

10 YEARS of publishing excellence

AN **STLE** PUBLICATION | DECEMBER 2013



Lubrication Fundamentals

Whether you're new to the world of fluids management or an industry veteran, there's something of interest for you in this 36-page special section from STLE.

69th STLE Annual Meeting & Exhibition

STLE 2014

May 18-22, 2014 Disney's Contemporary Resort Lake Buena Vista, Florida (USA)

Technical and professional development you can't get anywhere else!









When it comes to advancing your career and upgrading your technical knowledge, STLE's Annual Meeting & Exhibition is a unique event in the lubricants industry. 1,200 of your peers in the lubricants community are expected to participate in STLE's 69th Annual Meeting & Exhibition. Please join us in Lake Buena Vista for a unique experience that blends the best of industry education, technical training, professional certification and new technologies.

- 400 Technical Presentations
- 12 Industry-specific Education Courses
- 70-exhibitor Trade Show
- Commercial Marketing Forum
- Networking
- New Products
- Professional Certification
- Peer Recognition
- Emerging Technologies
- Student Posters
- Business Planning

Visit **www.stle.org** for regular program updates and to register.

Follow us on

Image: State of the s

Contents

- **3** Viscosity: A fluid's resistance to flow New to the world of lubricants? Here's more about rheology than you ever wanted to know.
- 6 The basics of viscosity index There are many factors to calculating the viscosity of a lubricant. But understanding its temperature in cold and hot environments is the first step.
- 8 The mysterious world of lubricant additives This handy primer is your guide to these multifunctional and all-important chemicals.
- **12 Consistently consistent grease** Several tests help us ensure that what we want is what we get—all the time.
- **15** The global case for green Good intentions aren't enough. You must get all parts of your operation working in environmental harmony.
- **18 Bearings and their lubrication** This primer will help you understand the basics—and prepare for the CLS exam.
- **22** The basics of filters and filtration Establishing a good relationship with your supplier is the best strategy to using these materials successfully.
- **24** The mysterious world of seals These important structures play a major role in making sure a lubricant stays in place.
- **26 Turbines: What goes around comes around** There are three main types of turbomachinery, and each has its own set of lubrication requirements.
- **29** What's a gear? An overview of the machine elements that keep the industrial world turning.



Evan Zabawski

Lubrication Fundamentals: A TLT special section

Regardless of where you are now in your career, all of us who earn a living through tribology or lubrication engineering started in the same place. With the basics.

If it's true that you can't run until you can walk, then neither can you make decisions about lubricants without knowing what viscosity means. Education has always been one of STLE's primary missions, and while the delivery methods have changed since 1944 when the society was founded, our commitment to technical training has never been stronger.

Each year hundreds of STLE members help educate their peers by writing papers, teaching courses at the annual meeting, conducting seminars and making presentations at local section meetings.

While this truly is a win-win scenario for all involved, coordinating all those activities is a Herculean task. For a decade now, the job has rested squarely on the shoulders of Dr. Robert M. Gresham, STLE's director of professional development and the author of this special section on lubrication fundamentals.

If you've been an STLE member for even a few years, you've probably either met Bob or benefited from his efforts. If you've been fortunate to spend time with him, you know Bob is an intelligent, focused individual with a lively sense of humor and a deep commitment to helping STLE members de-



Bob Gresham spent 20 years as an STLE member before joining the society's headquarters staff in 1988.

velop their professional skills.

While Bob has a hand in almost every area of member service, certainly his most visible role is writing TLT's monthly Lubrication Fundamentals column. Since Bob is the modest type, please allow me a moment to tell you a little more about the man behind the keyboard.

After receiving his doctorate in organic chemistry from Emory University in Atlanta, Bob spent 12 years in several manufacturing and customer service positions with the DuPont Co. He gained an additional 17 years of industry experience as vice president of technology with E/M Corp., a manufacturer and applicator of solid film lubricants. Before joining the STLE headquarters staff in 1998, Bob was a 20-year member where, among his many volunteer activities, he chaired the Solid Lubricants Technical Committee and Aerospace Industry Council. He gained an understanding of the society's governance structure as a board member, where he served as treasurer and secretary.

Bob's columns on Lubrication Fundamentals have been an integral part of TLT since the magazine was launched in 2003. For this special section, we've pulled 10 essays that span a fairly broad range of topics. In addition, be sure to check out the first issue of our new Lubrication Fundamentals technical e-newsletter for additional topic articles (*available at www.stle.org*).

Even though I've logged a few years of experience in this field myself, I really enjoyed and benefited from rereading these articles. Whether you're an industry novice or a veteran, I believe you'll have the same experience. Bob writes with style that is both informative and engaging.

Let the education begin.



Evan Zabawski, CLS, is a reliability specialist in Calgary, Alberta, Canada. You can reach him at **evan.** zabawski@gmail.com.

LUBRICATION FUNDAMENTALS

Editor's Note: This article was prepared in collaboration with STLE-member Dr. Philip Guichelaar, Western Michigan University.

Viscosity: A fluid's resistance to flow

New to the world of lubricants? Here's more about rheology than you ever wanted to know.

I HAVEN'T WRITTEN ABOUT VISCOSITY in

a long time, but it's a topic always worth revisiting. We frequently say that viscosity is the most important property of fluid lubricants. Recall that viscosity is equal to the shear stress/ shear rate. That's kind of abstract, so just think of it as the resistance to flow.

We can all think of thick and thin fluids, like water, syrup and the like, and that's kind of an obvious macro look at viscosity. What happens if we stir a can of oil at different speeds? Does it seem obvious that more effort is required to stir at a faster speed? What about other materials, like paint? More effort is required, but for some oils or other materials it is not proportionally more effort.

We can determine the effect of stirring rate with a rotary viscometer by rotating the spindle at different speeds. For each of these speeds, we calculate the shear rate (related to the rotation speed of the spindle) and measure the shear stress (related to the torque needed to rotate the spindle). Then we make a plot of the shear stress and shear rate, as shown in Figure 1. Ideally the data would fit a straight line starting from zero. The slope of that line (or its steepness) is the viscosity for that oil or test material at the temperature of measurement.



Figure 1 | The correlation between shear stress and shear rate defining the flow behavior of a liquid is graphically displayed. This diagram is called a flow curve.

KEY CONCEPTS

- Viscosity is defined as being equal to shear stress/shear rate, but it's easier to just think of it as resistance to flow.
- An oil whose viscosity remains constant as we increase or decrease the shear rate is a perfect fluid, also known as Newtonian.
- Several fluids are sensitive to the length of time they are being sheared, resulting in changes in viscosity with the duration of the experiment.

An equipment design engineer designing a bearing, gearbox or a lubricant dispensing device needs to understand the implications of rheology on the design.



Figure 2 | Newtonian behavior

Remember that mathematically and also graphically, an oil whose viscosity remains constant as we increase or decrease the shear rate is a perfect fluid, which is depicted in Figure 2. The term Newtonian is used to designate this behavior. Water, gasoline and most unmodified mineral oils display very nearly Newtonian viscosity curves.

Most fluids, including motor oils, are not perfect or Newtonian. The shear stress is not directly proportional to the applied shear rate such that when the shear stress is plotted against the shear rate, the points are not in a straight line. Often, the points do not begin from zero shear stress and zero shear rate.

Certain other fluids are sensitive to the length of time that the fluid is being sheared, resulting in changes in viscosity with the duration of the experiment. These kinds of fluids have interesting names:

- **Pseudoplastic Fluids.** The viscosity of pseudoplastic (and plastic) fluids decreases with increased shearing, as shown in Figure 3. Molten polymers have this characteristic, which is used to advantage in injection molding when the material flows through small cross section gates. Paper pulp suspensions also display pseudoplastic viscosity behavior.
- **Dilatant Fluids.** For these fluids, the viscosity increases with increased shearing, as shown in Figure 4. A mixture of water and cornstarch can have the consistency of thick cream if it is poured slowly but will form a thick paste if it is stirred briskly. Quicksand also has

this quirky viscosity behavior, with the valuable lesson that slow escape movements consume less energy than violent movements against an instantly thick morass.

