disrupt dispersancy and contribute to a host of other problems (corrosion, deposits, filter plugging, etc.).
- **Fuel Dilution and Fuel Quality:** Fuel dilutes additives and sulfur and aromatics into crankcase oils. Viscosity is also affected. Lubricant life is affected by the quality of diesel fuel and natural gas, especially relating to sulfur levels.
- **Air Cleaners:** Induction air filters sometimes become plugged and starve the engine. This over-fuels the mixture leading to higher levels of soot entering the crankcase oil.
- **Running Conditions:** Lugging, stop-and-go driving, intermittent service, cold ambient temperatures, idling, etc., have influenced the life of the crankcase oil.

Miscellaneous Influences on Lubricant Life

- **Oil Level:** Low oil levels concentrate heat, contaminants and catalytic wear metals. So too, low oil levels mean less additives are available to resist oxidation and lubricant degradation.
- **Abrasives:** Dirt and other solid contaminants attract additives and can catalytically advance the rate of oxidation. An even bigger problem is associated with the wear debris that is generated from abrasion and its influence as a pro-oxidant.
- **Water Contamination:** Water contamination leads to oxidation, additive distress, loss of dispersancy and many other lubricant-life related problems.
- **Sludge and Varnish:** Oil degradation products often contain high concentrations of carboxylic acids, free radicals and hydroperoxides. When oil is drained from a compartment but sludge and varnish remain, often the following oil change is short lived.

- **Makeup Rate:** Makeup oil refreshes additives and dilutes contaminants. Lube compartments with low makeup rates, while beneficial in one sense, also require more frequent oil changes. One engine manufacturer directs lube oil to the fuel system to force more frequent makeups, which has been found to extend the oil drain interval by as much as tenfold.
- **Lubricant Quality:** The quality of base oils and additives can have a marked influence on oil life.
- **Temperature:** High operating temperatures can sharply accelerate the rate of additive depletion and oxidation. Much has been published on this subject.
- **Other Contaminants:** The ingress of other contaminants can degrade additives and affect the quality of base oils. These include process chemicals, solvents, refrigerants, radiation, etc.

Optimizing the Timing of Scheduled Oil Changes

As previously mentioned, there are two ways an oil change is timed: to an interval-based schedule or based solely on lubricant condition. In some high-risk applications, a combination approach is selected, such as the oil is changed whenever one or the other first occurs (schedule or condition indication). Schedule-based oil changes can be keyed to a calendar (every six months), operating hours (250 hours), miles/kilometers, fuel consumption or production schedules.

If a time-based interval is preferred, oil analysis can be used to optimize the interval. This is done by testing the oil when the oil is changed, beginning with a trial interval. If the oil is typically exhibiting a high percentage of useful life remaining on repeated tests the interval can be increase incrementally. This is done until, say, on average 75 percent of the oil's life is consumed prior to the scheduled oil change, leaving a margin for error. Using this strategy, it is important that all critical tests be performed to properly characterize a lubricant's remaining life. For many lubricants, it may be justified to perform standard ASTM tests such as foam tendency, demulsibility, rust, RPVOT, thermal stability and hydrolytic stability. The exact test slate would vary depending on the lubricant and application.

Condition-Based Oil Change Scorecard

Because the decision to schedule oil changes, either interval-based or on-condition, must take into consideration a number of factors, a worksheet or scorecard has been developed to guide the process. This is referred to as the Condition-Based Oil Change Scorecard (Figure 1).

The Scorecard deploys a scoring system that enables the user to simply complete a series of nine questions, which when totaled, give a composite score. A composite score of 100 or more suggests that the machine is a good candidate to run oil changes based on- condition. A score greater than 200 gives near certainty to the decision. Following is a discussion of the rationale of the nine scoring elements:

Condition-Based Oil Change Scorecard

This scorecard is used to assess whether oil changes should be performed on a "scheduled basis" (for example, once per year) or "on condition" using oil analysis. Place a number one (1) in only one box for each of the nine questions below. The red numbers below each box are the assigned weighed score. Once all nine questions have been scored, the Total Score is registered at the bottom. A "condition-based" oil change is generally recommended for machines that score 100 or more.

Machine I.D.:

Injection Molding Hydraulic System

1. What is the volume of fluid contained in machine compartment, including circulating lines?

<input type="checkbox"/> < 5 gallons	<input checked="" type="checkbox"/> 6 - 20 gallons	<input type="checkbox"/> 21 - 100 gallons	<input type="checkbox"/> > 100 gallons	10
0	10	40	100	

2. How much makeup fluid as a percent of total volume is added per year or between oil changes?

<input type="checkbox"/> < 1% per year	<input type="checkbox"/> 1 - 5% per year	<input checked="" type="checkbox"/> 6 - 15% per year	<input type="checkbox"/> > 15% per year	15
0	5	15	25	

3. What is the cost of the lubricant or hydraulic fluid?

<input checked="" type="checkbox"/> < \$2 per gallon	<input type="checkbox"/> \$2 - 4 per gallon	<input type="checkbox"/> \$5 - 10 per gallon	<input type="checkbox"/> > \$10 per gallon	0
0	5	25	50	

4. What is the cost of performing an oil change (not including the lubricant cost)?

<input type="checkbox"/> Insignificant	<input checked="" type="checkbox"/> Moderate	<input type="checkbox"/> High	<input type="checkbox"/> Very High	10
0	10	20	50	

5. How accessible is the machine for changing the oil?

<input type="checkbox"/> Very accessible	<input checked="" type="checkbox"/> Moderately	<input type="checkbox"/> Difficult or machine is infrequently available	<input type="checkbox"/> Not accessible or available	10
0	10	20	30	

6. What is the OEM recommended oil change interval?

<input type="checkbox"/> 1 month or less	<input checked="" type="checkbox"/> 1 - 3 months	<input type="checkbox"/> 4 - 12 months	<input type="checkbox"/> > 12 months	5
0	5	10	20	

7. What is the availability of oil analysis (based on turnaround time)?

<input type="checkbox"/> > 10 days turnaround	<input checked="" type="checkbox"/> 5 - 10 days turnaround	<input type="checkbox"/> 2 - 4 days turnaround	<input type="checkbox"/> Onsite or < 2 days turnaround	10
0	10	20	30	

8. What is the general cost/penalty of machine failure if oil is not changed on time?

<input type="checkbox"/> Extremely high	<input checked="" type="checkbox"/> High	<input type="checkbox"/> Moderate	<input type="checkbox"/> Very low	-20
-50	-20	0	30	

9. What is the quality of filtration?

<input type="checkbox"/> No filtration provided	<input checked="" type="checkbox"/> Periodic and/or coarse filtration (> 15 microns)	<input type="checkbox"/> Continuous filtration (6 - 15 microns)	<input type="checkbox"/> Continuous filtration (< 6 microns)	5
0	5	20	40	

Total Score	45
-------------	----

Figure 1. Condition-Based Oil Change Scorecard

1. **Lubricant Volume:** If time and effort must be exerted to extend oil drains using a condition-based strategy, the total amount of lubricant involved needs to be factored in. If the extended drain saves little fluid (small oil compartment) the cost may not be justified, even if the benefits were extended threefold. Read on, because there are other cost/benefit factors to consider.
2. **Makeup Rate:** Lubricant compartments that undergo high makeup rates due to leakage, oil burn or other causes of fluid loss may never need to be changed. The new makeup fluid not only introduces more additive to the system but also dilutes the concentration of contamination (water, dirt, etc.), acids and other degradation precursors.
3. **Lubricant Cost:** The more expensive a lubricant, the greater the motivation to save the oil from a premature drain. Many specialty and synthetic fluids can cost 10 times more than their less expensive counterparts. Because one of the driving factors for purchasing specialty lubricants is long life, a more precise decision in timing the oil change is justified in most cases. Reclaiming used oils is also a consideration here. The cost of reclaiming and reconstructing additives, when needed, is in essence an oil change but at a lower cost (potentially) than the physical replacement of the oil. A partial drain (bleed and feed) is yet another consideration.
4. **Nonlubricant Costs:** There are many cost factors in performing an oil change that go beyond the cost of the oil itself. These need to be weighed in terms of the benefit coming from more precisely selected lube change intervals using the on-condition strategy. For typical examples of such costs, refer to the above list in the article "Hidden Costs of an Oil Change."²
5. **Machine Accessibility:** Many machine lubricant compartments, including fill and drain ports, are not accessible for routine maintenance. In such cases, the need for access must be planned well in advance, keeping the frequency to a minimum. The use of oil analysis to forecast oil change needs to avoid unnecessary change-outs could be of considerable practical benefit.
6. **OEM Recommended Change Interval:** Many OEMs have precise guidelines for when lubricants should be serviced. Others offer minimal advice. Because machine operating conditions (loads, speeds, temperatures, etc.) vary considerably, the service manual

recommendation will often be on the far side of conservatism. This can lead to repeated premature interval-based scheduled changes. This part of the scorecard favors condition-based oil changes when the OEM advises longer change-out intervals. In such case, there is a more manageable timeline to monitor the oil and plan lubrication work orders.

7. **Oil Analysis Availability:** While oil analysis is highly accessible for most organizations, there are many instances when machine lubes cannot be sampled or convenient laboratory analysis is not available. This may be due to geography (remote locations of equipment), manpower issues or a host of other reasons. Clearly, the more frequently oil analysis can be performed, the more effective and dependable the on-condition oil change strategy can be. On-site oil analysis offers clear benefits here but the cost and manpower to provide the service on-site can, in cases, be a significant offset.
8. **Penalty of Failure:** For machines that present high safety risk or downtime cost in the instance of operational failure, it may be prohibitive to switch entirely from interval-based programs. In these cases, the benefits don't outweigh the risks. Often, when a high degree of reliability is desired, the best plan is a combination of condition-based and interval-based - the oil is changed whenever either first occurs. Because oils can occasionally experience premature failure or a wrong lubricant is introduced, such a combined strategy can make the best business sense.
9. **Quality of Filtration:** Proactive maintenance is what gives lubricants longer and more reliable service life. When lubricants are routinely kept clean, dry additives last longer and lubricated surfaces are less challenged (corrosion, abrasion, etc.). High quality contamination control improves the opportunity to extend and plan drain intervals on-condition. In contrast, lubricants loaded with contaminants due to high ingress or poor filtration will often need to be changed to avoid distress to surfaces, regardless of whether other fluid properties have degraded. In such cases, the oil change becomes the default maintenance procedure for eradicating dirt and water from the machine - not exactly ideal, but often the only practical plan. Also worth consideration is the concern that new lubricants may not be much cleaner than the lubricant being replaced. Moreover, the cost of filtration is a factor as well.

	Prior Year	Year 1	Year 2	Year 3
New Purchases	10,000 gallons	4,500 gallons	2,100 gallons	1,420 gallons
Machine Volume Charge	4,200 gallons	4,600 gallons	4,600 gallons	4,800 gallons
Consumption Ratio	2.4	0.98	0.49	0.29

- Seek 50% reduction each year until a consumption ratio of less than 0.1 is achieved. Varies by industry and age of machine.

$$\text{Consumption Ratio} = \frac{\text{Annual Oil Purchases}}{\text{Machine Charge Volume}}$$

Figure 2. Lubricant Consumption Ratio

Side Benefits to Monitoring Remaining Useful Life of Lubricant

Using oil analysis to monitor the remaining useful life of lubricants is often thought of as its primary application. However, as many proponents of oil analysis will profess, there is an assortment of other important benefits as well. After all, when monitoring the oil you should, at the same time, monitor other vital signs of machine health and oil condition including wear, lubricant contamination, wrong oil, lubricant compatibility, etc.

Not all in-service lubricants have a well-defined and predictable wear-out rate or mean-time-between-failure (MTBF). The reason for such randomness stems from varying lubricant quality, changing contaminant ingress rates, application-dependent duty cycle, seasonal ambient conditions and other forcing functions of degradation. If an interval-based oil change criterion was used with a reasonable safety margin (confidence level: changing the oil ahead of actual need more than 95 percent of the time) then on average, many lubricants would be changed when the remaining useful life is more than 50 percent of the new oil. Naturally, such guesswork results in wasted effort, time, money and resources in the same proportion.

