High-Performance Industrial Gear Lubricants

FOR OPTIMAL RELIABILITY

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Management Summary

In recent years, gearbox technology has advanced and original equipment manufacturers (OEMs) have specified required gear oils to meet the lubrication requirements of these new designs. Modern gearboxes operate under severe conditions while maintaining their reliability to ensure end-user productivity. The latest generation of industrial gear lubricants can provide enhanced performance—even under extreme operating conditions—for optimal reliability and reduced cost of operation.

This paper describes how gear lubricants function in gearboxes and discusses the facts versus myths of industrial gear lubricants. The paper will show how advanced gear lubricant technology can optimize the life of the gears, bearings and seals. Opportunities to use advanced synthetic gear lubricants to achieve operational benefits in the areas of improved energy efficiency, wider operating temperature ranges, extended oil drain intervals and equipment life will be discussed.

Types of Lubricating Film Classifications

Knowledge of the types of lubricating film will assist in understanding the formulation and application of gear lubricants.

The two types of lubricating film relevant to gear lubrication are boundary and elastohydrodynamic lubrication (EHL). Understanding the characteristics of each is important in understanding the lubricant performance requirements.

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Figure 1 shows that boundary lubrication exists during sliding motion where metal-to-metal contact occurs between the two surfaces. The coefficient of friction ranges from 0.1 to 0.15 between the metal surfaces in this lubrication region. In the absence of specialized anti-wear additive technology, increased wear rates will occur during boundary lubrication.

The amount of wear will depend on temperature, speed, surface finishes, material, lubricant viscosity and effectiveness of the additives. Gears operate with combined sliding and rolling motion above and below the pitch line. Under low-speed and high-temperature conditions, the EHL film will be relatively thin and boundary conditions will dominate.

EHL occurs when the lubricant film thickness reduces metal-to-metal contact and local contact pressure between the surfaces is high enough to cause elastic deformation. This creates a small but finite area of contact, often referred to as the Hertzian contact zone. The high contact pressure also acts to increase the lubricant viscosity as it is drawn into the contact zone. This increase in viscosity helps generate the lubricant film that maintains the separation of the two surfaces. With this high viscosity and the short time in the contact area, the lubricant cannot escape and separation of the surfaces is achieved. The film thickness generated in EHL contacts of this type is very thin and is typically between 0.1 to 0.5 micrometers. Film thickness is a function of temperature, speed, load, geometric conformity of the surfaces, initial lubricant viscosity and the rate at which viscosity increases with pressure. This last characteristic is often quantified by the pressure-viscosity coefficient of the lubricant, and varies with its composition.

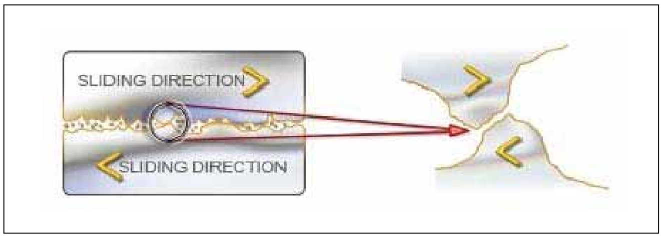

Figure 1—Boundary lubrication.

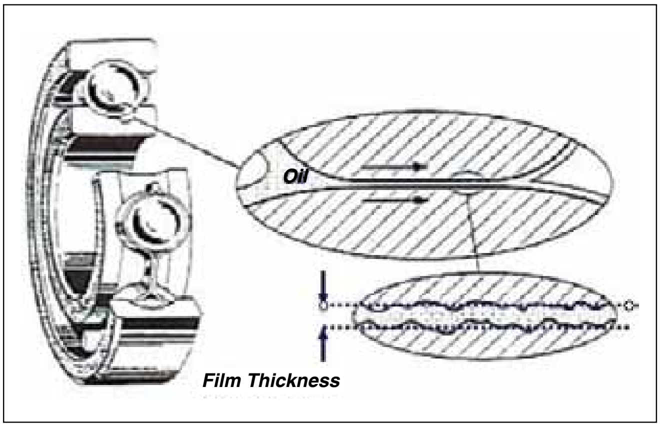

Figure 2—EHL in bearing.