- **Bingham Plastic Fluids.** The viscosity curve for Bingham plastic fluids does not go through the origin. As shown in Figure 5, the shear stress can be substantial even at a small shear rate, but once the fluid moves the shear stress is directly proportional to shear rate in exactly the same manner as for Newtonian fluids. Water suspensions of rock particles behave in this manner. More familiarly, mashed potatoes, a suspension of tasty solids in a liquid, flow in the bowl when you stir, flow harder when you stir harder and assume a mountain peak shape if undisturbed.
- Shear Time Dependent Fluids. For these fluids, the shear stress changes with time of shearing. This behavior is related to breaking bonds between particles or molecules or to changes from the at-rest shape of long molecules.
- **Thixotropic Fluids.** Fluids that are thixotropic are not simply small molecules aggregated together such as water. They include molecules that have a longer range structure that can be altered with mechanical shearing. For most of these fluids, the viscosity decreases at higher shearing rates, as shown in Figure 6. Mayonnaise has this characteristic. It is not a Bingham plastic fluid because its viscosity decreases with higher rates of shearing-but only after a minimum amount of shear is reached. Yogurt (without the tasty fruit addition) also is reputed to have this behavior. Finally, good quality wall paint and motor oils are carefully compounded to be thixotropic. Can you explain why users of these fluids would be pleased to have thixotropic behavior?
- **Rheopectic Fluids.** This behavior is not common or very useful because the viscosity increases with additional shearing after the minimum amount of shear is exerted. Some clay solutions in water behave in this manner. Can you imagine the behavior of rheopectic paint? It thickens into clumps when you apply it, and when you stop trying to smooth it out, it runs down the wall.



Figure 5 | Pseudoplastic Flow



The non-Newtonian fluids discussed before have important behaviors. For example, in pseudoplastic fluids, flow does not begin until a minimum shear stress level is reached. This is important for printing ink rheology where we would not like the ink to move until it is deposited on paper.

Once the minimum shear stress has been reached, the fluid thins with increasing shear rate and penetrates the structure of the paper. When the shear stress goes back to zero, the ink does not move.

Similarly with thixotropic fluids, flow can vary with applied shear stress and/or rate, becoming rapidly thin with increasing shear time. But when shear forces are removed, the fluid rapidly becomes thicker or more viscous.

Paint is usually compounded to be thixotropic. It applies easily (high shear stress and rate) but it doesn't sag or run when the brush is removed, yet has time to flow and level out before thickening. At low temperatures, wax particles in lubricating oils can cause the non-Newtonian thixotropic behavior of the oil to become even more pronounced.

How does a pseudoplastic oil behave in a hydrodynamic bearing? At startup, the shear rate is slow and the oil has a high viscosity such that the transition to mixed lubrication is facilitated. As the shaft speeds up, the viscosity decreases, but the hope is that the increased speed compensates and the system remains in the mixed lubrication regime or transitions into the hydrodynamic regime. On the other hand, with a thixotropic fluid, at startup if the shear rate is slow the oil initially supports the bearing. If the shear rate remains constant, the oil will eventually thin and not support the bearing.

A dilatant fluid is the opposite of a pseudoplastic fluid in that its viscosity increases with shear rate. This would be very bad for a paint system, as spreading the paint evenly would be very difficult. If a lubricating oil was dilatant, its viscosity would increase with speed and friction losses would increase, not a good outcome when the general objective is to decrease energy consumption.

Clearly, viscosity and rheology are important to the proper operation of mechanical equipment. An equipment

design engineer designing a bearing, gearbox or a lubricant dispensing device needs to understand the implications of rheology on the design. If we know the conditions under which the "converging wedge" is operating, the rotating speed, the load and the possibility of any intermittent changes in pressure with time, and if we can predict the range of operating temperatures, we can specify a viscosity and viscosity index for effective lubrication. Conversely, if we know the viscosity profile of a lubricant, we can design a mechanical system to operate reliably.

Lubricant formulators must keep all of these concepts in mind and under control when developing new products.

The basics of viscosity index

There are many factors to calculating the viscosity of a lubricant. But understanding its temperature in cold and hot environments is the first step.

KEY CONCEPTS

- Viscosity Index is a means of expressing the lubricant's variation in viscosity with respect to temperature.
- The less a lubricant varies with temperature, the more it can be used in cold as well as hotter environments.
- Viscosity Index is calculated from measured viscosity at 40 C and 10 C using ASTM Method D 2270.

AS HAS BEEN SAID MANY TIMES in several articles published in TLT, viscosity is the most important property of a lubricant. And so it is important to understand the concepts fully. In this article, we'll take a look at viscosity index (VI).

VI is a means of expressing the lubricant's variation in viscosity with respect to temperature (*see Figure 1*). In general, this means the viscosity increases with cold and decreases with heat. Each machine is designed with an optimum lubricant viscosity range to insure sufficient film thickness to reduce friction and prevent wear. Clearly, the less a lubricant varies with temperature, the more a lubricant can be used in cold as well as hotter environments.



Figure 1 | A lubricant's variation in viscosity with respect to temperature.

This cuts two ways. When a lubricant is too cold (not up to operating temperature), either because of the environment, as in winter, or just because we are just starting up a machine, the viscosity is too high, the lubricant doesn't flow well and wear can ensue. Equally, if the lubricant is too hot because of the environment or because we are overworking a machine, the viscosity is too low, and we don't have sufficient film thickness to prevent wear.

So if this is important, how do we determine the VI of a lubricant? VI is calculated from the measured viscosity at 40 C and 100 C using ASTM D2270. Unfortunately, the method is a wee bit awkward and arcane, yet widely used. Its utility is in characterizing base oils or finished lubricants and cannot be used as blending guidance (i.e., blending two oils 50-50, which have VIs of 80 and 100 don't necessarily provide oil with a VI of 90).

The idea of the method is to measure the viscosity of a test oil at 100 C (called Y). Then, consulting a huge chart in the ASTM method and using the measured viscosity of the test oil, the tester looks up values for two parameters called L and H. L is the 40 C viscosity of some mythical oil having the same viscosity of our test oil at 100 C, defined as having a VI of 0. H is also the 40 C viscosity of another mythical oil having the same viscosity of our test oil at 100 C but defined as having a VI of 100. High VI is defined as having less variation with respect to temperature; thus L is larger than H. The VI of the test oil is defined by the relationship of its 40 C viscosity (called U) to the parameters L and H. Thus, the VI of the test oil becomes the percent of the way U is from L to H, as shown in the following formula:

VI = 100 X (L - U) / (L - H)

This is pretty exciting stuff, right? Perhaps the example below will help. For an oil of 10.0 centistokes (cSt) viscosity at 100 C, the table in ASTM D2270 provides L= 147.7 and H = 82.87. If the test oil has a 40 C viscosity of 110 cSt, it would have a VI of 58 using the formula below:

VI = 100 X (147.7 - 110) / (147.7 - 82.87) = 58

If this isn't painful, awkward and arcane enough, if the VI is over 100, as many mineral oils and synthetics now are, we have to go to a completely different calculation. As of now, when dealing with VIs of 100 or more, U, the viscosity of the test oil at 40 C, is less than H. For these oils, VI is defined by a new parameter, N, calculated from Y and H rather than H and L as before. Thus, a new formula is shown below:

VI = 100 + 140 X ((antilog N) - 1), where

$N = (\log H - \log U) / \log Y)$

We're having fun now! So what's a poor soul to do? Probably the easiest and fastest thing to do is to call your supplier. Second, grind it out with ASTM D2270, ugh. Finally, you might find a computer program that will calculate it all for you.

The point of all this is that viscosity index is an important parameter in characterizing base oils and lubricants.

LUBRICATION FUNDAMENTALS

Dr. Robert M. Gresham / Contributing Editor

THE MYSTERIOUS

This handy primer is your guide to these multifunctional and all-important chemicals.

enerally in most applications, lubricants must *clean* by washing away wear debris or metal chips in metalworking operations, *cool* by removing heat from machine or machining surfaces, *lubricate* by separating moving surfaces and *seal* by filling voids and gaps in surfaces.

Lube 101 tells us that oil viscosity is one of the most important properties of lubricants. Likewise, the chemistry of the oil (synthetics, Group I, II or III mineral oils, etc.) is critical for the intended application. But once the formulator identifies the right oil for the application, the properties of the oil are augmented by lubricant additives.

Lubricant additives are used in metalworking fluids, oils and greases. Often the additives are dissolved or dispersed in a medium that makes it easier to use in its intended application such as a water or oil-based MWF, engine oil or grease. Aside from the thickeners in greases, additives generally perform the same functions in greases and oils. In MWFs, many of these same additives are also used for these same purposes.

But in MWFs, additional additives also must be present to perform yet even more tasks. MWFs must promote tool life by removing heat, cooling, (because, just as with oils and greases, heat kills), lubricate the interface between the tool and work piece, clean by carrying chips away and preventing in-process corrosion.

KEY CONCEPTS

- Lubricants in most applications clean, cool, lubricate and seal.
- Additives are chemical components or blends used at a specific treat rate to provide one or more functions in the fluid.
- Additives can carry negative attributes. A skilled chemist, preferably one CLScertified, is needed to safely manage these materials.