Trend Your Success Using Consumption Ratio Monitoring

Many people monitor improvements in lubricant consumption by monitoring the Lubricant Consumption Ratio (LCR). LCR is the ratio of the amount of lubricants and hydraulic fluids added to machines each year divided by the amount of fluids these machines

hold (Figure 2). By applying oil analysis along with proactive maintenance, a significant downward trend in consumption ratio is generally achieved in the first several years. An example of how to achieve improvements in consumption ratio was presented in the Tutuka Power Station case study in the May-June 2001 issue of *Practicing Oil Analysis* magazine.³

Summary

There are many factors and considerations to making the oil change decision. For critical machinery and in cases when the cost of the oil change is high, there is real need to challenge the norm and past assumptions. The scorecard presented in this paper offers a systematic process to efficiently use a customized weighing process to arrive at a near optimal decision.

The author welcomes comments or suggestions on how the scorecard could be improved.

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Condition-Based Maintenance and Flushing for Hydraulic and Rotating Machinery

BY TOM ODDEN – MATOR AS

Component breakdowns and intrusion of external contamination will occur from time to time, even with an effective and reliable condition-based maintenance in place. Most systems are designed to prevent particle contaminations from spreading in the system. Moisture can easily be spread, and organic growth will typically occur in the most inaccessible places in the system. To correct these situations, we cannot take a casual approach, merely limiting the actions to replace components and change filters. When detecting deviations during routine condition monitoring, we must verify the extent of the problem and determine the level of system cleaning and flushing needed. With a practical approach, we can bring the system back to design performance and minimize the consequential damages without forgetting to evaluate the cost-benefit.

Introduction

Most systems are designed to perform the main task: to produce compressed air or gas, to pump oil or water, etc. The design of the lube and hydraulic systems are seldom made for optimizing long life and easy service. Often, the result is that the reservoirs accumulate contaminants and moisture. After some time, the pump chews dirt and spreads it throughout the system.

Inside the reservoir, tube and pipe system, moisture forms a film at the surfaces, and after some time, develops into slime.

In this film or slimy surface, particles stick easily and contaminants will accumulate in the system.

Due to these contaminants – or addition to – components will wear out and will have to be replaced. These situations will increase the amount of contaminants in the system.

If the condition monitoring does not unmask the situation, we can add a breakdown, and we have a complete disaster.

Unfortunately, it is more a rule than an exception to replace the defect component and start the system as soon as possible, for time is money! At best, the system is topped-up with filtered oil.

All contamination ingested during service, wear debris after breakdown and accumulated contaminants after years in service will stick in the oil and at the surfaces. The amount of slime will increase, as bacterium and yeast continue to grow. This is common situation for many plants.

When to Flush System

A newly fabricated system or one that is in-service requires different approaches for when and how to perform flushing. In most cases, practical limitations and overall requirements for individual machines impose restrictions on how to flush. It is important to be aware that flushing can become time-consuming, and it may be difficult to predict the time required.

Often, due to system design constraints, as little as one-third of the total time is spent on the flushing activity itself. Two-thirds of the time is used to mobilize flushing equipment and workers, disassemble sensitive components, assemble by-pass lines, connect flushing hoses, preclean the flushing fluid, fill the system and heat the flushing fluid and piping. Well-planned and well-performed flushing practices give considerable return on investment.

In this case, we focus on systems in-service and therefore do not discuss flushing at a fabrication stage.

The foundation of the flushing results from condition monitoring, time-based maintenance or after service on the system. Every time a machine is opened for service, one must consider whether flushing needs to be performed.

Flushing of a System In-Service

Outdated system designs result in accumulation of contaminants in the reservoir. Low fluid velocity allows contaminants to settle in piping as well. Lack of sufficient filtration intensifies the accumulation effect. Layers of contaminants will occasionally rip off and could result in breakdown and/or function failure.

In some cases, it is more cost-efficient to perform periodic cleaning (such as a proactive flushing) instead of a costly upgrade or a complete modification of the system. It is often possible to perform a flush while system is in operation or with short shut-down periods.

Cleaning After Breakdown, Repair or Time-Based Maintenance (Inspections, etc.)

In a properly designed system, contaminants from pumps or motor failures are restricted to a certain part of the system by inline

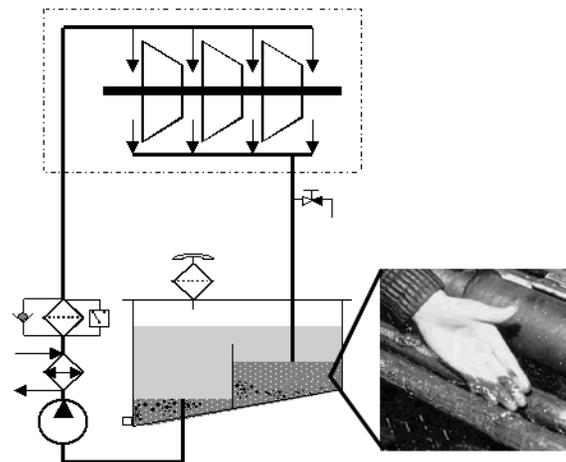


Figure 1. Example of Compressor Lube System

filters. In these cases, flush the reservoir, piping and components within the contaminated area.

In most cases, contaminants from breakdowns are spread throughout the system. Although some contaminants may be removed by an in-line return filter (with by-pass) and some may settle in the reservoir, the whole system must be cleaned.

It is possible to start up a system without extensive flushing when replacing complete components (such as bearings or pumps) before breakdowns. By doing this, it is important that the system runs without full load (unpressurized) until the contamination level is confirmed to be within acceptable limits.

Flushing After Modifications and/or Updates

Should be handled similar to newly fabricated systems.

Condition-Based Flushing (Proactive Flushing)

To decide when to flush a complex system requires good sampling practice to determine the right conditions. Typical systems with this complexity are hydraulic cargo systems in oil tankers (remote-operated valve systems, winches etc.) and top-side hydraulics at oil platforms. Both types of systems have a central hydraulic power unit (HPU) and ring-lines with several connected users.

It is easier to make a decision regarding a less complex system such as standard hydraulic systems and smaller lube systems. Lower initial costs also make it easier to make the right decision.

If the system is heavily contaminated - for instance, with leaking water, particle contamination and bacterial growth - one must seriously consider both chemical cleaning and hot oil flushing. This is the same procedure as the final step in a fabrication. If the condition-monitoring program is set up the right way, you will avoid this costly reset of your system.

The environment also effects how to perform the flushing. Weather and accessibility are important factors.

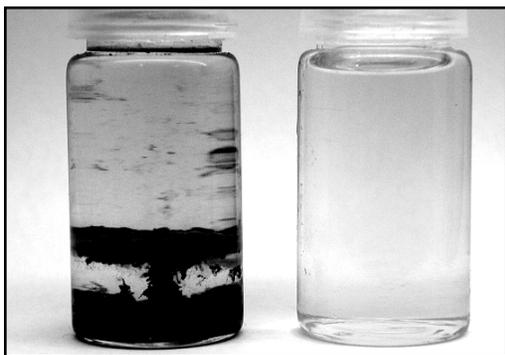


Figure 2. The left sample is from a reservoir with bacterial growth. The sample to the right is after cleaning.

Inspection and Sampling

Samples must be taken from the most outlying parts of the system and from the reservoir, to clarify how far in the system the contamination has spread.

Representative flushing samples are vital to get the right information. In a reservoir, samples are taken from the lowest point (drain plug), or by sampling from lowest bottom at lowest point. Pipe system samples must be taken from places with low flow and from dead legs.

It is often necessary to open some components to visually inspect them.

The Flushing Plan

Flushing demands good planning, experienced professionals, as well as teamwork.

The need for an external pump system must be evaluated. If the system does not have available a high-capacity accumulator system or oversized system pumps, an external flushing rig is needed.

Be aware that this method of cleaning is not as efficient as hot oil flushing, but will be sufficient in most cases, according to cost-benefit evaluation.

The main tasks to be considered include:

- Decide if external experts and capacity are needed.
- Establish a procedure: Use guidelines from international standards and existing procedures, and adjust them to your system.
- Calculate necessary flushing rig capacity in order to achieve:
 - Turbulent flow ($Re^3 > 4,000$)
 - A fluid velocity $n^3 > 3m/s$ to loosen and transport contaminants out of the system
 - As high fluid temperature as components can accept to melt down the dirty oil film at the surfaces
 - Filters to reach sufficient cleanliness



Figure 3. The left sample is from a hydraulic system showing rust, oxidation and wear debris. The sample to the right is from new and clean oil.

- Specify the fluid to be used during flushing:
 - If system fluid has a high viscosity (>32 cSt), it is often necessary to choose a another oil with 15 to 22 cSt which are compatible with the original system fluid. This is to fulfill the requirement of turbulent flow and high velocity without oversizing the flushing rig unnecessarily.
 - Operating viscosity is vital for the required pump capacity.
- Mark flushing loops: Obtain necessary framework, tubes and piping
 - Specify by-pass loops to protect sensitive components.
 - Install loops to achieve enough flow in all parts of the system.
- Establish an isolation plan:
 - To divide the system in modules for easier cleaning.
 - To prevent damage to sensitive components.
- Safe job analysis:
 - To secure safety of personnel
 - To secure functional operation and prevent damages and breakdowns.

Execute Flushing and Reset the System

To clean systems with piping dimensions above 4" require similar dimensions of flushing hoses and pump capacity.

- Time consumption: In general, plan your time consumption in



Figure 4. Offshore supply boat operating in the North Sea



Figure 5. Left picture is Echa dip sticks with bacteria (left) and mold (right). To the right is a microscope picture of particles from a heavily contaminated system, close to breakdown.

three equal parts: one-third to mobilize, disassemble the system and assemble the first loops, one-third to perform flushing, one-third to disassemble the flushing loops, assemble the system and de-mobilize.

- Basic specifications: Figure 8 indicates that to keep a velocity above 3 m/s, the flow must be increased above the minimum turbulent flow ($Re=4000$).

As Figure 9 shows for piping above inner diameter 20mm, we must control the flow according to velocity in order to flush and transport contaminants out of the system.

Be aware that by lowering the viscosity, we can lower the pump capacity accordingly.

If we do not consider the velocity and operate only by Reynolds number (4000) for turbulent flow, we will have only 0.3 m/s in 200mm pipe (8 inch), thereby using a pump capacity of 560 l/min. To satisfy the velocity requirements³ 3 m/sec, we need ten times this flow (5,600 l/min).

Seldom do we have the possibility to operate with flows in a system in-service as specified above. These figures are mainly to be used after a disaster or after large rebuilds and factoring. When performing condition-based flushing (proactive flushing), it is important to make short flushing loops and to pulsate the flow as much as possible for stressing the pipes and tubes to loosen the contaminants from the surfaces.

- Cleaning of Reservoir: Reservoirs must be cleaned by drain down and mechanical/manual use of rags to clean the surfaces.



Figure 6. A truck arrives at site with flushing rig, hoses, armatures, pipes and tubing. It was necessary to use an external rig.



Figure 7. Left picture is 8" pipe-bend, to be connected into a flushing-loop. The picture to the right is from assembling a flushing-loop.

- Use lint-free rags.
 - Use environmentally friendly detergents.
 - Top-up the tank with filtered and cleanliness-controlled oil and start circulating with a filtration unit.
 - Do not circulate any oil in the system before cleanliness is controlled and approved.
- **Cleaning of gear:** It is difficult to make a common procedure for all types of gear, but the following guidelines should be considered. If the gear is split and components changed, it is easy to manually clean the housing at the same time. Generally, the best practice is to circulate clean oil with a filter unit from the drain plug to the filling plug and turn the gear slowly until proper cleanliness is achieved.
 - **Cleaning of accumulators and cylinders:** If there is no damage, sufficient cleaning can be achieved by operating the equipment. Accumulators can be pressurized and drained several times. Cylinders can be operated in a controlled way with return oil drained directly to a sump. Also consider the designed lifecycles for the components. Some actuators, for instance, operate remote-controlled valves designed for an operating life time of only 500 strokes.
 - **Documentation:** Document the basic parameters as they're achieved: cleanliness level, organic growth, moisture content, temperature and flow.

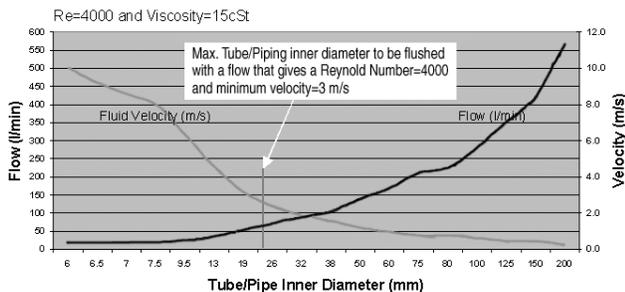


Figure 8. Flushing diagram

Summary

Proactive flushing based on a condition-monitoring program is in many cases a cost-efficient alternative to costly rebuilds and upgrades of the system.