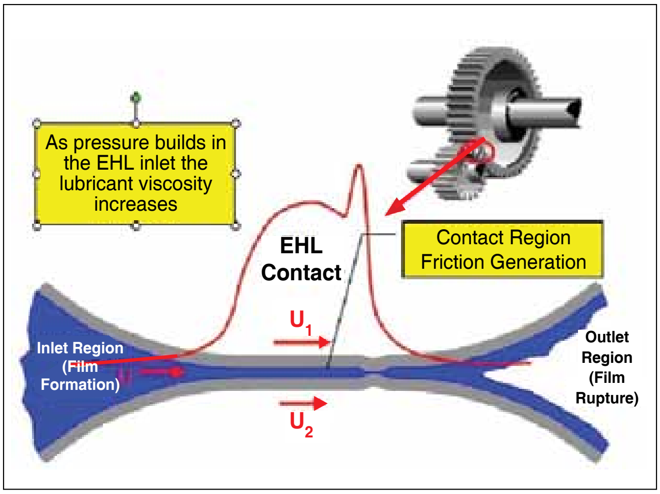

Figure 3—EHL in gears.

Surface finish also influences the state of lubrication between two surfaces. The more polished the surface, the lower the lubricant film thickness that is required to achieve separation between the contacting surfaces. This is often quantified in the Lambda value or specific film thickness. This is merely the ratio of the EHL film thickness to a measure of the combined surface roughness. Thus a high specific film thickness indicates that the surfaces are well separated. Conversely, a low specific film thickness indicates poorer surface separation, which may result in higher friction and potentially increased rates of wear.

Two examples of EHL lubrication classification are when gear teeth mesh at the pitch line and in the load zone of anti-friction bearings (Figs. 2–3).

Gear Lubricant Requirements

The lubricant formulator must consider many factors and components in developing a proper lubricant for an enclosed gearbox. The most important components are the gears—i.e., gear teeth, bearings and seals. The factors influencing the lubricant and the reliability of the gears, bearings and seals are:

- Gear type
- Gear speed
- Reduction ratios
- Operating temperatures
- Filterability
- Input power
- Load characteristics
    - -Shock in a steel mill
    - -Steady in a power plant cooling tower
- Drive type
- Application method
- Water contamination
- Ambient conditions
    - -Arctic temperatures below –20°F
    - -Tropical, high-humidity temperatures above 100°F
- Maintenance access
    - -Easy access; walk-up to the gearbox
    - -Located under an evaporative-type cooling tower
    - -Located aboveground in a wind turbine or overhead crane
- Industrial specifications
    - -AGMA (American Gear Manufacturers Association)
    - -DIN (Deutsches Institut für Normung)
- Original equipment manufacturers (OEM) specifications

The goal is to develop a lubricant that uses high-performance base stocks balanced with the proper additive technology to achieve the optimum performance and reliability of the gearbox.

When gearbox operating conditions are severe, such as extreme temperatures, loads and speeds, synthetic lubricants may be necessary for reliable operation. A synthetic lubricant that offers extended drain intervals may also be desirable where equipment is not readily accessible. An example of an application that meets the preceding criteria would be gearboxes in wind turbines.