WORLD OF LUBRICANT ADDITIVES

These are the macro issues. However, embedded in these functions are events that need to be prevented, including:

- poor surface finish
- chemical attack on the work piece
- mechanical damage to the work piece
- metallurgical change to the work piece
- thermal damage
- electrical changes to the work piece.

But these are just the operational parts. Additionally, MWFs can contribute to a number of negative things, all of which must be minimized:

- mist leading to respiratory problems
- dermatitis
- fungal and microbial growth.

All of these can lead to employee health and safety issues, plug filters and cause other operational problems.



The properties of the oil are augmented by lubricant additives.



Speaking as a chemist, whether it be grease or oil but especially with a MWF, these issues pose a formidable set of interrelated and interacting problems. How do chemists balance all these different issues? Aside from choices of base fluid material, they use a mystifying array of additives.

First, what do we mean by additives? Additives are a chemical component or blend used at a specific treat rate to provide one or more functions in the fluid. Ideally, additive components are multifunctional and generally used at treat rates from < 1 to 35 percent. They are soluble in mineral oil, water or both in some cases.

Second, additives provide or assist in a wide variety of functions:

- boundary lubricity
- extreme pressure (EP)
- corrosion inhibitors
- reserve alkalinity boosters
- metal deactivators
- emulsifiers
- couplers

- water conditioners/softeners (chelating agents)
- antimisting
- antimicrobial pesticide
- antifoam additives and defoamers
- dyes.

That's quite a list! Thus, it is easy to see why chemists look for additives that can be multifunctional and why with so many different chemicals in a formulation, additive compatibility, both with other additives as well as the base fluid, is of critical importance.

Are you mystified yet? Let's take a very quick look at the most common of the performance-related additive types.

Boundary Lubricity Additives enhance the lubricity of the fluid by adsorbing on the surface of the metal to form a film, reducing metal-to-metal contact. These additives typically have a polar group that interfaces with metal and tail that is compatible with mineral oil or water. Examples are lard oil and canola oil. Solid lubricants also are used for boundary lubrication.



Extreme Pressure Additives are a special type of boundary lubricity additive that actually reacts with the metal surface, instead of adsorbing on the surface, to form a metal salt layer between mating surfaces that reduces friction, wear and damage. In metalworking, the layer is between the tool and the work piece.

These different additives have different temperatures of activation. Thus, the chemist also chooses the additive according to the application conditions so that the additive is, in fact, activated at operating temperatures. Examples of the various chemistries are ZDDP, chlorinated paraffins, sulfurized lard oils, phosphate esters and overbased calcium sulfonates.

Corrosion Inhibitors prevent the fluid from corroding the machine surfaces, metal work piece, cutting tool and machine tool. Corrosion inhibitors perform in two ways by either forming a protective coating on the metal surface (as shown in the graphic below) or by neutralizing corrosive contaminants in the fluid. Examples are overbased sulfonates (we saw where some of these also can act as extreme pressure additives), alkanolamides, aminoborates and aminocarboxylates.

Reserve Alkalinity Additives maintain the fluid's corrosion protection by neutralizing acidic contaminants and by maintaining the pH in a suitable range, essentially a buffer. These additives also can act as form emulsifiers with other components to stabilize the fluid. Examples are alkanolamines like monoethanolamine (MEA), triethanolamine (TEA), aminomethylpropanol (AMP) and 2-(2-aminoethoxy) ethanol.

Metal Deactivators prevent the MWF from staining nonferrous alloys

(such as copper and brass) and reduce corrosion when dissimilar metals contact each other. They act by forming a protective coating on the metal surface. Examples are mercaptobenzothi-

It is important to have a good working relationship with top suppliers of lubricants, MWFs and additives.

azole, tolyltriazole and benzotriazole.

Detergents stabilize dirt and wear debris in oil formulations. **Emulsifiers** stabilize oil-soluble additives in waterdilutable MWFs by reducing interfacial tension between incompatible compo-





nents by forming micelles (a submicroscopic aggregation of molecules, as a droplet in a colloidal system). These droplets then can remain suspended in the fluid. Milk is an emulsion. In MWFs, examples of emulsifiers are sodium petroleum sulfonate and alkanolamine salts of fatty acids.

Detergents and emulsifiers all are similar in that they typically have a socalled polar (hydrophilic) head and a hydrocarbon (hydrophobic) tail. The nature of these two parts depends on the application. Dispersing and/or emulsifying dirt, oils etc., is what you do when you wash your hands—you form micelles to solubilize and disperse the dirt and oils.

Couplers assist in stabilizing waterdilutable MWFs in the concentrate to prevent separation of components. Couplers facilitate formation of emulsions for soluble oils. Examples are propylene glycol, glycol ethers and nonionic alkoxylates.

Chelating Agents (also known as water softeners or conditioners) reduce the destabilizing effect of hard

water (calcium and magnesium ions) on MWF emulsions. Chelating agents bind calcium and magnesium salts to prevent them from reacting with anionic emulsifiers such as fatty acid salts of alkanolamines. An example might be ethylenediaminetetracetic acid (EDTA).

Antimist Additives minimize the amount of lubricant that disperses into the air during machining. They are typically polymers and/or wetting agents. For oil-based systems, ethylene, propylene copolymers and polyisobutenes are used. For water-based systems, polyethylene oxides are typical.

Finally, **Dyes** give the lubricant or MWF a specific color type desired by the customer. After all, "Everybody knows red grease is better than green grease!" Right! Their main value is in water-diluted fluids to indicate that product is present, since some of these can be clear and water-like in appearance. However, dyes carry some negatives as well, as they can stain skin and paint. Some water-soluble dyes are unstable and can change color. And some dyes can pass thru waste treatment systems, resulting in pollution downstream.

Clearly, this is quite a list, and a chemist's skill is needed to keep everything under control. Arbitrary use of additives at the tankside carries substantial risk, if not done under the supervision of a chemist familiar with the original formulation. Thus, it is important to have a good working relationship with top suppliers of lubricants, MWFs and additives. The pages of TLT are full of ads from such companies.

STLE certification holders are aware of all these issues. They maintain good relations with suppliers, and they can keep your system in balance and safely working at optimum performance levels. Indeed, this is what they do best.



Bob Gresham is STLE's director of professional development. You can reach him at rgresham@stle.org.

Editor's Note:

For a more in-depth overview about greases, check out the STLE Webinar: "Fundamentals of Grease," presented by Bob Gresham. Archive recording available for purchase at the STLE store. Details at www.stle.org.

Consistently consistent

Several tests help us ensure that what we want is what we get-all the time.

KEY CONCEPTS

- Manufacturers strive to make grease's consistency consistently consistent.
- If the consistency of a grease isn't thick enough, it has a hard time staying put. Too thick, and we have trouble pumping it.
- Several tests help keep grease consistent, and NLGI has a classification system.

ONE OF THE MAIN GOALS IN MANUFACTURING is to make the same product the same way to the same specifications—or consistently consistent. In the case of one of the properties of grease products, we strive to manufacture grease to a consistently consistent consistency. Sound like I'm playing with you? Perhaps, I am—just a little.

What is consistency in grease? Consistency is a basic property describing the softness or hardness of a grease, i.e., the degree to which grease resists deformation under the application of force. Consistency is the one property that is always specified on purchase (except in the retail world). The consistency of grease depends a little bit on the viscosity of the base oil and some additives, and, to a much greater ex-

Consistency is a basic property describing the softness or hardness of a grease.





Figure 1 | In most applications, grease stays put, however, it can "slump" or flow slowly. (Courtesy of John Doner, ExxonMobil)

tent, the type and proportion of the thickener.

Why do we care if the consistency of the grease is consistently consistent? One of grease's jobs is to stay put. Grease is a semi-solid that in most applications is supposed to remain where it is applied to provide lubricant when it is needed. Most equipment designs are based on the grease staying put in order to lubricate and also to act as a seal to prevent contamination from entering into the contact area. In some designs, the grease is asked to "slump" or flow but slowly. Further, the consistency might need to be adjusted to enable pumping through a central lubrication system, especially in winter. This property, slumping, is illustrated in the pictures shown in Figure 1.

Consistency is usually measured by means of The Cone Penetration Test, per ASTM D-217. The results also can be affected by recent agitation or applied shear stress. To take this phenomenon into consideration, grease is usually subjected to "working" (a standardized churning process) prior to measuring its penetration value. The Cone Penetration Test is one of the most commonly performed tests on grease products. In the test, a brass cone is dropped into the grease and the degree to which the cone penetrates into the grease is measured on the dial in millimeters. Figure 2 shows a picture of the penetrometer, the device used to measure penetration.