Well-funded work routines, skilled personnel and a dependable condition-monitoring program can keep a system reliable and increase its expected life time.

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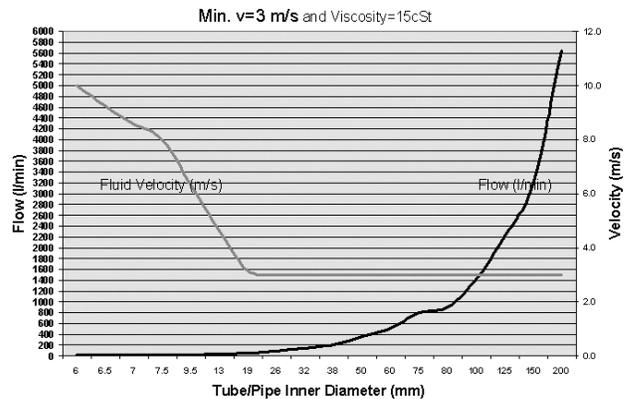


Figure 9. Flushing diagram

Selecting the Proper Lubrication System for Your Plant

BY STEVE CARTWRIGHT – LUBRISOURCE

Selecting an automatic lubrication system (ALS) for your equipment can be rather confusing. Understanding your plant requirements and production schedules, skill sets of your maintenance personnel, and machine lubrication needs are the first steps in implementing the right system for your equipment.

Important considerations in selecting any lube system include reliability, ease of maintenance, diagnostic feedback (fault indication) and cost. Before discussing the equipment selection, first create a profile of your production requirements and how critical they are to the overall plant production needs. An example of this is that your plant may be a job shop, with stand-alone machines for short production runs. In most cases, if a machine went down due to improper lubrication, you may be able to run the remainder of your quota on another machine while the lube system is being repaired. While such machines are critical to production, one lube failure may have little impact to the overall production quotas of your company. We refer to this type of plant as a class C facility. Another type of plant is a cell-manufacturing operation, with several machines supporting the main production line. A good example might be trim pressed in a die-casting plant. The actual die-casting machines are critical to production, and system reliability is paramount. Experiencing a bearing failure here could impact plant production, bottom-line profits and could take several weeks to repair. While your trim press is easier to repair, other presses may be able to produce the needed output until the downed press is repaired. This facility would be referred to as a class B operation. The class A plant is normally critical to a production facility, and any machine failures due to improper lubrication will affect the plant immediately, for example, paper mills, steel mills, transfer line production, power house, automotive plants. Also, plants with “JIT” requirements may qualify as a class A facility.

Now that we have identified your plant, you can also apply the same classifications to the machinery in the plant. Here is a quick outline of machines and their possible classifications.

Class C machine	Off-line machines	Bridgeports Small lathes, saws, Jig boring Small grinders
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Note: Any machine that does not directly support or affect production is considered a nonproductive machine, or in some cases, off-line.

Class B machine	Online support	Trim press Shuttle feeds, (press room) Small “C” faced press CNC machines
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Class A machine	Production machinery	Transfer lines Die-casting machine Injection molding Paper mill/steel mills Casting mills Press rooms Automotive lines
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This outline should provide a simple profile on which ALS will provide the maximum protection with a cost-effective approach.

I. Machine Architecture

A. Bearing types

1. Precision bearings cost to replace
2. Size
3. Load/speed each bearing is subject to

B. Bearing location

1. High wash areas
2. High contaminants area
3. Accessibility for repair
4. Sealed or open?

In summary, we now have plant classification for overall equipment specification that should be established plant-wide. Our individual machine classifications will now provide which ALS equipment may be the overall standard for the plant. Now we have individual machine profiles to confirm actual system controls, open loop or closed loop systems, fault indication, including final plumbing components, fitting types, hard line and flex line selection.

By developing a plant specification for components and specific ALS, we need to address the most critical issues in product reliability. The first is the maintenance personnel’s core competency in automatic lube equipment, proper installation procedures and maintaining the ALS.

Continuing education on your lube equipment is crucial to reliability and preventing bearing failure due to improper lubrication. Maintenance staffs are confronted with many problems with various products everyday. Creating a lube equipment specification will only streamline the learning curve on how to maintain and troubleshoot your ALS equipment. The outline listed below is a minimum standard for a class A plant.

I. Training Program

- A. Annual refresher all personnel
- B. New personnel lube course 101
- C. Service manuals on specific equipment for each maintenance employee

II. Dedicated Employee to Lube Maintenance Equipment Assessment

- A. Trained in specific machine lube intervals
- B. Trained in each ALS profile
- C. Has input on all capital equipment entering the plant for production
 - 1. Type of ALS
 - 2. Plant specifications met
 - 3. Initial start-up
- D. In some cases, the person will have the authority to stop machinery to avoid catastrophic bearing failures

III. Employee Will be Trained in Basic Fluid Management Skills

Most ALS units that show a lube fault is left alone because maintenance personnel are not confident in how the equipment works, let alone on how to troubleshoot the system.

In my opinion, this is the most important issue in improving the overall reliability in your plant lube equipment performance. It is simply good fluid management! More than half the ALS failures are due to contaminants. Most all ALS have small orifices, tight “spool to gland” fits on lube blocks. How you handle the lubricants from the dock to the hinged lid of the lube reservoir is important. The outline for basic fluid management plant requirements is for class A, class B and class C plants.

I. Fluid Storage

- A. Sealed drums with desiccant venting
- B. Mounted horizontal in racks
- C. Lubricant stored in one area in the plant
- D. Labeling of each grease gun
- E. Labeling of each grease reservoir with manufacturer of grease being used*

*Cross-contamination with grease manufactures can create complete equipment failures. It is not uncommon to scrap the entire ALS due to the grease solidifying within the system.

II. Fluid Transport

- A. Lube carts with labeling on each cart
- B. Tramp oil cart for pulling off lost fluids (usually color-coded)
- C. Pour containers should be airtight, oilsafe or equivalent

III. Plant Fluid Specification

- A. Establish baseline for new ISO target levels
- B. Install filters on all ALS units
- C. Recommended fluid cleanliness target for most ALS units is 30 microns
- D. Oil analysis on all recirculating lube systems
- E. Require lubricant supplier to meet a minimum ISO standard on all fluids for ALS units

	Fluid Mgmt.	Open Loop	Closed Loop	Positive Displacement	Fault Feedback	Oil Only	Oil Grease
Orifice Systems	H	√			P	√	
Series Progressive	M/H		√	√	VG		√
Injectors	M	√			F		√
Piston Distributors (PDI)	M	√			F	√	*
Recirculating	H	√		√	G		√
Dual Line	M		√	√	G		√

*NLGI 000/00 only

G = Good, VG = Very Good, F = Fair, P = Poor, H = High, M = Moderate

Table 1. Automatic Lubrication Systems

Using the Blotter Spot Test to Detect Soot, Fuel and Glycol in Engine Oils

BY GERARDO TRUJILLO - NORIA LATIN AMERICA

The blotter spot test dates back to the early 1950s and is one of the oldest techniques used to identify excessive engine soot, evaluate the dispersancy performance of lubricants and detect the presence of glycol, diesel fuel and other contaminants in diesel engine crankcase lubricants. Several different field methods and even sophisticated instruments are in use to take advantage of the benefits of this simple technique.

An excellent paper presented at the 1999 Practicing Oil Analysis Conference by Esteban Lantos, "The Blotter Test: A Simple Method for Monitoring Internal Combustion Engines," induced us to try to put in place this technique to monitor in field, three of the four killers of diesel engines: fuel dilution, soot load and glycol contamination. Dirt is the fourth killer, but it cannot be detected using the blotter spot test.

This paper is a compilation of the methods and experiences gained during the implementation of the blotter spot test in the one of the most important passenger ground transportation companies in Mexico.

Scope

The company operates more than 2,500 buses, which travel approximately 500 miles daily. A standard oil change procedure has been put into place which requires the oil to be changed every 25,000 miles. This equates to 1,500 oil changes per month. At the start of the program, an oil sample was taken every oil change and sent to the laboratory for complete oil analysis.

Oil analysis was performed in an independent laboratory located in Houston and the results were delivered electronically to each service shop for trending and interpretation. The turnaround time from the time the oil sample was collected to the time analysis results were received, averaged 16 days. This was mainly due the logistics associated with consolidating the oil samples from different service shops and sending them to the lab.

The oil analysis program delivered some benefits to the company, alerting it about diesel fuel leaks and glycol contamination, and helping detect combustion problems and abnormal wear. However, the maintenance manager was not satisfied, because he had to wait up to 20 days to find out that an engine had a problem in the last oil change. In some cases the problem could be present in an engine for more than 40,000 miles before oil analysis detected the problem.

A plan was presented to refine the procedure and use the blotter spot test on-site, as a primary way to detect problems in diesel engines and as a decision tool for maintenance inspections and actions.

The Blotter Spot Method

When a drop of used crankcase oil is deposited on the surface of chromatographic paper, capillarity causes the oil to spread. The linear velocity of oil decreases as the border of the resulting oil spot recedes from the deposition point, until the oil finally stops expanding. Solid materials dispersed in the lubricant are retained by the capillaries of the paper. The smaller the particle, the farther it is likely to travel from the center of the spot. Identically sized particles should travel identical distances.

Procedure

- Shake sample vigorously for one minute.
- Uncap sample bottle.

- Draw oil sample with a sampler.
- Place one drop of oil on the mark of chromatographic paper.
- Deposit excess oil from the sampler into the waste oil container.
- Clean the oil sampler tube with paper.
- Let chromatogram develop six hours (soot and glycol).
- Inspect blotter for soot and glycol.
- Compare chromatograms with standard comparator.
- Record results in data sheet.
- Let chromatogram develop 18 additional hours (24 total) for fuel dilution development.
- Inspect chromatogram with UV light for fuel dilution.
- Compare chromatogram with standard comparator.
- Record results in data sheet.
- Report abnormal conditions.
- Send oil sample to laboratory for exception testing if necessary.

Methodology

The blotter spot test procedure is extremely simple and inexpensive, but we found that interpretation can be somewhat complicated. It depends on several factors:

- Sample preparation,
- Sample amount,
- Paper type and development position,
- Development time,
- Time to interpretation, and
- Interpretation conditions (white light and UV light).

The strategy of sending oil samples to a laboratory for complete oil analysis continued, but the samples were also tested individually

on cards of Whatman #4 paper. Each chromatogram was identified and filed for posterior comparison with lab results. When oil analysis results arrive from the laboratory, only abnormal results are compared with their respective blotter, then results and observations are registered on the same card. Abnormal laboratory results and their respective blotters are separated and classified in three groups-soot, fuel and glycol.

With time, technical personnel gained visual experience and were able to identify suspected problems based on the chromatogram's appearance and the results of formal oil analysis. After this learning experience, interpretation was attempted before laboratory results. Diagnosis was made based on chromatograms interpretation. The diagnosis was then confirmed with oil analysis results from the laboratory until personnel gained enough knowledge to be able to depend on the blotter spot method.

Abnormal results were classified according to severity and a code was created for each category. This simplified the interpretation and decision process. Also, a reference standard was created to help implement the program in different service shops (Figure 1).

The Blotter Codes

A three digit blotter code was created to report results. The first digit is soot load, the second is for fuel dilution and the third relates to glycol contamination (soot-fuel-glycol). Each code has three possible categories which are related to the observed conditions and correlated to laboratory data (Figure 2).

When results are reported, the position relates to the contaminant or condition, while the numbers identify the severity of the problem. For example, an oil sample showing excessive soot load, but fuel and glycol negative, will have a 3-1-1 result. (3 Soot, 1 Fuel, 1 Glycol).

Chromatogram Patterns

Four different zones can be observed on each chromatogram (Figure 3):

- C - Center Zone: where the original oil drop was initially deposited
- A - Aureole Zone: Rings formed outside of central zone
- D - Diffusion Zone: Area of diffusion of medium to small size particles
- T - Translucent Zone: End of the chromatogram (base oil and diesel fuel)

Inspection/Interpretation

After six hours of developing, chromatogram is placed on a box light to examine for soot and coolant (glycol) (Figure 4). The white light provides a uniform light source and a uniform amount of light during interpretation. It also reduces variability of intensity and color. The technician compares the chromatogram with the respective standard and reports the condition in the data sheet.