Gear Lubricant Characteristics

The necessary characteristics for a gear lubricant can be stated as:

- Correct viscosity at operating temperatures to assure distribution of the lubricant to all contact surfaces and formation of an EHL film over the range of operating speeds and loads.
- Adequate low-temperature fluidity to permit circulation at the lowest expected start-up temperature.
- Chemical stability to minimize oxidation under elevated temperatures and agitation in the presence of air, and to provide the desired lubricant life for the maintenance service intervals.
- Good demulsibility to permit water separation for removal.
- Good anti-wear performance to protect against wear under boundary lubrication.
- Extreme pressure additives to minimize welding of metals under excessive loads.
- Low traction to control operating temperatures under severe service.
- Anti-rust properties to protect gears and bearing surfaces from rusting.
- Non-corrosive chemistry so that gears and bearings will not be subjected to chemical attack by the lubricant.
- Foam resistance to allow entrained air to separate from the lubricant.
- Compatibility with commonly used seals.

A properly formulated enclosed gear lubricant is a balanced formulation that will provide gear protection, bearing protection, corrosion/rust resistance, seal compatibility, filterability, oxidation resistance and anti-foam/air release (Fig. 4).

Gear Protection

The gear lubricant functions are to cool, reduce wear and to assist in sealing for optimal protection of the gearbox components. An area of concern for lubricant gear protection is excessive wear. Several types of wear might take place including pitting, micropitting and scuffing.

Pitting can be in the form of micropitting or macropitting. Micropitting is surface metal fatigue that causes tooth profile shape deviations that can reduce gearbox efficiency while increasing noise and vibrations. Two commonly used terms to describe micropitting are "grey staining" or "frosting" of the gear tooth face. Contact stresses located below the pitch line (dedendum) of the driving gear tooth are higher because of the shorter radii of the tooth curvature (Fig. 5).

Gears that are overloaded for any reason will develop fatigue failure, and pitting of surface metal will occur in the dedendum area after long periods of time. As the pitting increases, it can be called macropitting. If an overload is great enough, this type of fatigue failure could occur in a relatively short period of time (Fig. 6).

Micropitting is talked about more in current gear designs than those of 30 years ago. There are many operational and design factors that increase the tendencies for micropitting. Listed below are potential solutions to reduce micropitting in gears.

Solutions for reducing macro/micropitting mechanically:

- Use quality steel; properly heat treat to desired hardness.
- Reduce contact stresses by reducing load.
- Optimize gear geometry.
- Polish to smoother surface finishes.
- Assure uniform load distribution.

Solutions for reducing pitting through lubrication:

- Check to ensure the use of the proper viscosity. Higher-viscosity lubricant directionally may be a solution, but beware that the higher viscosity may cause issues with

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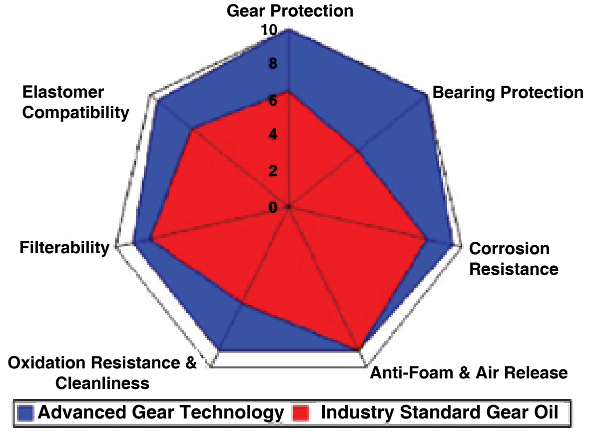


Based on AGMA 9005 EO2 EP Lubricant

Figure 4—Balanced gear oil formulation.

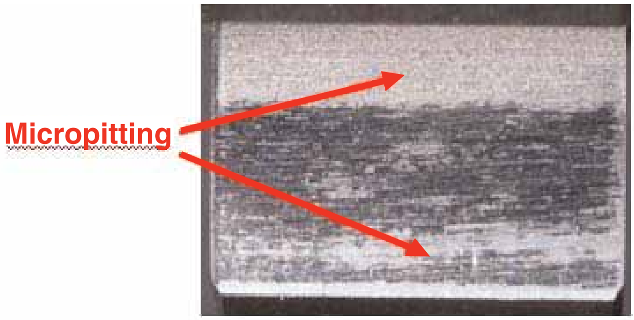


Figure 5—Micropitting example.