Figure 2 | A brass cone is dropped into the grease and measured for penetration. (Courtesy of John Doner, ExxonMobil)

The sequence in Figure 3 shows varying degrees of penetration or consistency with the left-hand picture depicting the beginning alignment of the cone, the middle picture shows the cone dropped into a thicker grease, and the right-hand picture shows the cone dropped into a slightly less thick grease. Grease can be affected by agita-



Figure 3 | Varying degrees of grease penetration.

tion or shear stress. To determine this property, we drive a perforated plate through the grease via a so-called stroker for a specified number of cycles, usually 60 strokes. But for applications where shear stability is critical, 100,000 strokes are applied. This equipment is shown in Figures 4 and 5.

The National Lubricating Grease Institute (NLGI) has developed a classification system for rating the consistency of greases based on the millimeters the cone penetrates the grease, as shown in Table 1.

Consistency is the one property that is always specified on purchase (except in the retail world).

Grease with a penetration of 265-295 millimeters is classified as a NLGI No. 2. This grade is far and away the most common, certainly the default grade for most equipment designs (and usually what you buy in retail stores). It has a nice smooth consistency that allows the grease to be easily spread onto surfaces, pretty much stays put and yet is thin enough that it can be pumped in many systems operating at moderate ambient temperatures.

Every time we discuss test methods and the results that we obtain, we need to take into consideration the precision and accuracy of the test method. Accuracy seeks to answer the question, "Did you get the correct measurement value?" Bias is a systemic error that contributes to the difference between the mean of a large number of test results and an accepted reference value. The accepted reference value is considered the true value and therefore, bias has to do with the degree to which that true value is not obtained. Thus, in general, through calibration, bias can be reduced or eliminated. Precision has to do with the variability of the test method itself.

Table 1NLGI Classification System forRating Grease Consistency.

Worked Penetration	NLGI Grade	Grease Consistency
445-475	000	Semifluid
400-430	00	
355-385	0	
310-340	1	
265-295	2	Smooth
220-250	3	
175-205	4	
130-160	5	Hard/Block



Figure 4 | Stroker



Figure 5 | Perforated Plate

Table 2	Doproducibility	and Poproducibility	of ASTM D217
IdDle Z		/ and Reproducibility	

Penetration	Penetration Range	Repeatability, One Operator and Apparatus	Reproducibility, Different Operators and Apparatus
Unworked	85 to 475	8 units	19 units
Worked	130 to 475	7 units	20 units
Prolonged worked	130 to 475	15 units	27 units
Block	Under 85	7 units	11 units

Does the method provide the same number every time, or does it vary, and if so, by how much? In ASTM parlance, precision is stated in their published standards as the repeatability and the reproducibility of the method. Repeatability has to do with the difference between two test results performed by the same operator in the same laboratory with the same apparatus on the same test material under constant operating conditions. Reproducibility has to do with the difference between two single and independent results obtained by different operators working in different laboratories on identical test material in the normal and correct operation of the test method.

The method for measuring consis-

tency of greases, ASTM D217, states that the method's worked penetration variability for greases, like a No. 2, for more than one lab and operator is 20 units (see Table 2). Thus, in a given situation, the test results could vary by 40 units (+/-20) and statistically have the same result.

So what we find at the end of the day is that to make a grease of consistently consistent consistency, we must use a method that in and of itself is not especially consistently consistent. Fortunately, for the industry's needs, the method seems to be neither a blessing nor a curse; rather, it is good enough. But specification writers need to be aware of these kinds of issues when they write their specifications.

The global case for Office of the second se

Good intentions aren't enough. You must get all parts of your operation working in environmental harmony.

KEY CONCEPTS

- Smart industrial managers think in terms of sustainability and green chemistry.
- There are four key principles to successfully implementing a green strategy in your facility.
- A well-meaning operations manager can cause major problems and add significant costs to the waste-treatment process.

"GREEN" HAS PRETTY WELL TAKEN OVER OUR CONSCIOUS LIVES. Everyone, at least in the reasonably industrialized nations, is embracing the green culture on some level.

Sure, there are plenty of environmental wackos of whom my father would say, "I could throw a dog through the cracks of their reasoning." However, smart industrial managers think in terms of sustainability and so-called green chemistry.

Remember, sustainability is the idea that we need to make our efforts and processes sustainable in the long term. On a theoretical level, the goal is to live off the sun with maximum efficiency. Ideally, we should survive as long as the sun does.

An easier way to look at sustainability is meeting the needs of the present, without adversely affecting the future, to quote STLE-member Jim D'Arcy of GM. Green chemistry is the idea that we design chemical products and processes to reduce or eliminate the use or generation of hazardous substances. Aside from obvious toxicity in the definition of "hazardous," we also can include a reasonable level of biodegradability or at least reduce the hazards to the environment. The concepts of sustainability and green chemistry must involve global cost-competitiveness. Global here means not only geographically and geopolitically but also from a total systems perspective that is consistent with productivity and profitability. The concepts of sustainability and green chemistry must also involve global cost-competitiveness.

Properly managing fluids and waste streams is an opportunity to maximize profitability, internalize the environmental culture and enhance the company's green image in the community. With proper attention, waste and fluid management can be a source of indirect revenue by reducing both new lubricant purchases and the cost of waste treatment, selling certain wastes as boiler fuel, reducing negative environmental impact and eliminating fines and a negative societal image. In other words, a global business case can and should be made for proper fluid and waste management to achieve green goals.

All this sounds good, but note that the following tenets are essential if your program is to work:

1. **A proactive maintenance program** must be in place and operating properly. This is important because fixing leaks comes first. This directly reduces new lubricant costs as we decrease waste—plus we protect the environment by reducing pollution load and minimizing employee exposure.

Second, by proactively ferreting out root causes of equipment failures and fixing them, we reduce downtime, the costs of spare parts, overtime, etc. Third, we save the costs associated with manufacturing and shipping new parts, calling people in on overtime to fix broken equipment and so on. All this leads to living more efficiently and, therefore, more sustainably.

2. **A top-down commitment** must be made to reducing waste and pollutants, conserving resources and recy-

cling materials at every stage of the product life cycle with the objective of improving the environment at each of these stages. This is pretty self-evident, but the key is that every manager and employee must buy into the concept.

The second part of this is tracking performance; most of these improvements are achieved in small increments, so-called cherry-picking. Do we have a proactive oil analysis program that tells us what we need to know about our fluids in use? Can we extend lube change intervals by modest recycling or refurbishing of the fluid at tank side by filtration, dehydration or another simple process? Can we use a fluid that is more biodegradable or less toxic, which, in turn, puts less load on our waste-treatment budget and reduces health and safety costs related to employee exposure?

The point is, by looking for opportunities at all aspects of the operation, the dividends continually add up to substantial cost savings, leading to a more sustainable, greener life as well as improving profitability and productivity.

3. Whether new, used, refurbished or recycled, only use lubricants or metalworking fluids **meet the specifica-***tions* for their application. This is very important.

For example, it is a good idea to reduce inventory costs by consolidating lubricants. It makes sense to recycle or refurbish lubricants to extend their usable life. But it makes no sense to risk a multimilliondollar piece of equipment using fluids that don't meet

Green chemistry is the idea that we design chemical products and processes to reduce or eliminate the use or generation of hazardous substances.



specification. This again goes to the cherry-picking idea—where it works, it works; where it doesn't, it doesn't. But at least through a proper risk assessment you can justify the costs in real dollars and cents.

4. Recycling only makes sense when a **global business case** can be made for it. This, too, is somewhat selfevident or should be. By tracking the costs at every stage of the product life cycle, we have a viable tool for measuring the impact of any changes on the whole business. The idea of sustainability is inherently a global concept. Thus, our thinking regarding maintenance and fluid management has to be global as well.

I hope it is clear that a global approach to manufacturing is needed for success. Compromising product quality, machine and tool life, manufacturing productivity and the environment is just not acceptable. Rather, we want to maximize each of these in concert. Whether directly or indirectly, these can be measured by global financial results—the overall system must reduce total cost per unit manufactured to achieve maximum profitability.

All that is fine, well and good, but sooner or later you have to send your spent fluids to the waste-treatment plant. This, too, should be part of our global business case and part of our thinking regarding sustainability and use of green chemistries.

While listening to STLE-member John Burke of Houghton International give a presentation on waste management as part of STLE's Metalworking Fluids certificate course, I was struck by another indirect factor impacting the cost of waste management. This has to do with managing the chemistries of the fluids and additives used in our processes to minimize negative impact on the waste-treatment system operation and costs.