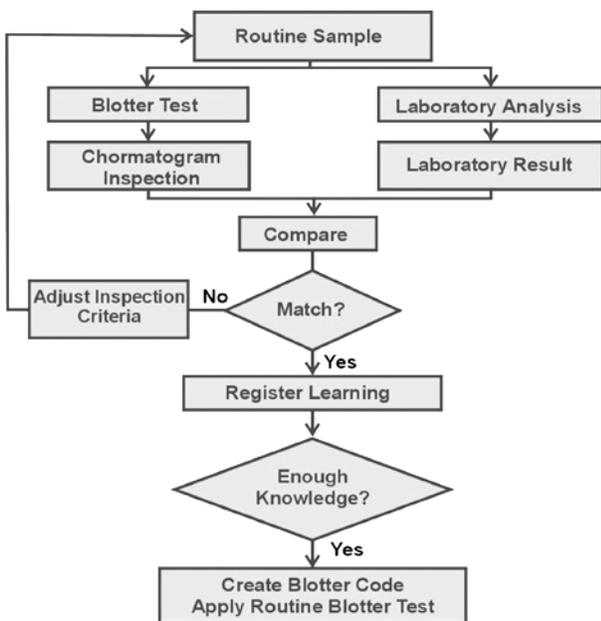


Figure 1

Codes Correlation

Code	1 - Normal	2 - Abnormal	3 - Critical
Soot	Up to 1.5%	1.5 to 4%	4% +
Fuel	0 to 2%	2 to 4%	5% +
Glycol	Negative	Traces	Positive

Figure 2

Chromatogram Patterns

Code	Soot		Fuel		Glycol	
	C	A	C	A	C	A
1	C	None	C	None	C	None
	A	None	A	None	A	None
	D	Large, gray, traslucent	D	Large, black/gray, traslucent	D	Large, black/gray, traslucent
	T	Small	T	None fluorescent*	T	Small
2	C	Medium, black, opaque	C	Medium, black, opaque	C	Medium, black, brownish, opaque
	A	None	A	Well defined ring	A	Possible outer ring
	D	Small, gray to black, opaque	D	Medium, gray to black, opaque	D	None
	T	Medium	T	Small, flurescent ring*	T	Medium
3	C	Small, black, opaque	C	Large, black, opaque	C	Small, black, sticky, pasty
	A	None	A	Well defined ring	A	Well defined outer ring (sharp edged)
	D	None	D	None	D	None
	T	Large	T	Large fluorescent ring*	T	Large

*Using UV light

Figure 3

Soot

Excessive soot contamination or extended drain intervals causes the depletion of dispersant additives and the agglomeration of soot particles, forming larger particles. Once this occurs, the oil's viscosity increases. When the oil drop is deposited on the chromatographic paper, the larger particles will not travel with the base oil and will form a black spot from the point of deposition.

If additives are doing their job, soot particles will be small and finely suspended in the lubricant. When the oil drop is deposited on the chromatographic paper, soot particles will travel easily and the chromatogram will show a translucent gray color.

Key indicators for Soot:

- Size of center spot.
- Color of center spot.
- Size of diffusion zone.
- Color of diffusion zone (black, gray).
- Aureole formation (incorrect injection condition).
- Density (translucent or opaque).

Coolant (Glycol)

Detecting glycol using the blotter spot test can be difficult because of its effects on a lubricant's dispersancy. Coolant contamination forms acids in crankcase oil affecting soot dispersancy, even at low soot loading. Glycol contamination can also form destructive "oil balls" and additive precipitation when thermally aged in crankcase lubricants. When an oil drop of a lubricant that is contaminated with glycol is placed on the chromatographic paper, the soot particles can be agglomerated due to dispersant depletion and will not travel. A dark or brownish stain in the center of spot could be due to disrupted dispersancy and soot coagulation, a common consequence of glycol contamination. A black sticky paste with a well-defined (sharp

edge) periphery is cause for serious concern. Very often a soot ring develops around a yellow/brown center when glycol is present (Figure 5).

Key indicators for Glycol

- Size and color of center spot.
- Texture of center spot (sticky, pasty).
- Size of blotter.
- Color of patterns (black, orange/yellow).
- Aureole formation (glycol presence).
- Density (translucent or opaque).

Diesel Contamination

After 24 hours of development, chromatogram is placed under a lamp of UV light in a dark room (Figure 6). Inspecting chromatogram under white or solar light interference will make it difficult to interpret.

Diesel fuel dilution directly affects additive concentrations, causing premature loss of dispersancy and leading to deposits and filter plugging. Also, if the problem's source is dribbling injectors, poor injection timing and/or excessive ring clearances, excessive soot levels that can affect dispersancy can be produced. The light ends of diesel fuel diluted in the lubricant will travel faster than base oil and other contaminants, creating a distinctive translucent zone at the outer ring of chromatogram. When inspected under UV light, this will show a fluorescent ring. The size and fluorescence will be proportional to the amount of fuel dilution.

The presence of well defined inner rings in the chromatogram is an indicator that at least one cylinder is working out of balance.

Routine Blotter Spot Test Program

The fleet is using the blotter test routinely (every time the bus is in the shop) as a screening tool to detect abnormal conditions.



Figure 4

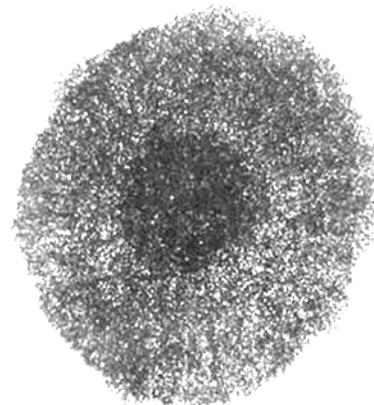


Figure 5

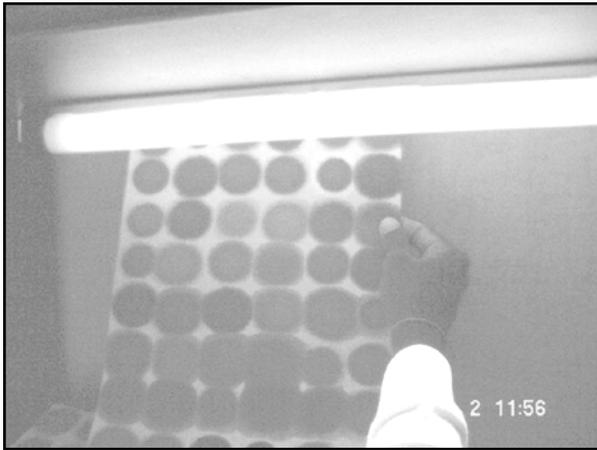


Figure 6

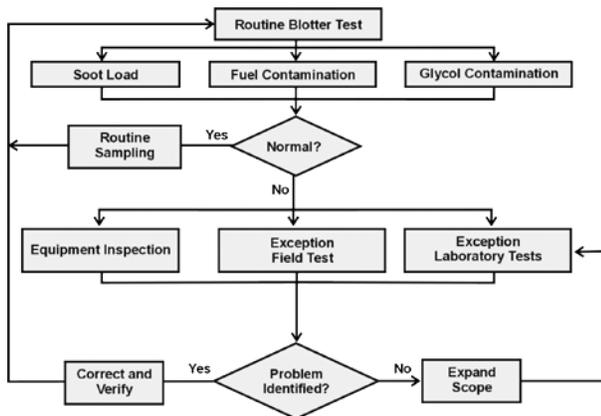


Figure 7

The most frequently detected problems are diesel fuel dilution and excessive soot load. Glycol has been the most difficult to detect, but when samples are suspected to have glycol contamination because of severe dispersancy failure, a filter inspection is ordered to confirm the glycol (refrigerant) leak. Saturated and wavy filter paper with some gel or sticky materials confirms glycol contamination.

Since the routine blotter spot test program started, no major failures have occurred to the fleet and problems detected are controlled in the early stages, helping to increase engine life.

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Practical Lubrication Strategies for Bearing Life Extension

By JOSEPH B. CONYERS AND GARY B. PATRICK - SKF RELIABILITY MAINTENANCE INSTITUTE

Reliability and maintenance eEngineers are often given the task of improving the reliability of bearing arrangements in a variety of applications. Lubrication is a key area to explore for improvement opportunities. During this presentation, we will use New Life Method to review typical bearing applications from a lubrication standpoint. New Life Method is the latest calculation technique for predicting the effects of lubrication and contamination on bearing life. Techniques such as determining proper lubrication schedules, choosing correct lubricant viscosities and film thicknesses, identifying and removing contamination sources and temperature control will be advanced as potential strategies for bearing life extension. Attendees will be shown how New Life Method allows them to select cost-effective, practical solutions from a toolbox of available practices - without guesswork. This can be the first step for reliability and maintenance engineers to plan a strategy for implementing a successful bearing lubrication program plant-wide.

History

The current basic method for determining bearing life (originally by Lundberg and Palmgren) is well-known. Bearing life is a function of the applied load vs. the basic dynamic load rating:

$$L_{10} = \left(\frac{C}{P}\right)^p \text{ and } L_{10h} = \frac{1,000,000}{60n} \left(\frac{C}{P}\right)^p$$

- = basic rating life, millions of revolutions
- = basic rating life, hours of operation
- = equivalent dynamic load
- = basic dynamic load rating
- = exponent for the life equation
- = 3 for ball bearings; 10/3 for roller bearings
- = speed, revolutions per minute

Equation 1. Basic Life Equation

Two general conclusions we can draw from the Basic Life Equation (Equation 1) are:

- Bearing life varies inversely with speed (double the speed, life is reduced by half).
- Bearing life varies exponentially with applied load () (double the load, life is reduced to 0.125 of its original value for ball bearings, even more for roller bearings).

The effects of these conclusions can be operationally dramatic. Consider a conveyor belt system whose speed we wish to increase 25 percent. Perhaps we can accept a bearing life reduction of 25 percent due to the speed increase. Are there other considerations? More material will be conveyed per unit time, increasing the weight on the system. Loads on the bearings will increase. If sheaves are changed out to achieve the speed increase, the V-belts may begin to

slip on the sheaves, which will be tightened to compensate. If the combined effect of these changes increased the overall load only 10 percent, life for the ball bearings in this application will be reduced an additional 25 percent. The overall loss of life may be unacceptable. Significant design changes may be required to offset the reduced bearing life from something that appears at the outset as only a straightforward speed increase.

Adjusting the Basic Life Equation

The advent of cleaner bearing steels in the late 1950s had a dramatic improvement on bearing life. Bearing manufacturing processes also continued to improve, and the basic life equation was extended to reflect these improvements. The Adjusted Life Equation was the result:

$$L_{na} = a_1 a_{23} \left(\frac{C}{P}\right)^p \text{ and } L_{nah} = \frac{1,000,000}{60n} a_1 a_{23} \left(\frac{C}{P}\right)^p$$

- = Adjusted Rating Life, revolutions
- = Adjusted Rating Life, hours
- = reliability adjustment factor
- = material and lubrication adjustment factor

Equation 2. Adjusted Life Equation

Reliability		
90%		1
95%		0.62
96%		0.53
97%		0.44
98%		0.33
99%		0.21

* Adjustment: Factor ₁

Figure 1. Values for Reliability

The a_{23} factor allows us to adjust the basic life rating equation for reliability greater than 90 percent (Figure 1). This factor can be used to down-rate applications where safety is critical. Another use of the a_{23} factor is in high-reliability applications. Bearings in aircraft turbine engines, for example, require extreme reliability. The weight penalty from enlarging the bearings and support components to meet reliability needs would be unacceptable. A more cost-effective decision in this case is to use smaller bearings and change them out at an operational life well below the predicted fatigue failure life to achieve an adequate safety margin.

The factors a_{23} (material adjustment) and a_{23} (operating conditions) are interdependent and are combined as a_{23} . These adjustments correct for the effects of modern steels and consider lubricant film thickness as a factor in bearing life. Figure 2 illustrates the relationship more clearly.

In order to use Figure 2, we must first determine the viscosity ratio, κ (kappa). Kappa is the ratio of the actual viscosity (ν) to the required viscosity (ν_1) of the application at the operating temperature. These viscosities can be calculated or selected from charts as in Figures 3 and 4.