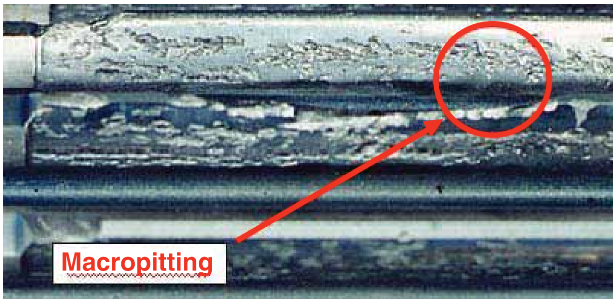


Figure 6—Macropitting example.

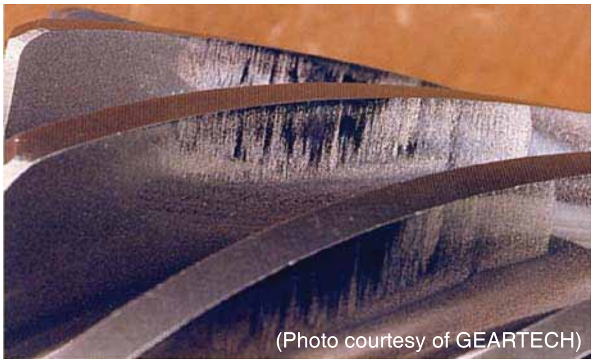

(Photo courtesy of GEARTECH)

Figure 7—Scuffing.

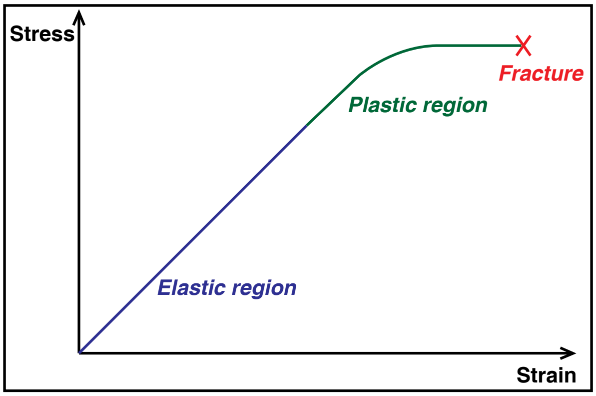
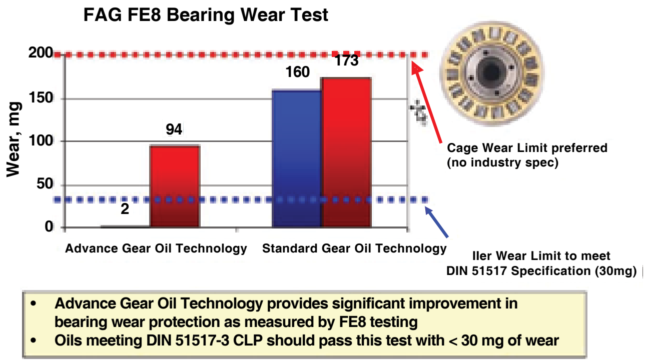


Figure 8—Stress/strain curve.



- Advance Gear Oil Technology provides significant improvement in bearing wear protection as measured by FE8 testing
- Oils meeting DIN 51517-3 CLP should pass this test with < 30 mg of wear

Figure 9—FAG FE8 roller bearing test.

the bearings or other gears in the gearbox.

- Use a lubricant containing micropitting-resistant additives.
- Reduce lubricant operating temperature.
- Use synthetic lubricant to provide higher film thickness at operating temperatures and to reduce shear forces in the sliding-contact area through their inherently lower-traction coefficient versus mineral oil.