One of the more common and cost-effective waste-treatment systems is chemical treatment. This involves separating waste oil from water through chemical additions to achieve precipitation and flocculation, then settling or flotation of oil-containing wastes. These wastes then are removed by filtration or drawing off the concentrate from either the bottom or the surface, depending on the nature of the waste.

All too many plant operations people are not particularly aware of the issues affecting the operation of the waste-treatment plant. This is especially the case when multiple waste streams from a wide variety of operations are dumped into the treatment system. Thus, a well-meaning operations manager can inadvertently cause the waste treatment plant manager major problems and add significant cost to the overall operation of the plant.

In chemical treatment of waste, we are basically reversing everything we have done to make the fluids we are using stable—this is a key concept. In the waste-treatment plant, we add any of a number of additional chemicals to overpower the chemicals used to stabilize the fluid. All too many plant operations people are not particularly aware of the issues affecting the operation of the waste-treatment plant.



Thus, to the extent that we can use green chemistries in the types of chemicals and the fluids as purchased, or the additives used at the tank side to maintain the fluid life, we reduce the load on the waste-treatment plant and reduce cost. Clearly, this is a balancing act. The more stable the fluid during its use, the longer it lasts and the less frequently we send it to the waste plant.

On the other hand, if the fluid is so stable (not green) that we can't treat it without resorting to extreme measures, the money we saved in the operations is consumed in the wastetreatment plant, possibly for an overall net loss. Again, this shows the importance of global thinking in our operations. Probably the simplest thing we can do in the plant is use only very good quality water. If the quantity of deleterious ions in the water is low, then we won't need the quantity of additives to overpower them. With fewer additives, whether green or not, the treatment plant costs less to operate.

Smart managers think in terms of sustainability and socalled green chemistry. Sustainability is the idea that we need to make our green efforts and processes sustainable in the long term. Green chemistry is the idea that we design chemical products and processes to reduce or eliminate the use or generation of hazardous substances. All these efforts only make sense if a global business case can be made. Saving money and improving productivity, safety and profitability all are part of sustainability thinking.

Bearings and their lubrication

This primer will help you understand the basics-and prepare for the CLS exam.

KEY CONCEPTS

- Plant managers often blame a bearing failure on its manufacturer or the oil supplier without understanding how these components work.
- The correct bearing must be selected for the application, properly installed, maintained and lubricated.
- Bearing types include plain, rolling-element, magnetic, jewel and air.

SOME TIME AGO I WROTE ABOUT HOW PEOPLE should work through the process of how bearings are used in their plants before blaming the bearing manufacturer or lubricant supplier for a failure. This is both a simple and yet difficult subject for the average person responsible for equipment that has bearings.¹

Key points of the article were to first ascertain such things as:

- Was the right bearing installed (size, type, etc.)?
- Was the installation correctly carried out (seated properly, alignment checked, etc.)?
- Was the bearing correctly lubricated with the right lubricant and did the lubricant meet proper specifications for the service?
- Were the seals the right type, properly installed and adjusted?
- Was the equipment operated within design limits?
- Was there any chance for contamination during any of the above?

Plain bearings are compact, lightweight and have a high load-carrying capacity.

There are also more obscure failure modes such as pitting due to electrical arcing across the bearing or false brinnelling when shipping cars or machinery long distances and the machine bounces or rocks back and forth on the bearings. Perhaps you can think of other examples, but the point is this: It is not until these kinds of questions are answered that we can start to become suspicious of the equipment manufacturer, bearing manufacturer or lubricant manufacturer.

In the previous article, in the interests of brevity, I did not cover the basic types of bearings we most commonly encounter. Unless we are designing the equipment or work for a bearing company, a basic knowledge should be enough. When you purchase the equipment, the manufacturer and bearing company will have figured out the proper type of bearings. Assuming you use the equipment as intended, everything should work out. They also should recommend a maintenance cycle and procedure; again things should work out if you use the equipment as intended.

BEARING BASICS

So we can all catch up, the purpose of this article is to review the basic types of bearings, both plain and rolling element.

A plain bearing, also known as a plane bearing or a friction bearing, is the simplest type of bearing, comprising just a bearing surface. A simple linear bearing can be a pair of flat surfaces designed to move—for example, a desk drawer and the slides it rests on. In a shaft application, the journal (the part of the shaft in contact with the bearing) slides over the bearing surface either axially or radially, or I suppose both.

Plain bearings are the least expensive type of bearing. They are also compact, lightweight and have a high load-carrying capacity. Lubrication is generally provided by grooving that supplies and distributes the grease or oil (grooves are placed out of the load zone). The correct oil film thickness is determined by viscosity, surface roughness, speed, load and clearances for the specific application. Examples of such bearings include:

Plain Journal Bearings



Plain Sleeve Bearings



In addition to these designs, there are also plain spherical bearings and plain angular contact bearings.

Plain Spherical Bearings



Best suited for applications requiring loads under oscillatory and/or continuous rotational motions. They are also intended for applications with angular misalignment.

Plain Angular Contact Bearings



Best suited for applications with heavy loads, single direction, thrust load. If thrust load reverses, an angular contact bearing will separate. For applications requiring reversing thrust load, use a pair of angular contact bearings.

When up to speed, the lubrication regime is hydrodynamic. Thus, theoretically the bearing can last forever, as shown in Figure 1, where the journal runs on a full film of oil with no real wear.



Angular ball bearings are designed to handle both radial and light axial loads.

The next major class of bearings is rolling element bearings, which the ball bearing is one of the most common. Ball bearings tend to have lower load capacity for their size than other kinds of rolling element bearings due to the smaller con-

Figure 2 | Deep Groove Ball Bearing



tact area between the balls and races. They can tolerate some minor misalignment of the inner and outer races.

Of the various ball bearing types, one is the so-called deep grove ball bearing (*see Figure 2*).

In a deep-groove radial bearing, the race dimensions are close to the dimensions of the balls that run in it. Deep groove bearings can support higher loads because of more area of surface contact.

Angular ball bearings are designed to handle both radial and light axial loads.

Similarly, for applications where axial loads are part of the design as well as radial loads, there are axial ball bearings, which are a more extreme version of angular ball bearings.

For those applications where the shaft may stress the bearing by not staying perfectly aligned, there are self-aligning ball bearings.

Self-Aligning Ball Bearings





For those applications where the load is purely axial, there are thrust ball bearings:

Thrust Ball Bearings



The next major class of rolling element bearings is the roller bearings. These are designed for higher loads and handle similar design problems as ball bearings. First of these is the tapered roller bearing where the key element in the design comes from the fact that cones (*see Figure 3*) can roll over each other without slipping.

Figure 3



Again, when some flex is experienced or angular error in alignment can be expected, there are spherical roller bearings. For high radial load applications, there are cylindrical roller bearings. And for high-load thrust bearing applications, there are thrust tapered roller bearings. These bearings enable axially very compact bearing arrangements. They can carry very heavy axial loads, are insensitive to shock loads and are stiff. They are available in single-direction tapered roller thrust bearings and double-direction tapered roller thrust bearings.

Likewise for high thrust loads, there are cylindrical roller thrust bearings. Cylindrical roller thrust bearings are suitable for heavy axial loads. They are relatively insensitive to shock loads, are very stiff and require little axial space. Further, they are usually available as single-direction bearings, which can only accommodate axial loads acting in one direction.



Spherical Roller Thrust Bearings

One of the most versatile designs is the spherical roller thrust bearing. Here, the load is transmitted from one raceway to the other at an angle to the bearing axis. Thus, they can accommodate radial loads in addition to simultaneously acting axial loads. Their self-aligning feature makes them relatively insensitive to shaft deflection and misalignment. They can, therefore, support very heavy axial loads and relatively high-speed operation.

A special case of rolling element bearings are needle bearings. Needle bearings have a large surface area in contact with the bearing outer surfaces compared to ball bearings. They are compact—less added clearance (difference between the diameter of the shaft and the outer diameter of the bearing). Thus, they can handle extremely high radial load-carrying capacity.

Some specialty types of bearings include magnetic bearings, which suspend the shaft by electromagnets surrounding the shaft. Thus in operation, it exhibits no wear and, of course, very low friction. Obviously these are very expensive bearings to purchase and operate.

Jewel bearings are yet another unusual type but which are commonly used in clocks, watches and other fine mechanisms. They can be extremely small and often are not lubricated.

Finally, air bearings are yet another specialty bearing, which overcomes the disadvantages of oil or grease lubrication systems in equipment such as turbochargers. Here oil



Needle Bearings



Jewel Bearings in a watch

can enter the intake air and have a negative impact on exhaust emissions in the turbocharger. Also, oil supplied to a roller bearing creates some level of hydrodynamic drag. That is eliminated in an air bearing. Oil will coke if the engine is turned off when the turbo is still very hot.