Practically Applying the Adjusted Life Equation

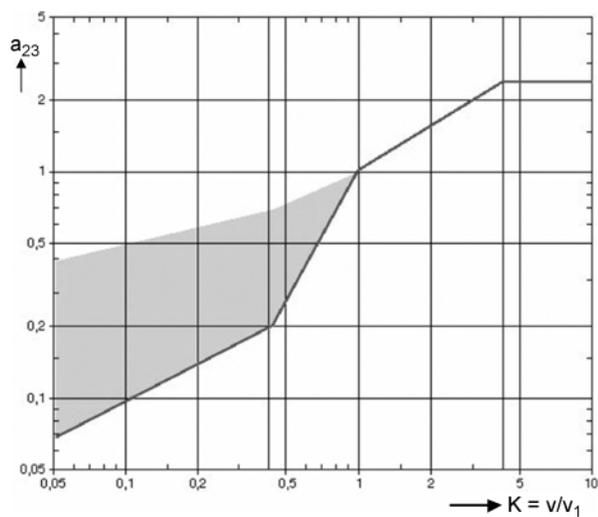
To illustrate the effects of the Adjusted Life Equation, we'll examine a 6210 ball bearing in an oil-lubricated application. From the catalog:¹

Bearing: 6210
 Bearing Boundary Dimensions: 50mm bore x 90mm outside diameter x 20mm wide
 Basic Dynamic Load Rating: 35,100 N
 Operating Conditions
 Applied Load: 4,500 N radial load
 Speed (n): 3,600 rpm
 Bearing Operating Temperature: 70°C

$$L_{10h} = \frac{1,000,000}{60n} \left(\frac{C}{P}\right)^3 = \frac{1,000,000}{60 * 3600} \left(\frac{35,100}{4500}\right)^3 \cong 2,200 \text{ Hours}$$

From Equation 1

To determine the adjusted rating life, we'll need the a_{23} and a_{23} factor. We'll assume no change in desired reliability above the standard 90 percent, so $a_{23} = 1$. To select a_{23} , we need to know the required oil viscosity at the operating temperature of 70°C. We use good quality, lightweight mineral oil (ISO VG32, VI 95). Figure 3 gives the required oil viscosity for a 6210 bearing, as 9 mm²/s. The actual viscosity of our ISO VG 32 oil at the bearing operating

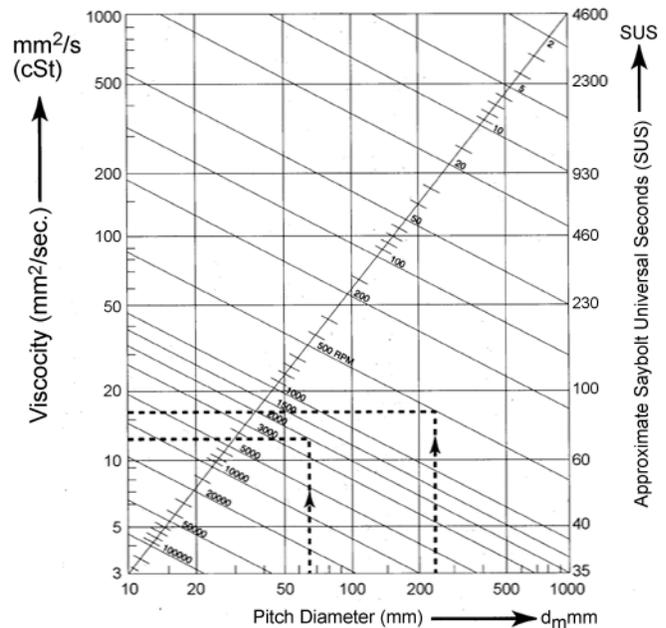


Use this chart to choose the value of a_{23} from a known viscosity ratio, Kappa (k).

The darkened area under the curve represents better performance that may be achieved with the addition of EP additives to the lubricant.

Note: This chart applies only to standard 52100 bearing steels. Contact your manufacturer if using stainless, ceramics or other bearing materials.

Figure 2. Factor a_{23}



Use this chart to determine the required minimum viscosity for bearings. Enter at the bottom of the chart with Pitch diameter ($d_m = (D + d)/2$). Go vertically until you intersect the sloped lines at the rotating speed of the bearing. Then proceed horizontally (right for viscosity in Saybolt Universal Seconds, left for viscosity in Centistokes) to get the minimum required viscosity at the bearing operating temperature.

Note: Higher minimum viscosity values are often recommended for proper lubrication of sliding contacts within the bearing. Contact your manufacturer for details.

Figure 3. Required Viscosity

temperature is about 11 mm²/s, giving a viscosity ratio, kappa, of ~1.2. Figure 2 gives us a resulting κ_{23} value of 1.15.

$$L_{naah} = \frac{1,000,000}{60n} a_1 a_{23} \left(\frac{C}{P}\right)^p = \frac{1,000,000}{60 * 3600} * 1 * 1.15 * \left(\frac{35,100}{4500}\right)^3 \cong 2,530 \text{ Hours}$$

From Equation 3

In this case, life is increased slightly when the effects of the oil film are included.

New Life Method

In many cases, using the Adjusted Life Equation was good enough as starting design point. But some lightly loaded, clean applications had operational lives far in excess of the life predicted by the Adjusted Rating Life Equation. Contaminated applications were tough design problems (and extremely dirty applications still defy accurate life prediction.) The SKF New Life Method is an extension of the Adjusted Rating Life Equation that predicts bearing life much more accurately when lubrication and contamination conditions are better known. It has allowed designers and manufacturers to take advantage of controlled downsizing, exploit the enhanced life potential of modern bearings and recognize the significance of contamination. A simplified equation illustrating the relationship to the two ISO (or ABMA) life equations has been derived:

$$L_{naa} = a_1 a_{skf} \left(\frac{C}{P}\right)^p \text{ and } L_{naah} = \frac{1,000,000}{60n} a_1 a_{skf} \left(\frac{C}{P}\right)^p$$

- = Adjusted Rating Life, New Life Method, millions of revolutions
- = Adjusted Rating Life, New Life Method, hours of operation

Equation 3. SKF Life Equation

The a_{skf} factor brings in two new concepts regarding bearing life. The first is that there is a minimum load for every bearing below which fatigue failure will not occur. In other words, the stress levels in the bearing are too low to produce subsurface cracking that eventually causes fatigue spalling in the bearing. The second concept is that the effects of solid particle contamination on bearing life are quantifiable. The relationship is complex but has been simplified through the use of charts, as in Figure 5. Three general conclusions that may be drawn from Figure 5 are:

- The thickness of the lubricant film has a significant role in bearing life.
- Oil film thickness greater than four times the required oil film thickness provides marginal benefit.
- Reducing the contamination in applications will greatly extend life.

Determining a more precise value of η_c requires a firm knowledge of application conditions. However, we can successfully examine the effect on life when changes are made to existing conditions (Figure 6).

Using Tables to Explore New Life Method

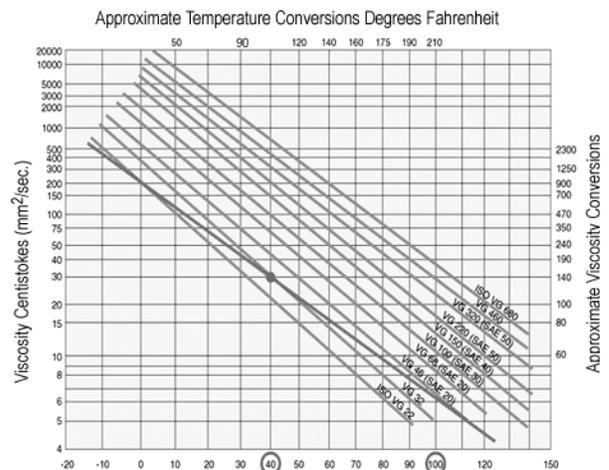
Our life for the ball bearing application was relatively short, on the order of three months, perhaps three and a half months using adjusted life. What can be done to extend the life of this application?

One technique is to use a table of values. We can explore the effects of varying a single controllable factor at a time and observe the result on bearing life. This will assist in the selection of the best practical solution for extending life. Exploring alternatives is made easier with the use of calculation programs (see Reference 2). The user can easily change operating parameters such as bearing size, oil film thickness, operating temperature and contamination conditions and record the results for a variety of cases. Reference 2 was used to produce Table 1, although similar results can be achieved using the tables and charts contained in Reference 1.

Example 1

6210 Single-Row Deep-Groove Ball Bearing (Table 1).

Bearing:	6210
Bearing Boundary Dimensions:	50mm bore x 90mm outside diameter x 20mm wide
Basic Dynamic Load Rating:	35,100 N
<i>Operating Conditions</i>	
Applied Load:	4,500 N radial load
Speed (n):	3,600 rpm
Bearing Operating Temperature:	70°C



Viscosity classification numbers are according to International Standard ISO 3448-1975 for oils having a viscosity index of 95. Approximate equivalent SAE viscosity grades are shown in parentheses. The red line indicates oil with a viscosity index of 138.

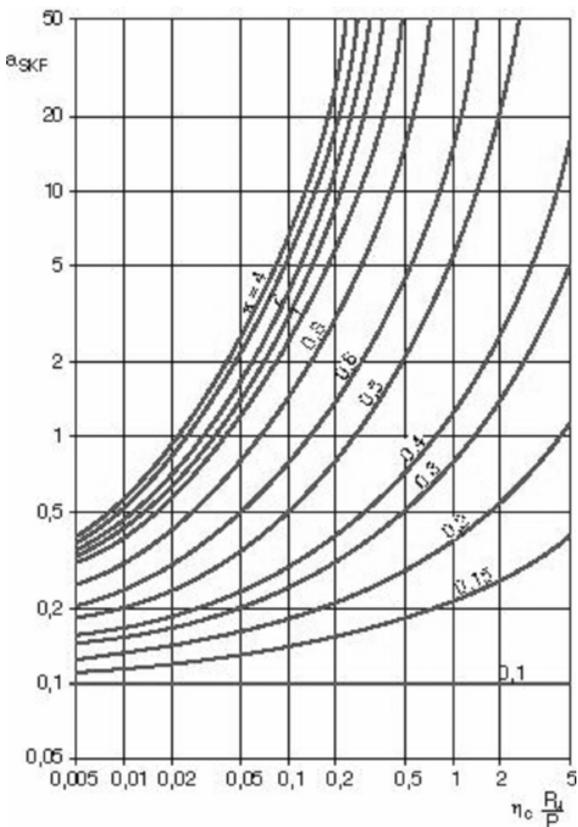
Note: When computing kappa using synthetic oils, use the same values as for mineral oils.

Figure 4. Temperature Viscosity Chart

Note: We have ignored secondary effects that may occur as a result of changing a single parameter. For example, increasing oil viscosity may result in an increase in friction, lowering the oil viscosity. For more accurate results, actual bearing temperatures can be estimated - contact your manufacturer.

Analysis: Sealing the bearings (Case 5) gives the most dramatic life improvement, about six times that predicted by the adjusted life calculation. Controlling the contaminants entering the bearing nets a huge improvement in overall life for very little cost. Secondary benefits with seals are controlled lubrication and prevention of overlubrication.

The other cases give significant life improvement, but may or may not be practical in the application. For example, increasing the



Similar charts are available for other bearing types, such as radial roller bearings, thrust ball bearings, etc.

P_u/P is the ratio of minimum fatigue load (available from the catalog) to the application's applied load.

η_c (pronounced ate-a-see) is the contamination factor for the bearing (see Figure 6).

Values are selected by entering the chart at the bottom with the calculated value of:

$$\frac{P_u}{P} \eta_c$$

Proceed vertically until you intersect the appropriate kappa value, then left to find the s_{kf} factor.

Values of s_{kf} over 50 are unreliable and should be disregarded.

Figure 5. Factor s_{kf} for Radial Ball Bearings

oil viscosity (Case 2) may be precluded by other components in the application that require the original oil, as in a compressor. Reducing the temperature (Case 3) or redesign to accept a larger bearing (Case 4) may be cost prohibitive. Adding cost analysis to the tables will reveal your best choice.

Example 2

Paper Machine Drying Cylinder (Table 2).

- Bearing: 22244
- Bearing Boundary Dimensions: 220mm bore x 400mm outside diameter x 108mm wide
- Basic Dynamic Load Rating: 1,760,000 N (Reference 3)
- Operating Conditions*
- Applied Load: 200,000 N radial load
- Speed (n): 250 rpm
- Bearing operating temperature: 110°C

Analysis: This application's adjusted rated life is severely degraded by the lack of adequate oil film thickness. The Basic Rated Life of 10.7 years is reduced to just 4 years due to poor oil film thickness (and resultant low kappa values) in the application. Readjusting with the new Life Method gets us back to 6.8 years, still quite low for a paper-making machine.