Further, an oil-lubricated turbocharger would need to be designed to supply oil and with drain hoses and perhaps a cooler, all of which increases cost and complexity of the turbo. Use of plain and rolling element bearings would need a relatively large blade tip clearance, whereas air bearings have a very low profile.

Well, that is probably more than you ever wanted to know about bearing designs. Yet, for those preparing for the CLS certification examination, you will need to have an awareness of the different kinds of bearings and how to troubleshoot them.

REFERENCES

 Gresham, R.M. (2005), "When Bad Things Happen to Good Bearings," TLT, **61** (12), pp. 18-19.

The basics of filters and filtration

Establishing a good relationship with your supplier is the best strategy to using these materials successfully.



KEY CONCEPTS

- There are three major types of filters, each of which have their own unique properties.
- Developing a good relationship with suppliers is helpful in making the right filter choice and how best to use them.
- The cost of filters is inexpensive as replacing or shutting down a valuable piece of equipment and interrupting production.

FILTERS AND FILTRATION ARE SUBJECTS that seem simple to understand on the surface but, like so many things, are much more complex in detail. And, of course, the devil is in the details. It is well beyond the scope of this article to delve too deeply, as there just isn't enough space in this issue.

For example, there are a wide variety of filters used in the chemical industry to separate a crystalline product from its reaction mass; we are all familiar with various air filters, starting with those used in our home heating systems or automobiles, and there are a large number of liquid fluid filters ranging from beer to gasoline.

When you boil it down, solids, liquids or gases can contaminate solids, liquids or gases—that covers a lot of ground. Nevertheless, the basic principles by which all these different filter problems are managed are fundamentally the same, but the details are often unique. So let's try to limit the playing field and just look at the very basics.

First, let's only look at the removal of relatively large (> 1-5 micron) insoluble contaminants via a porous medium, as typically encountered in the lubricants industry. These are also the more common kinds of filtra-

tion problems. There are three major types of filters:

- 1. Mechanical. Metal screens or discs that remove only coarse particles.
- 2. Absorbent (inactive). Resin-impregnated paper, cotton, etc., that remove smaller particles and some water.
- 3. Adsorbent (active). Charcoal, diatomaceous earth, which is not used in hydraulics because it may strip additives.

There is also gravity/density filtration (centrifuge and settling), vacuum dehydration (removes water only) and ultrafiltration (removes oil and certain larger particles). These are well beyond the scope of this article.

For this discussion, we are considering absorbent (inactive) filters. Probably the most important recommendation from this article would be to develop a good relationship with your filter supplier, as he can guide you in making the right choice of filters and how best to use them. I hope the wisdom of this will become apparent. There are some terms often used: nominal rating (rates size of pores in filter, for example, 5-micron nominal), absolute (gives largest opening in media) and beta ratio/efficiency (how many times through the filter before all particles of a certain size are removed).

Regarding beta ratio, the idea is to rate the efficiency of the filter. For example, if we pass a fluid (notice I said fluid, because the fluid could be air or hydraulic fluid) with 1,000 particles > 5 microns through a nominal 5-micron filter and we measure 500 particles > 5 microns in the output, then the beta ratio is 1,000/500 = 2, which represents an efficiency of 50 percent. Or if we pass a fluid with 1,000 particles > 5 microns through a 5 nominal micron filter and 10 particles > 5 microns pass through the filter, then the rating is 100. This is written as:

 β_5 = 1000/10 = 100 (Note: this represents an efficiency of 99 percent)

Already we are beginning to see that all filters are not the same.

In TLT we've discussed contamination and the need to set contamination limits for each piece of equipment.¹ With this information, in a system of several operating components such as a hydraulic system, we can select the most sensitive machine (component) in the system. In addition, we can begin to determine the correct filter placement and establishment of a cleanliness target. Further, we need to know the maximum system pressure, the maximum flow through the filter and the viscosity of the fluid. Also, we need to know the temperature range and the pressure range that the system and filter will experience. Starting to get just a little complicated, isn't it?

Let's think about a hydraulic system: first to fill the reservoir (which we will assume is clean but in practice don't make that assumption), we should have a filter on the fill

line to insure that we don't add contaminants to the reservoir. What's the pressure and flow of the fill pump? After the reservoir is filled, we will need a breather cap fitted with a filter to keep dust and airborne contaminants from entering the reservoir as tank levels fluctuate. Then we should have a filter (often just a screen filter) on the intake line at the bottom of the reservoir (where a lot of big stuff tends to settle) and another finer lower-pressure filter just before the pump to protect it. Then another higher pressure filter on the output side of the pump (the pump tends to grind dirt and generate wear particles, as well).

At this point, the actuators and control valves should be seeing pretty clean fluid. However, as the fluid returns from the actuators, the fluid picks up contaminants from rod seal leakage, so we need a filter on the return line to the reservoir. Then, if that is not enough, in some systems it is also necessary to employ an offline filter connected to the reservoir (see Figure 1).



Figure 1 | Typical filter placement in a hydraulic system.

How is a poor soul supposed to sort all this out? Well, there are a number of ANCI and ISO tests that assure filterelement quality (burst resistance, element material compatibility, flow fatigue resistance, flow versus pressure drop, etc.). This is why I think it makes a lot of sense to develop a good working relationship with a credible filter supplier. Don't skimp on the quality or number of filters-get what is needed for the system. The cost of filters is cheap next to the cost of replacing or shutting down a valuable piece of equipment and interrupting production. Once installed, maintain the filters properly. If you don't keep the filters working properly, it is as foolish as trying to pull up a stump with a logging chain tied to the stump with a piece of yarn.

It is just like the man from the old Fram automobile oil filter commercials said, "You can pay me now or you can pay me later!" **TLT**

REFERENCES

1. Gresham, R.M. (2007), "What's The Deal with Contamination Control," TLT, 63 (12), pp. 22-24.

The mysterious world of **Seals**

These important structures play a major role in making sure a lubricant stays in place.

IN THE WORLD OF TRIBOLOGY, seals are a bit mysterious. Most things that move relative to something else need to be lubricated in some fashion—we all pretty much have that figured out. And, intuitively, it seems to make sense that to lubricate two surfaces, we need a way to keep the lubricant where we want it.

However, many systems do not have that requirement, including chainsaw bars, trackside lubricators and the rapidly becoming obsolete two-cycle engines. These all use the lubricant once and then pass it on irretrievably to the environment. In other more common systems, something must help hold the lubricant in place, and that something is a seal. But here's where it gets interesting, the lubricant may not necessarily be a lubricant as we most commonly think of it but I'm getting ahead of myself.

KEY CONCEPTS

- Seals can be classified into two major categories: static and dynamic.
- Not all seal designs require physical contact with a mating surface to seal.
- There are several sources of seal failure such as mishandling and misalignment during installation.



(Photo courtesy of SKF USA, Inc.)

The main function of seals can be summarized as follows: seals are present to prevent or minimize passage of fluid through gaps between mechanical elements of a machine. There are many different types of seals that are used in various applications.

First, seals can be classified into two major categories: static and dynamic. Static seals, which are the simplest form, seal two objects together that have relatively little or no motion such as thermal expansion. These seals are usually in the form of gaskets or sealant compounds. The more dynamic applications (pun intended) require dynamic seals. Of these seals, there are two major types: those sealing rotating motion and those sealing reciprocating motion (*see chart on page 24*).

As you can see, there are a lot of different kinds of motions that must be sealed and a lot of different methods have been devised to do so. Often these varied designs were the result of the nature of the material being sealed and the negative consequences of that material being released into the environment, especially with regard to employee safety. It is beyond the scope of this article to go into all the different designs and materials of construction, except to say that in addition to sealing some materials in, we may also be sealing an environment out—or vice versa.

To be less abstract, first consider that many seal designs need a small amount of lubricant to function. The lubricant may not be a lubricant as we normally think of it but, rather, as in a chemical plant, the very chemical we are working with. Such is the case in sealing a pump shaft for a pump that is designed for pumping water, solvents, gases, caustic acids,



crude oil or whatever. This obviously makes the job more difficult, as some of these substances are not only potentially hazardous but also not very good lubricants and may be deleterious to many types of sealing materials.

Thus, there are a number of considerations when it comes to the proper use of seals in machinery. In this article, we'll review the major issues. Not all seal designs require physical contact with a mating surface to seal. A good example is labyrinth seals, which provide a tortuous path progressively building sufficient back pressure to prevent leakage.

However, with the more common seals that do have contact, the sliding surfaces of the seals are always lubricated by the fluid sealed or by supplementary lubrication fed directly into the space ahead of an exclusionary seal or from impregnated solid lubricants at the seal interface. Therefore, one has to consider wear of both the seal and its mating surface.

Ideally, the mating surface should be of a hard, wear-resistant material relative to the seal and the substance being sealed (which also can include slurries or other entrained particulate material). The hardness of the seal material and its compatibility with the fluid sealed are clearly critical factors. Thus, ideally, when it is necessary to replace the seal, only the seal should be replaced and the mating surface only cleaned or lightly polished.

High surface-sliding speed and/or excessive pressure between sliding surfaces increases temperature. At low speed with high pressure, lubrication may be difficult. These factors can change seal/face geometry, which results in seal failure. As alluded to above, abrasives in the fluid sealed or rough seal seats or mating surfaces can cause damage and leakage. Abrasion resistance of the seal material is an important factor. Interestingly, too much or too little surface roughness on sealed surfaces can equally be a problem.

SEAL FAILURE

Given the proper design considerations of speed, pressure, abrasion resistance, chemical resistance, surface roughness and materials of construction, there are other important factors that can result in seal failure. Probably the most comSeals are present to prevent or minimize passage of fluid through gaps between mechanical elements of a machine.

mon is mishandling, which results in scratches, dings or chips in the seal face. This damage to the seal or its mating surface usually occurs during installation, storage or handling. Misalignment during installation is another major source of failure.

Even with proper design and installation, we are not out of the woods yet. We can have failure at startup where the seal faces are not lubricated. An example would be running the seal dry because a valve on the suction side of a pump was left closed.

Finally, like most mechanical systems, proper maintenance is important. Two key factors are "unscheduled movement," which can be excessive axial or radial movement of a shaft against the seal; that is, excessive vibration or any other kind of related movement that is not part of the design. This could arise from a pump and motor that are firmly attached and aligned to a solid base. The other key factor is excessive contamination, which is often due to improper maintenance of filtration systems.

Like so many things we encounter in this tribologically influenced world of ours, there is often more to it than meets the eye, and seals are no exception. Without effective seals, our cars burn oil (bad rings), our environment is polluted due to leakage, employee safety can be jeopardized and the workplace becomes a pig sty with material leaking across the floor and a haze in the air.

In 1993 the Clean Air Act was introduced and since then the seal industry has implemented many very effective practices when it comes to the proper installation and maintenance of seals. Even the most cursory look at our environment versus 20 years ago clearly shows these advances.

TURBINES: What goes around comes around

There are three main types of turbomachinery, and each has its own set of lubrication requirements.



- Hydro-turbines are driven by water and connect to an electricity generator or more properly turbo-alternator to produce electricity.
- Industrial steam turbines have multiple uses such as driving compressors, turbo-alternators, blowers and pumps.
- Gas turbines are a good application for synthetic lubricants such as polyalphaolefins and ester-based oils.

I MAKE NO CLAIM TO BEING AN EXPERT IN TURBOMACHINERY, but these gadgets have always intrigued me as a class of machinery. At STLE's Annual Meeting & Exhibition, most of the education courses and practical papers tend to gloss over lubrication of turbomachinery. So here goes.

In the world of turbines, there are three main types: hydro, steam and gas. Well, I guess you should also include wind turbines, but they are quite a bit different than the above three. While I suppose you

could call wind turbines a special case of a gas (air) turbine, to me they are a big wind-driven propeller hooked up to a gearbox that is, in turn, hooked up to a generator or alternator.

HYDRO-TURBINES

These machines are driven by water and connected to an electricity generator or, more properly, a turbo-alternator to produce electricity. Hydro-turbines are on the low end in terms of application requirements but still significant. Thus, the lubricating oil sees temperatures in the oil sump on the order of 40 C-60 C with peak temperatures in the circulation system to maybe 70 C-95 C. Speeds are also moderate at around 50-600 rpm.

The oil also must lubricate guide vanes and control system components. The main lubrication issues for these kinds of turbines are water contamination and service life. Thus, mineral oil-based R&O oils that have good water demulsibility are needed. The long service life is desirable to reduce maintenance costs and downtime. These are important due to the physical location of these turbines and the need for uninterrupted electrical power output.

STEAM TURBINES

Industrial steam turbines have multiple uses, usually to drive compressors, turbo-alternators, blowers, pumps and the like. In compressor applications, steam turbines and the compressor itself are similar in that they are both turbomachines. As such, they can behave similarly in terms of speed versus output. Thus, steam turbines are excellent for variable-speed turbo-compressors.



Figure 1 | Schematic of a hydro-turbine installation.



Figure 2 | Schematic of a steam turbine.



Figure 3 | Schematic of a hydro-turbine.



Figure 4 | A steam turbine installation.



Figure 5 | General Electric LM2500 Gas Turbine

Steam turbines can take on many different configurations, an analysis of which goes beyond the scope of this article. However, all multistage steam turbines require cool, clean oil supplied to their journal bearings.

This oil is supplied from several types of systems, but the key is that the oil must be delivered at the right flow rate, pressure and temperature. Often the driven equipment, such as the compressor, is also lubricated with the same oil, again at the right level of cleanliness, flow, pressure and temperature. Furthermore, additional equipment also might be lubricated by this same system such as various control valves.

In compressor applications, steam turbines and the compressor itself are similar in that they are both turbomachines.

In general terms, steam turbines can operate up to speeds of 3,000 rpm, oil sumps around 40 C-70 C with peak or hot spot temperatures as high as 150 C. Clearly, aside from particulate contamination, which is always a problem, steam turbines are subject to the effects of water and steam. Typically turbine oils for steam turbines must be primarily resistant to rust and oxidation, the so-called R&O oils. Additionally, turbine oils may contain antiwear and EP additives. Further, they should exhibit good demulsibility of water and be low foaming.

Interestingly, when one thinks about the highly formulated automotive oils (10-20 percent additives), turbine oils by contrast are typically formulated with not much more than 1 percent additives. Therefore, the base oils are important. They can vary from Groups II, III, III+ or IV. The higher refined oils tend to have more inherent oxidation stability but, especially in the old days, they also tended to exhibit more varnish formation, likely because less refined oils tend to solublize varnish rather than letting it form deposits.

More modern formulations along with effective filtration generally manage excessive varnish formation, or at least they should. Such oils typically have a viscosity index (VI) in the range of 95-100 so that the viscosity doesn't vary too much from startup to peak temperatures.

GAS TURBINES

Industrial gas turbines, which are basically land-based jet engines (windmills notwithstanding), have some similarities to steam turbines except that steam is replaced with hot combustion gases. Thus, water contamination is not so much a problem with gas turbines. However, sump temperatures can range between 50 C-100 C with hot spot peaks up to 280 C. Speeds also are higher on the order of 3-7,000 rpm. Therefore, the performance requirements of the lubricating oil are necessarily higher, while lubricating oils based on hydro-treated basestocks are used for the less stringent applications.

Clearly, gas turbines are a good application for synthetic lubricants such as polyalphaolefins and ester-based oils. Many of the larger, higher-performing industrial gas turbines (like the one shown in Figure 5) often use an aircraft engine core and require similar lubricants. For more advanced aircraft jet engines, which really are just higher-performing gas turbines, we have to kick it up a notch.

These turbines use primarily ester-based lubricants for their wide-temperature range capabilities such as those described by military specifications MIL-L-7808 and MIL-L-23699. For even higher-temperature resistance with operating temperatures as high as 300 C, polyphenylether lubricants, as described in MIL-L-87100, could be used. But these are not for the financially faint of heart, and the polyphenylethers have poor low-temperature performance, which is not so critical for an industrial gas turbine but can be a showstopper for an airplane.

Clearly, turbomachinery, like the applications described above, affect our everyday lives in many ways. Keeping them going around allows us to go around.

What's a gear?

An overview of the machine elements that keep the industrial world turning.

KEY CONCEPTS

- Gears are machine elements that transmit motion by means of successively engaging teeth.
- Gears are classified according to the relative position of the axis of their revolution.
- Gears are made from a variety of materials depending on cost and application.

HOW MANY OF YOU ARE OLD ENOUGH TO REMEMBER WALT DIS-NEY'S GYRO GEARLOOSE? Probably not many. I suppose he was



the first fictional tribologist. In fact, old Gyro was around before the word tribologist was coined. Gyro, who first appeared in Walt Disney Comic Book No. 140 in 1952, was a brilliant inventor of all kinds of humorous gadgets and devices, many of which included quite novel gear sets.

One can't help but wonder how much he knew about the lubrication of his somewhat uniquely geared inventions. So let's take a brief look at the world of gears.