Reducing the temperature of the application (Case 5) might be accomplished by increasing oil flow rates. This may be impractical as drying cylinder oil flow rates have generally been optimized by the manufacturer.

Changing to oils with EP additives (Case 4) must be undertaken with extreme care. Some EP additives used in applications over 80°C can have a detrimental effect on bearings steels. They may chemically react with the steel, causing surface distress and premature failure.

Condition Values	η^1
Very clean	1
Debris size of the order of the lubricant film thickness	
Clean	0,8
Conditions typical of bearings greased for life and sealed	
Normal	0,5
Conditions typical of bearings greased for life and shielded	
Contaminated	0,5 ... 0,1
Conditions typical of bearings without integral seals; coarse lubricant filters and/or particle ingress from surroundings	
Heavily contaminated	0
(under extreme contamination, values of η_c can be outside the scale resulting in a more severe reduction of life than predicted by the equation for L_{naa})	
1) The scale for η_c refers only to typical solid contaminants. Contamination by water or other fluids detrimental to bearing life is not considered.	

Figure 6. Guideline Values for Factor η_c for Different Degrees of Contamination

Heavier oils (Case 3) should be considered. A thorough analysis (contact your manufacturer) should be made of the operating temperature change that may occur when a thicker oil is used. The temperature increase may offset the beneficial effect of the thicker oil on kappa values and a_{skf} .

Filtration (Case 2) is a good area to explore for improvement. This case introduced a 12-micron absolute filter to improve the η_c value from 0.50 to 0.74, resulting in a life improvement to 9.7 years. Exploring different filtration cases may help choose the most-cost effective strategy.

Additional Strategies

You can extend the value of these tables by factoring in the costs for applying the solutions and the expected return on your investment. The objective is to ensure the practicality of the applied solutions to extend life.

Improvements to reduce application contamination should be explored:

- Cleaner mounting processes - Simply putting up plastic barriers or moving the bearing assembly area to a cleaner atmosphere will result in life improvements.
- Grease and oil quality sampling as part of your supplier acceptance process.
- Oil prefiltering.
- Cleaning and flushing new applications after run-in.
- Consider portable and fixed water removal systems. New Life

Method does not account for contamination other than solid particles. The effects of water and other chemical contaminants, if present, must be addressed to achieve acceptable life extension using New Life Method. Anecdotal evidence reveals that as little as 0.1 percent water in oil (approximately one teaspoon water in one gallon of oil) can reduce the effective viscosity of oils by as much as 50 percent. Strive for 200-500 ppm water in your bearing applications.

After applying your solution, take time to verify your results. Lubrication condition monitoring can be prime sources for data. Particle counting, ferrography and spectroscopy can determine the size, number and composition of contamination particles before and after you implement your improvement strategy. Collect failure statistics. Examine failed bearings for root cause and correlate the results with your life improvement tactics.

Conclusion

New Life Method can be used to explore practically deployable strategies to successfully extend the life of bearings in rotating mechanical equipment. Using Case Analysis Tables with New Life Method for bearings allows us to start choosing the most cost-effective course of action to significantly extend bearing life.

Acknowledgements

Dan Snyder, director, SKF USA Applications Engineering Mark Cutler, North American engineering manager, SKF USA Industrial Division

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Case No.	Conditions	Temp. (°C)	η_c	Kappa a_{skf}	a_{23}	L_{10ah}	L_{10ah}	L_{10aah}
						Hours		
1	Existing Dirty Application	70	0.2	1.2	1.15	2200	2530	2480
2	Use Heavier Oil (VG 46)	70	0.2	1.6	1.4	2200	3050	2910
3	Reduce Temperature	50	0.2	2.4	1.8	2200	3900	3540
4	Increase Bearing Size to 6211	70	0.2	1.3	1.2	4210	4990	6220
5	With Sealed Bearings	70	0.8	1.2	1.15	2200	2530	14,900

* Modified Values are indicated in bold

Table 1. Extending Life - 6210 Single-Row, Deep-Groove Ball Bearing

Case No.	Conditions	Temp. (°C)	η_c	Kappa a_{skf}	a_{23}	L_{10ah}	L_{10ah}	L_{10aah}
						hours		
1	Existing Application	110	0.5	0.6	0.4	93800	35000	59500
2	Filter to Improve Contamination	110	0.74	0.6	0.4	93800	35000	84800
3	Use Heavier Oil (VG 320)	110	0.5	0.7	0.6	93800	53200	110000
4	Add Lube with EP additives	110	0.5	0.6	0.8	93800	73400	136000
5	Reduce Temperature	90	0.5	1.0	1.0	93800	94000	257000

Modified Values are indicated in bold

Table 2. Extending Life - 22244 CCK Spherical Roller Bearing

Best Practices for Flushing Gearboxes and Bearing Housings

By MIKE JOHNSON – NORIA CORP. AND GERARDO TRUJILLO – NORIA LATIN AMERICA

Gearboxes and bearing housings periodically need a thorough flushing rather than a simple drain and fill. There are several tell-tale signs that would point to the requirement, such as overheating of the sump, gross liquid or solid contamination, development of a severe wear pattern, etc. Material evidence in the form of sludge, rust, moisture, wear metals, gel or other viscous residue noted at the initial moment that the drain begins should confirm to the technician that a flush is in order. A thorough flush is also useful to remove construction and assembly contaminants from equipment sumps prior to commissioning.

With these factors in mind, what constitutes a thorough sump flush? Are there any particular problems that the operator should be careful to avoid? What equipment can or should be used for this purpose? Finally, what items should be included in a detailed flushing procedure?

What is Flushing?

Flushing is a clean fluid circulation process designed to remove water, chemical contaminants, air and particulate matter (not fixed to surface) resulting from construction, normal ingress, internal generation or component wear.

Flushing process can be useful in many different circumstances, such as:

- For new or rebuilt machines to remove contamination resulting from manufacture, service or overhaul. The fluid system can be seriously contaminated from dirty assembling elements, corroded surfaces, water, oxidation products and incompatible elastomers such as seals, sealants, coatings, etc. Also, during the assembly process, dirt is ingested and debris is generated due to threading, joining, welding, etc.
- For in-service machinery after an oil change due to heavy fluid contamination, component failure, extremely degraded lubricant (oxidation), or if a system flushing has not been performed in the past three years.
- For gearboxes and bearing housings that are not fitted with filtration, flushing is required to remove contamination and sediment. Water, rust, excessive wear debris, sludge, varnish or lacquer, hard to open drain port, etc., all suggest system contamination problems and should trigger a hard look at a thorough flush, because 10 percent of the old contaminated or depleted lubricant may be enough to use up most of the additives of the new oil.

What Can and Cannot be Removed by Flushing

Material attached to contact or noncontact surfaces that may be harmful to lubricants or critical working surfaces is generically called soil. Soil may be composed of material that is generated internally, such as varnish, carbon deposits, chemical residues, sludge, rust, etc., or may be composed of material that is generated externally, such as scale, welding slag, rust, machining swarf and metal debris.

Soils may be mechanically or chemically removed. Flushing is a

type of high-pressure, high-flow fluid circulation used to generate physical movement of contaminants. At the pressures/flows used for flushing, circulation of clean fluid in the system cannot clean rust and scale from the piping, deburr machined elements or remove flux or weld slag.

Flushing Methods

Depending on the machinery's internal conditions and type of contaminants required to clean from the system, three levels of system flushing are practiced:

- **Recirculation cleaning:** recirculation of clean fluid at a high velocity to achieve a turbulent flow to help contamination to be removed from fluid system.
 - Power flushing: A variation of recirculation, where the oil level in the sump is reduced and a high-velocity fluid is applied to:
 - mechanically dislodge, lift and entrain particulate debris
 - suspend and transport particles
 - absorb air, chemical products and water from the system
 - release the contaminants to a filter.
 - Wand flushing: A wand is attached to one of the cart hoses and is used first to discharge at high pressure (kicking up adherent debris) and then the flow is reversed and the wand vacuums the sediments.
- **Solvent cleaning:** Use of solvents to remove organic deposits that cannot be removed by recirculation. Solvent cleaning may incorporate the use of organic (hydrocarbon-based) halogenated, nonhalogenated and blends solvents (type A-1 cleaners such as kerosene, or A-2 cleaners such as naphtha and Stoddard solvent are common) to dissolve heavily crusted or layered carbon residues.

Organic solvents tend to be blends of aliphatic and aromatic hydrocarbons and tend to dissolve soil as opposed to emulsifying soil. These materials may be warranted if evidence of heavy carbonaceous residue exists. Solvent cleaning is outside the scope of this paper.

- **Chemical cleaning:** Use of chemicals that can dissolve inorganic components. Chemical cleaning may incorporate the use of aqueous alkali or acid solutions to accomplish the desired result. Chemical cleaning is outside the scope of this paper.

Key Factors for Effective Flushing

- **Fluid properties:** Fluid solubility and hygroscopic characteristics influence removal efficiency of water, air and chemical contaminants. Most oil companies supply special flushing fluids (rust-inhibited oils with good solvency power) that demonstrate the following desirable properties:
 - Compatible with system components and lubricating fluid
 - Noncorrosive to machine components
 - Low viscosity (lower than the lubricating oil used in the system)
 - High density to suspend particles
 - Low surface tension to eliminate air
 - High solvency
 - Hygroscopicity (for water removal)
 - Nonflammable
 - Economical
 - Reclaimable.
- **Fluid Turbulence:** To remove particles, the flushing process depends on the lift forces, drag forces and the depth of the laminar sublayer in the stagnant fluid next to the conduit wall. To achieve a good particle removal, the fluid must be turbulent. The indexless Reynolds number measures turbulence. In general, a number greater than 4,000 represents turbulent flow and less than 2,000 represents laminar flow. Hydraulic and circulation system designers strive to create laminar flow conditions. For gearbox and bearing housings fed with a central system, turbulence is necessary. For stand-alone housings, the effect of turbulence and the ability to direct the force of the fluid facilitates movement of soil.

The Reynolds number can be calculated by:

$$Nr = 3160 * GPM / CS * D$$

Where

GPM = flushing fluid flow rate in gallons per minute
 CS = flushing fluid viscosity – centistokes at 40°C
 D = pipe/tube inside diameter – inches

There is some risk associated with the high-velocity flush. Circulation of a fluid at high velocity with particulate contaminants can damage sensitive components (pumps, heat exchangers and valves). Also, such high pressures and flow can affect system filters. It is necessary to bypass flow or contaminant-sensitive components.

Filter housings can be left in place if filter elements are removed.

Components that restrict the flow rate, and thereby increase the pressure drop, should be isolated from the flushing circuit and cleaned individually.

Flushing Equipment

The flushing equipment required depends on the size, location and installed devices on the machinery.

- A mobile filtration unit is of great help if the pumps are capable of providing a flow rate at least twice that normally used in the fluid system or the flow requirements for the proper Reynolds number (see below).
- Air breather is required to prevent dirt ingress during flushing.
- Use large duplex filters (Beta 3= 200 or higher) with differential pressure indicator to allow changing the filters without interrupting the flushing.
- If water removal is desired, include a filter with water-absorbing capabilities.
- A heater should be required in case of low ambient temperature to maintain or reduce fluid viscosity and achieve the flow requirements.
- Permanently installed quick-connectors are of great help for flushing or filtration if the connector and piping are large enough to facilitate flow.
- In some cases a reservoir other than the machinery sump is needed to contain the high volume of fluid required for the appropriate flushing.
- A sampling port should be included upstream of the filter in order to analyze the fluid to know when system cleanliness is achieved.
- An in-line, flow decay-type particle counter is the best option for this. If particle counters are not available, the use of an optical filter patch can help to determine cleanliness of the system.

Flushing Procedure

The flushing procedure depends on the specifics of machinery, plant conditions and flushing equipment. To obtain the best results follow these guidelines:

- Drain the used oil while hot, so the viscosity is low and contaminants are still suspended and can be drained within the oil.
- Inspect the drained oil and drain ports for excess of contamination that may indicate the need for power flushing or wand flushing.
- If drain port is not located at the lower point, heavy solid particles, water, emulsions, etc., will stick to the bottom of the reservoir. Wand flush will be required.
- Remove oil filters from system.
- Block or bypass sensitive components.

- Block or bypass components that can reduce fluid velocity.
- If necessary, divide the system in sections.
- Connect the flushing equipment to gear box or bearing housing.
- Install air breather.
- Circulate and heat the fluid if necessary to reduce viscosity and pressure drop.
- Flush at specified Reynolds number to achieve turbulent condition.
- Monitor the contamination level (in-line particle counter readings or sample fluid and optically inspect filter patch).
- Circulate fluid an additional 15 minutes after cleanliness level is achieved.
- Drain and blow the system with dry, filtered air.
- Remove flushing connectors.
- Empty and clean filter housings and install new filter elements.
- Refill the system with filtered specified lubricant.
- Circulate (filter) new oil at least seven times before operating the equipment. Use a filter cart in systems without filtration.
- Label and store flushing fluid.
- Analyze flushing fluid for suitability for further use.

Flushing Cleanliness Targets

For gearboxes and bearings, the target cleanliness level for flushing should be at least one number below the cleanliness level for the operating fluid. A minimum of 16/14/12 (ISO 4406.99) is recommended for critical gearboxes and element bearings.

Conclusions

Flushing process may be perceived to be an expensive, complicated and time-consuming extra task for an oil change. However, some conditions justify the effort. Highly contaminated reservoirs on critical systems warrant extra attention to assure a high state of reliability.

Flushing is required for new and rebuilt equipment prior to commissioning to sustain high levels of reliability. A proactive maintenance approach of deploying flushing for in-service bearings and gearboxes helps to increase lubricant life and equipment durability. Generally the flushing efforts and costs are well compensated with increased reliability related to system cleanliness.

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Building Compressor Reliability with Lubrication Best Practices

BY DARYL BEATTY - DOW CHEMICAL COMPANY

Several mega-trends in our world have either influenced or accompanied changes in compressors and compressor lubrication in the past 25 years. Environmental awareness, and the awareness of limited resources accompanied the shift away from reciprocating compressors, which required enormous amounts of lubricant, and discharged it all into the air and the environment. The shift to rotary and centrifugal compressors addressed this issue and resulted in greatly reduced consumption of lubricants, and at the same time did a better job of keeping the fluid in the compressor. Also, the lubricants changed. Hydrocarbon lubricants were subject to frequent change schedules to avoid varnish problems in the compressor. Synthetics were developed to resolve those problems. These went even further, as many synthetics are now biodegradable and even have limited solubility in water. This means that the small amount of lubricant that leaves with the compressor condensate causes no problem for waste-water treatment plants. Another trend, like it or not, is the trend toward reduction of labor for maintenance. Longer-life fluids, and compressors requiring less maintenance have accompanied this trend. The mega-trend toward energy conservation was met with a new generation of rotary compressors, incorporating two stages, capacity controls, variable speed drives and varnish-free synthetic lubricants that avoid the unnecessary losses of energy efficiency. Change and progress will continue.

What does the future hold in the area of compressor lubrication? What are the current best practices in lubricant selection and lubricant analysis for air compressors? What specific types of lubricants are commonly used in compressors to meet the needs established here? When should synthetics not be used? What are the necessary components of an effective lubricant analysis program for compressors, along with change intervals, and common lubrication-related compressor maintenance pitfalls?

Types of Synthetic Lubricants Commonly Used in Compressors

Virtually every type of basestock has been used with some degree of success as a rotary compressor lubricant. The lubricant must fill several functions, sealing rotors, lubricating bearings, and also serving as a heat transfer fluid. In addition, it should not varnish, should have excellent corrosion protection, and have a low vapor pressure to assure low fluid carryover into the air system. What types of fluids meet these requirements? Table 1 shows the basestock types for the standard factory fill fluids for the major rotary compressor companies in North America.

Although there is some variation among the recommendations of compressor OEMs, there are some general trends and useful observations. Polyglycol/ester blends and PAOs have largely replaced hydrocarbons and the earlier synthetic fluids, such as diesters. The compressor OEMs are about equally divided on ISO 32 viscosity versus ISO 46 viscosity. Most of those using PAO are

specifying ISO 46 fluids, which yield a viscosity at 100°C similar to that of an ISO 46 polyglycol/ester type fluid. Viscosities of the actual fluids tend to be 7 cSt to 10 cSt at 100°C. Also, three of the four largest compressor companies in North America are now using polyglycol / polyol ester blends as the primary recommendation and factory fill in the compressors. In all cases, PAO fluids are available for use in H-1 food industry applications. A few also have other types of fluids available for specific uses, such as silicone, polyol ester and hydrotreated hydrocarbons.

When Should a Synthetic Fluid Not be Applied?

Nearly all compressor OEMs now use and recommend long-life synthetic fluids. Exceptions to those recommendations are generally made after the fact, when an application is found to have excessive levels of acid gases and other air contaminants, that would cause early fluid failure or accumulate in the fluid to caused corrosion in

Manufacturer	Standard Fluid Fill Type or Primary Recommendation	Other Significant Options
Ingersoll-Rand	ISO Polyglycol/Polyol Ester Blend	PAO - For H-1 Applications
Sullair	ISO 32 Polyglycol/Polyol Ester Blend	Silicone - Optional PAO - for H-1 Applications Hydrotreated Hydrocarbon
Gardner Denver	ISO 32 PAO	Polyol Ester - Biodegradable applications
Quincy	ISO 46 Polyglycol/Polyol Ester Blend	Polyol Ester for High Pressure Units PAO - For H-1 Applications and General Use
Atlas - Copco	PAO	Hydrotreated Hydrocarbon
Kaeser	ISO 46 PAO	Unknown
Palatek	ISO 32 Hydrotreated Hydrocarbon	Polyglycol/Ester Blend; Polyol Ester

Table 1. Factory Fill and Recommended Fluids of Major Rotary Compressor OEMs

the compressor. In those cases, hydrocarbon fluids are generally recommended because of low cost, and the fluid is changed on a 1000-hour or even more frequent schedule. Also, portable engine-driven compressors are typically supplied and recommended for use with hydrocarbon fluids, again due to the contaminants ingested in the environments they are commonly used in. These compressors are also typically changed on a 1000-hour schedule, with no analysis.

Gas Compressors

The recommendations of rotary screw gas compressor companies vary not only with the equipment, but with the pressure and type of gas being compressed. There is not a simple formula, and manufacturers such as Ariel supply tables to determine lubricant type and viscosity based on the application. Special water-soluble polyglycols, PAO, diesters, as well as hydrocarbon fluids are all commonly used in these compressors. Viscosities are typically much higher than those used in air compressors, ranging upward from ISO 100, due to the viscosity dilution effects of the gas being compressed when it dissolves in the lubricant.

Key Analysis Parameters for Compressor Fluids

Approach the development of a compressor fluid analytical program by first asking several questions.

- What are the goals of the analysis program? Three are suggested, two related to the fluid and one for the compressor itself. The most basic goal is to establish a fluid change interval and to assure that the fluid in use is still suitable. Second, and unique to rotary compressors, analysis serves also to identify problems and contamination in the inlet air, which is manifested as chemical and particulate contaminants in the fluid. Finally, various tools for particulate measurement are useful in tracking and alerting to wear conditions.
- What analysis is necessary to achieve the stated goals? What is useful, and what is just more numbers on the page? Which tests should be performed on a routine basis, and which are useful when the routine battery of tests alerts to an exception? Additional items not only drive up cost, but also divert attention from the truly important and critical parameters.
- Which analysis techniques will anticipate a problem, and which ones document the same problem after the damage is done? Obviously, the greater value is obtained by anticipating and preventing problems.

What's Important and What's Not

Is more always better? Referring to a thorough lubricant analysis report from a well-known and respected lab for a single compressor showed a total of 49 pieces of numerical data. That was in addition to the 98 data points for two previous samples, all on the same page. Another well-known lab gave 27 numerical results for a single compressor sample. This may be heresy, but the challenge is to

question how many and which of these really serve to meet the stated goals of establishing change intervals, monitoring contamination, and alerting to irregular wear conditions. Also, which data points and tests will serve as leading indicators, to prevent problems, and which are too late, after the fact?

What is the problem with too much data? In the sea of numbers, the few that are truly important are easily overlooked. If 48 of 49 data points are good, isn't everything fine? Can we get more information from fewer numbers? The canary in the mine did not identify which poison gas was present, or how much, but quickly alerted to an unsafe condition. Are there a few parameters that if monitored regularly will protect both the fluid and the compressor in nearly all cases?

Let's review a list of some common parameters measured in routine compressor fluid analysis, and question each from three standpoints.

1. The relevance of each for rotary screw air compressors. A number that may be very important in diesel engines may be useless in air compressors.
2. Is there another parameter that will give an earlier indication of a problem? Can we look for causes rather than waiting for effects?
3. Which tests are useful when an exception is identified, for diagnosis, but are not useful or cost-effective on a routine basis.

In this section, these items will be approached strictly for the application of rotary screw air compressors. The same tests may take on entirely different significance in other equipment.

Elemental Analysis

Elemental analysis by spectrometry - This test is fast, inexpensive, and yields up to 24 numbers, certainly giving that analytical report a got-your-money's-worth appearance. Analysis just isn't complete without it, or is it? The test obviously has some value. But consider Table 2 which evaluates the data generally given in this test.

Note how many of the elements have no relevance at all to rotary compressors, yet they are dutifully reported. Of the 24 elements listed and normally reported, only four (iron, copper, aluminum and silicon) have significant value in determining a potential problem. The other 20 do not contribute to the three stated goals for rotary screw compressor analysis, and serve only to confuse the recipient. Of the above, the most significant wear metal is undoubtedly iron. However, it is well-known that spectrometry fails to detect the large particulate which is most indicative of a critical wear problem. Only very small and dissolved iron is detected. Spectrometry is still useful, but is there a best way to achieve the goal of monitoring wear?

DR Ferrography and/or Particle Count

As an alternative to spectrometry, this is a little more costly but arguably more useful. DR ferrography gives a dimensionless number, which is useful as a scale in measuring ferrous, and to a

lesser degree nonferrous particulate in the fluid. In general, DR large (>15 micron) counts are more indicative of wear particles, while the DR small (<15 micron) count is more representative of rust and corrosion. Particle counting gives an absolute measure over several size ranges for a more complete picture of both ferrous and nonferrous particulate. Analytical ferrography is a valuable diagnostic tool when DR reveals high total levels of particulate. The dissolved corrosion metals, which are not detected by DR will be addressed later, with acid number or (AN).

Viscosity

Rotary screw compressors typically call for ISO 32 or ISO 46 grade lubricants. Viscosity increase in rotaries usually indicates fluid oxidation. Viscosity increase is not usually a serious threat to a rotary compressor, but will result in higher discharge temperatures until the fluid is changed. This is important to monitor and will usually measured as kinematic viscosity at 40°C.

Water

Water analysis in rotary compressors probably causes more confusion and consternation than any other parameter. Because of the continuous ingestion of humid atmospheric air into the compressor, water levels are always high in a rotary screw compressor. Depending on humidity and discharge temperature, the dissolved water level in the lubricant will typically range up to 3000 ppm. This is not a benefit, but it is normal and unavoidable in a rotary compressor. If a lab is not aware that the sample came from a rotary compressor, it will often be flagged as an exception. If lubricant is then replaced, water levels will return to equilibrium within hours or days, because the source of water is the air that is being compressed. There is a concern with water and that greater concern is free water. Analysis of greater than 5000ppm (0.5 percent) or accumulation of visible milkiness of the fluid, or a layer of free water are a serious concern and should be addressed.