First a definition: Gears are machine elements that transmit motion by means of successively engaging teeth. The gear teeth act as small levers. In general, gears are classified according to the relative position of the axis of their revolution. Thus, these axes are parallel, intersecting or, as you might guess, neither intersecting nor parallel—but non-intersecting.

Thus, gears connect shafts that operate from these different directions and, depending on the relative diameters and/ or numbers of teeth per gear, can multiply speed or force in a manner analogous to a lever. So gears can reduce or increase speed, transmit power, increase or decrease torque, change direction and change axis of direction. Pretty handy traits for design engineers. Some of the more common gear types are:

SPUR GEARS

Spur gears or straight-cut gears are the simplest type of gear. Spur gears connect parallel shafts and have involute (curling inward) teeth, parallel to the shafts (*see diagram*).



Involute Tooth



External Spur Gears



Internal Spur Gear

Spur gears consist of a cylinder or disk with the teeth projecting radially and, although not straight-sided in form, the edge of each tooth is straight and aligned parallel to the axis of rotation. These gears can be meshed together correctly only if they are fitted to parallel shafts. Spur gears are relatively inexpensive to manufacture, cause no axial thrust between the gears and, while giving lower performance than other gear types, are generally satisfactory in low-speed, simple applications. They can be noisy at higher speeds.

INTERSECTING SHAFT GEARS



Bevel Gears



Zerol Gears





Spiral Bevel Gears

Hypoid Gears

HELICAL GEARS

Helical gears offer a refinement over spur gears. Helical gears can be meshed in parallel or crossed orientations. Helical gears also have involute teeth and are cut at an angle (called the helix angle) to the axis of rotation. Since the gear is curved, this angling causes the tooth shape to be a segment of a helix. The mating gears must have the same angle but in opposite hands (left and right). The angled teeth engage more gradually than do spur gear teeth, causing them to run more smoothly and quietly because there is continuous tooth contact. A disadvantage of helical gears is a resultant thrust along the axis of the gear, which needs to be accommodated by appropriate thrust bearings. The greater degree of sliding friction between the meshing teeth is often addressed with antiscuff and antiwear additives in the lubricant.

Helical gears are found in high-speed applications where good performance is needed. As you might expect, they can carry higher loads as there is a greater tooth cross section. Obviously, they are more expensive to manufacture. Another way to combat the axial thrust property is to use herringbone gears.

HERRINGBONE GEARS

Herringbone gears consist of two helical gears of opposite hands that are mounted side-by-side on the shaft and thus cancel the resulting thrust forces.

BEVEL GEARS

Bevel gears have a conical configuration as opposed to cylindrical for spur and helical. Thus, the two gears are, in effect, two truncated cones in rolling contact. Within this configuration there are straight bevels, which are like spur gears with no helix angle. Examples of bevel gears are miter gears, equal in size with a 90-degree shaft angle, angular gears with shaft angles other than 90 degrees, and crown gears where one gear is flat with a pitch angle of 90 degrees. Zerol bevel gears are an intermediate type between straight and spiral bevel gears. Their teeth are curved or crowned, so that contact takes place at the tooth center but not angled. Spiral bevel gears are analogous to helical gears but with a conical configuration. A hypoid gear is an example of a bevel gear that is neither parallel nor intersecting. Other examples of non-parallel and non-intersecting shaft gears are crossed helical gears and worm gears.

Crossed helical gears are used where the shafts are not parallel and not intersecting but rather skewed. They can be at 90 degrees or other angles. The teeth necessarily slide more and are, therefore, less efficient and often require highly additized lubricants.

Worm gears are used when large gear reductions are needed. It is common for worm gears to have reductions of 20:1 and even up to 300:1 or greater. Many worm gears have



Parallel Helical Gears

Crossed Helical Gears

Herringbone Gears



Figure 1 | Key Elements of Gear Design





Rack and pinion (The rack is like a gear whose axis is infinity)



Crossed Helical Gears



Worm Gears

an interesting property that no other gear set has: the worm can easily turn the gear, but the gear cannot turn the worm. This is because the angle on the worm is so shallow that when the gear tries to spin it, the friction between the gear and the worm holds the worm in place. This feature is useful for machines such as conveyor systems in which the locking feature can act as a brake for the conveyor when the motor is not turning.

ROTARY TO TRANSLATION GEARS

These gears transmit rotary motion from the pinion to translational motion of the rack. The rack amounts to a gear of infinite radius with flat involute teeth.

The different designs of gears is an extremely complex subject and beyond the scope of this article. Figure 1 depicts a diagram of a gear that shows the key elements of gear design.

Gears are made from a variety of materials dependent upon cost and the application. These materials include cast iron, powdered metals, steel, a variety of special nonferrous alloys and non-metallics such as the group of engineering plastics: nylon, acetal, UHMWPE, etc.

Gears are used in a wide variety of combinations in a wide variety of applications, such as in clocks, copiers, huge bull gears in drag lines, drawbridges, industrial gearboxes and related industrial equipment and, of course, truck and automobile transmissions and differentials.

Basic Handbook of Lubrication

The only reference you need to understand tribology fundamentals!

Edited by STLE's Alberta Section, the Basic Handbook of Lubrication (Third Edition) is a comprehensive text authored by more than 25 contributors. At 360 pages, this technical reference thoroughly covers some 30 topics with material edited to help newcomers and veterans to the lubricants industry. **This reference is included in the recommended study material for STLE's Certified Lubrication Specialist**[®] **and Oil Monitoring Analyst**[®] (**1&11) certifications.**

CHAPTER TITLES

- Oil viscosity & selecting correct grade depending on temperature
- Friction and lubrication regimes
- Mineral base oils
- Synthetic base oils and finished lubricants
- Used oil re-refining to create base oils
- Additives used in formulating lubricants
- New lubricants analysis & testing
- Bearing lubrication
- Engine oils
- (Stationary) natural gas engine lubrication
- Enclosed gear oils: Classifications and additives
- Hydraulics fluids & related properties
- Hydraulic system components
- Hydraulic system components sample calculation
- Hydraulic system components sample calculation appendix
- Air compressor lubrication
- Reciprocating natural gas compressor lubrication
- Lubrication of electric motor bearings

- Turbine oils
- Refrigeration system lubrication
- Grease, an introduction
- Solid film lubricants
- Metalworking & preservative fluids
- Environmentally friendly lubricants
- Solvents & cleaners
- Aftermarket additives
- Centralized lubrication systems
- Pneumatics
- Filtration
- Introduction to seals
- Wear types
- Degradation and analysis of oils in service
- Condition monitoring & industrial machinery
- Effective bearing failure analysis
- A guide to purchasing lubricants
- Storage of new lubricants (health, safety and environmental considerations)
- Used oil collection
- Glossary of lubrication terms

Price: \$125 to STLE members. \$159 to others.

Comes in spiral-bound and perfect-bound editions. Available only through STLE! Order at **www.stle.org**, or call 847-825-5536.





Education Your Way. Focused. Flexible. Accessible.



STLE University is your personalized, centralized location for continuing education in the field of tribology and lubrication engineering. We provide you with the latest educational information in the field while at the same time providing opportunities to enhance your career and create value for your company.

STLE University was designed with our members in mind. STLE provides education that is:

- **Focused:** STLE offers a variety of courses and webinars that are designed for specific audiences working in the field of tribology and lubrication engineering. Our offerings vary by topical area, level of expertise (basic to advanced) and audience segment (formulators, salespeople, distributors, students, etc.).
- **Flexible:** Courses are available in-person and online to fit around any busy schedule, and are designed to meet your varying educational needs. If you need a short course, an introduction/overview or a long, in-depth course, chances are STLE University has something to fit your needs. There are varying types and formats of courses to match up with your available time commitment.
- Accessible: STLE offers a variety of educational opportunities, both in-person and online. Our in-person education locations change yearly, ensuring you have a chance to visit one nearby. Our online options allow you to purchase a course at any time and start it immediately. As long as you have a computer and an Internet connection, you have online education. Also, STLE University is not limited to members. However, you receive significant discounts if you become a member.

All of our educational opportunities also apply towards STLE's recertification requirements. Visit **www.stle.org/university** for more information and schedule of upcoming courses and webinars.

Find out more about STLE! Sign up and follow us on: 🛅 📔 📋



Choose from a variety of educational formats:

Online Offerings

- Online certificate courses
 - Fundamentals of Lubrication
- Online short courses
 - Basic Lubrication
 - Lubrication Composition
 - Fluid Management & Recycling
 - Metalworking Fluids
- Monthly Webinars

Topics include bearings, gears, hydraulics, MWFs and much more!

In-Person Offerings

- Annual Meeting courses
- Local Section courses
- Certificate courses
- On-site education courses