Element	Is Element a Rotary Compressor Material?	Compressor Lubricant Additive?	Wear Metal In Rotary Compressors?	Other Significance in Rotary Compressor?	Is This Element Useful Data For Routine Testing?	If So, What Test Would Better Meet the Goal?
Aluminum	Oil Coolers	No	No	Corrosion of Cooler	Marginal	AN and pH, Note 3
Antimony	No	No	No	None	No	-
Barium	No	Yes	No	None	No	-
Boron	No	No	No	None	No	-
Cadmium	No	No	No	None	No	-
Calcium	No	Yes	No	Hard Water Contamination	No	-
Chromium	Bearings, Note 1	No	Note 1	No	Marginal	DR Ferrography, Note 4
Copper	Thermal Valve	No	Note 2	Possible Corrosion	Rarely	-
Iron	Yes	No	Yes	Possible Corrosion	YES	DR Ferrography, Note 4
Lead	No	No	No	None	No	-
Lithium	No	No	No	None	No	-
Magnesium	No	No	No	Hard Water Contamination	No	-
Manganese	No	No	No	None	No	-
Molybdenum	Bearings, Note 1	No	Note 1	None	No	DR Ferrography, Note 4
Nickel	No	No	No	None	No	-
Phosphorus	No	Yes	No	Possible Additive	No	-
Potassium	No	No	No	Contaminant	No	-
Silicon	No	No	No	Contaminant or Antifoam	Yes	Particulate Count, Note 4
Silver	No	No	No	None	No	-
Sodium	No	No	No	Contaminant	No	-
Tin	No	No	No	None	No	-
Titanium	No	No	No	None	No	-
Vanadium	No	No	No	None	No	-
Zinc	Separator Element	No	Note 2	Sacrificial Corrosion of Plating	No	-

Notes:

1. This element is present, but never without iron, and in small quantities it may not be detected reliably by test. It is better to look for more abundant iron.
2. This is a possible result of corrosion, but not wear.
3. Lubricant pH and Acid Number (AN) serve as leading indicators prior to the corrosion of most metals.
4. DR Ferrography and particulate counts distinguish between particle sizes, helping to distinguish between wear particles and corrosion. Also, large particles are not effectively detected by spectrometry.

Table 2. A to Z Importance of Elements Commonly Measured by Spectrometry in Rotary Compressor Lubricants

Beyond simply changing the lubricant, the cause must be addressed. This is typically a machine that runs too cool, or is left to idle excessively. Dissolved water is usually measured by Karl Fischer. Free water, if noticeable, does not need to be measured - any is too much, and the cure is the same. Note: It is not unusual when a sample is obtained from the bottom of the sump for free water to accumulate in the drain line over time, and does not necessarily indicate a problem. This again illustrates the importance of proper sampling technique.

Demulsibility (ASTM D1401) is not a relevant fluid quality test for rotary compressors, because the real issue is the presence of large amounts of water itself. A compressor should not be run in a mode where drainage of free water from the sump is a necessary and regular occurrence.

pH, Acid Number (AN) and Strong Acid Number (SAN)

When viewed together, pH and AN are extremely valuable as predictive and diagnostic tools. While spectrometry results may show the results of zinc, copper, aluminum or iron corrosion, wouldn't it be better to avoid the conditions that cause the corrosion? With any properly formulated rotary compressor fluid corrosion metals are unlikely to be an issue if pH and AN are monitored and fluid is changed accordingly. Low pH is an indicator of the presence of strong acid contamination in rotary compressors. Normal degradation of compressor fluids results in formation of weak acids, which result in a high AN, without greatly reducing the pH. Strong acids are not formed in the compressor, but are ingested as trace contaminants in the air from the plant environment. Low pH is an indicator of the presence of acid contaminants. Allowing time for the sample to stabilize and take a pH measurement before titration slows down the sample flow in the lab, so it is often omitted. Although pH is valuable, another measurement for indication of acidic contamination is the Strong Acid Number (SAN). Comparing the SAN and AN will allow diagnosis of the

cause of short compressor fluid life. Is it due to the fluid itself, or is this a contamination issue? Most titrators are capable of calculating SAN in addition to AN, but this is a valuable tool that is rarely used. With advanced synthetic fluids that are commonly used in rotary compressors today, if nothing else were monitored except pH, AN, viscosity and some type of particulate count, few problems would escape notice and reliable performance would be assured.

Other Analytical Tools

Oxidation by infrared absorbance is a useful measurement for monitoring hydrocarbon and PAO type lubricants as a tool to detect oxidation prior to the formation of deposits in the compressor.

Nitration and sulfation are routinely reported by many labs, but are more relevant to other applications, such as diesel engines.

Glycol percent - Glycol would be a problem if it were there, but approximately 80 percent of rotary compressors are air-cooled. There is no liquid cooling medium and no potential for glycol to be present. Of the water-cooled machines, only those on a closed loop cooling system have the potential for glycol leakage and contamination. For those, this is a useful measurement, for others, it is redundant information and an unnecessary measurement.

Flash point is seldom measured as a routine item. It is useful as a preventative measure in the rare instance when contamination of a compressor with flammable solvent is suspected. After a fire, compressor fluid flash point is always lower than new fluid. Tables 3 and 4 contain suggested test slates for rotary air compressors, based on lubricant type in service.

There are special instances where additional analysis will be beneficial. These suggestions are intended as a minimum requirement for normal conditions. If this seems slim, consider that approximately 80 percent of our compressor lubricant customers do no testing at all, simply relying on the periodic change recommendation. Upgrading to this program would be an improvement for most.

Test	Frequency	Significance	Alternatives
pH and AN	1000-2000 hours	Contamination, Oxidation	SAN
Viscosity	1000-2000 hours	Fluid Condition	-
DR Ferrography	2000 hours	Unit Condition	Particle Count, Spectrometry
Analytical Ferrography	When Indicated by DR Readings	Distinguish Wear Regime and Corrosion	-

Table 3. Rotary Compressor Test Slate - Polyglycol Blend or Polyol Ester Lubricants

Test	Frequency	Significance	Alternatives
pH and AN	1000-2000 hours	Contamination, Oxidation	SAN
Viscosity	1000-2000 hours	Fluid Condition, Prevent Deposits	-
RPVOT	4000 hours	Oxidation State of Fluid	Change Fluid to Avoid Cost of Test
DR Ferrography	2000 hours	Unit Condition	Particle Count, Spectrometry
Analytical Ferrography	When Indicated by DR Readings	Distinguish Wear Regime and Corrosion	-

Table 4. Rotary Compressor Test Slate - PAO and Hydrotreated Hydrocarbon Lubricants

Fluid Analysis for Centrifugal Compressors

The analytical needs for centrifugal compressors are different from rotary screw compressors. In the centrifugal air compressor, the lubricant is not subjected to extreme temperatures or exposure to large quantities of compressed air or contaminants. There is also virtually no opportunity for corrosion, because water and acid levels remain low in the sump. The stress on the lubricant itself is very mild. However, catastrophic bearing failure is imminent long before measurable amounts of bearing material would be detected in the fluid, by either spectrometry or DR ferrography. The earliest indication of bearing problems is normally an increase in vibration readings, indicated by on-board instrumentation. Analysis performed here rarely shows any significant particulate in centrifugal compressors, except those that have already suffered a catastrophic failure. The predictive value of this analysis is low for these compressors. This calls for some very different measures to assure reliability.

Considering one failure mode illustrates the value of spectrometric analysis in these compressors. The lubricant in many of these units is cooled by a tube and shell heat exchanger. Leakage of a small amount of the water into the compressor sump may go undetected, and the water may evaporate from the compressor fluid, and escape harmlessly. But what remains behind is the minerals in the water. In a sequence of events, some of those, especially calcium and perhaps magnesium may plate out on bearings, resulting in loss of clearance and failure. The detection of a significant level of calcium in the fluid in these units is a red flag indicating cooling water leakage into the sump, and can have dire consequences.

Fluid condition of synthetics in centrifugal compressors is easily monitored by trends of pH, AN and viscosity. The mild conditions and large sumps of these machines preclude any concern of additive depletions, as long as these parameters show little change. Proper viscosity and viscosity increase is a critical concern in these units, as

bearing designs and rotor stability are dependent on proper fluid viscosity. Excessive increase in viscosity will result in overheating and severe damage to babbit bearings.

When using PAO or hydrocarbon oils in these compressors, oxidation or RPVOT analysis to assure oxidation stability of the fluid and prevent varnish formation on bearings is probably also a worthwhile investment.

Establishing a Compressor Fluid Change Interval

In summarizing the discussion above, the change interval for rotary compressors is typically dictated by contamination or the oxidation state of the lubricant as measured by several metrics. 8000 hours is the typical change interval of an advanced rotary compressor fluid suggested by OEMs and manufacturers. This number is usually somewhat conservative, as many users do not perform any analysis at all, using only the change interval recommendations. Under good conditions with no contamination, the actual life of synthetic fluids as measured by analysis may reach 12,000 hours. A conservative change interval may still be wise to avoid contaminating the new charge, due to the difficulty of getting all the old fluid out of the compressor, and with hydrocarbon-based fluids the potential consequences of deposits in the compressor.

For centrifugal compressors, actual fluid life with polyglycol and other advanced synthetics may exceed 50,000 hours under normal conditions, due to the extremely mild nature of the oxidative environment, and limited opportunity for contamination. Typical recommendations in the absence of analysis to verify excellent fluid condition would range from 8,000 to 16,000 hours.

Avoiding Problems and Pitfalls in Compressor Lubrication

Several typical and common problems related to rotary air compressor lubrication and maintenance arise frequently in discussions with compressor field service personnel.

Test	Frequency	Significance	Alternatives
pH and AN	4000-8000 hours	Lubricant Oxidation	-
Viscosity	4000-8000 hours	Fluid Condition, Most Important	-
Spectrometry	4000-8000 hours	Contamination, Calcium and Magnesium	-
Analytical Ferrography	When Indicated by Spectrometry or DR Readings	Distinguish Particulate Types and Sources	-

Table 5. Centrifugal Compressor Test Slate - Polyglycol/Ester Lubricants

Test	Frequency	Significance	Alternatives
pH and AN	4000-8000 hours	Lubricant Oxidation	-
Viscosity	4000-8000 hours	Fluid Condition, Most Important	-
RPVOT	4000-8000 hours	Oxidation State of Fluid	-
Spectrometry	4000-8000 hours	Contamination, Calcium and Magnesium	-
Analytical Ferrography	When Indicated by Spectrometry or DR Readings	Distinguish Particulate Types and Sources	-

Table 6. Centrifugal Compressor Test Slate - PAO and Hydrocarbon Lubricants

Ingestion of Contaminated Air

Intake of contaminated air from inside some plants, rather than using a remote air inlet to obtain clean outside air results in short fluid life, and even potential internal compressor damage. In addition, remote air from a cooler location, typically outside the compressor room results in improved volumetric efficiency and energy efficiency for the compressor.

Improper Placement of Compressor

Placement of a compressor without regard to the need for heat rejection results in high discharge temperatures, shortening fluid life, in addition to other problems. Also, location near boilers, cooling towers, acid treatment tanks and other environmental concerns is a mistake.

Accidental Recycling of Used Fluid

When it is time for the annual fluid change, where is the used fluid placed? Often the fluid is placed in an empty drum of the same type. This is fine, if it is properly disposed of. More often, it then sits by the compressor, and eventually is used as make up fluid. Label used drums, and dispose of them promptly and properly.

Choice of Sample Location

Fluid sampled from the bottom of the sump will typically be very high in water. If it is taken from a long drain line without purging the line, the sample may actually be last year's fluid. Fluid poured from a filter when the filter is changed often contains high levels of particulate. Either sample can give an inaccurate picture of what is happening in the compressor, resulting in incorrect maintenance recommendations.

Choice of a Compressor Fluid Not Compatible with the Downstream Process

There are several examples of this. Silicone basestock fluids should not be used when painting or coating processes are the use of the air downstream, as they will cause paint defects. Also, diester-containing fluids should be used with caution where the air will contact solenoid valves, hoses, diaphragms or other parts not designed to be compatible with those fluids.

Inattention to Inlet Filtration

Failure to replace inlet filters or use of improper filters may result in high particulate levels in the compressor fluid and subsequent problems.

Fluid Compatibility with Compressors and Air System Components

Fluids which are not approved by the OEM may contain diester basestocks which cause swelling of elastomers, seals and hose liners. Users do not always associate the cause of the problems with the change of lubricant.

Overheating

Failure to clean oil coolers periodically, results in high discharge and fluid temperature, thereby shortening fluid life.

Running Unloaded

Running a compressor unloaded or at low loads a high percentage of the time not only wastes energy, but results in high water levels in the lubricant.

Mixing Fluid Types

Mixing fluids sometimes works, but sometimes causes serious problems. Silicone fluid, mixed with any other type even in small quantities, is likely to cause foaming in the compressor.

Summary

Major rotary compressor OEMs now rely on advanced synthetic lubricants to deliver enhanced performance and extended service life. With this generation of lubricants, a well-defined analytical regimen will assure superior compressor and lubricant reliability and service. Synthetic fluids are beneficial in the vast majority of applications where major inlet air contamination is not an issue. Synthetic fluids are also beginning to be more commonly used in centrifugal compressors, and delivering reliability and performance benefits in this application.

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