Scuffing (sometimes referred to as scoring by users of industrial gear oils) is severe adhesion and metal transfer between teeth due to welding. Under conditions of heavy loads, extreme temperatures, rough and irregular surfaces, loss of or inadequate oil supply, or the use of a lubricant with too low of a viscosity will result in only a partial lubricant film present in the loaded contact area. This partial lubricant film condition causes a degree of metal-to-metal contact between the surfaces that will tear and weld the gear material (Fig. 7). Listed below are potential solutions to reduce scuffing in gears.

Solutions for reducing scuffing mechanically:

- Use proper initial starting run-in procedures.
- Optimize gear geometry, use precision gear tooth design and maintain good helix alignment.
- Use smoother surface finishes.
- Use properly engineered materials for maximum scuffing resistance.

Solutions for reducing scuffing through lubrication:

- Use the proper viscosity lubricant. Higher-viscosity lubricant directionally may be a solution, but be aware that the higher viscosity may cause issues with the bearings or the other gears in the gearbox.
- Use a lubricant containing anti-scuffing additives; i.e., sulfur, phosphorous or borate.
- Reduce lubricant operating temperature.
- Use a synthetic lubricant to provide higher film thickness at operating temperatures and reduced contact area temperatures through its inherently lower traction coefficients.

Shock loading is a sudden application of excessive loads on the gear teeth, which can result in their plastic deformation. What is plastic deformation of a metal?

When a metal is loaded or stressed, it causes strain and stretches similar to a rubber band when pulling on the ends, but with much less movement to the material.

When a load (stress) is maintained in the elastic region of the material; when the load (stress) is removed, the metal will return to its original size.

However, if the load (stress) exceeds the elastic region of the metal, it goes into the plastic region. When this occurs, the metal does not return to its original size after the load is removed. When the load (stress) exceeds the yield point of the metal, it will fracture (Fig. 8).

Shock loading reduces the life of the gears. It is caused by the operational conditions in the process, which is being driven by the gearbox. Until the shock loads are reduced in frequency and/or amplitude, the gears will not achieve their optimum life.

Solutions for reducing shock load mechanically:

- If the loads are resulting in gear fracture and unscheduled downtime, change operational conditions to reduce the shock loads. Because there is a balance between optimum gear life and maximum production, overall knowledge of the plant operational goals is required.
- Use higher-horsepower-rated gearboxes. (Typically, the user will push the limits of the design to achieve maximum production.)

Solutions for reducing wear rates caused from shock load effects on gears through lubrication:

- Loads typically exceed the elastic region of the metal and a higher viscosity cannot "cushion" the force. Therefore, continue use of the proper or OEM-recommended viscosity lubricant to prevent other issues that can occur with a heavier viscosity lubricant.
- Use anti-scuffing additives—i.e., sulfur, phosphorous or borate—to reduce the welding of metal during the shock load.
- You can never reduce a mechanically induced shock load through lubrication.

Bearing and Seal Life

When a gear lubricant is formulated, consideration for the bearings and seals is also important. If premature bearing failure occurred, damage of the gears may follow. If the seals are not functioning as designed, or prematurely fail, other concerns may arise. These concerns are increased lubricant consumption and an increased level of detrimental contamination in the gearbox. The contamination results in decreased reliability of the gearbox.

Reports vary, but 40–60% of gearbox failures are initially bearing failures (Ref. 9). The bearing failure modes are micropitting, macropitting and spalling, caused by high surface stresses, abrasive wear and etching/plastic deformation caused by hard particles. Hard particles come from external contaminants, corrosion particles (rust), and wear particles from components in the gearbox. Bearings also fail because of insufficient lubricant or improper lubricant viscosity and/or additives.

A standard test is the FAG (an international roller bearing manufacturer) FE8 roller bearing wear test. This multipurpose laboratory rig test can evaluate friction, bearing wear and the deposit-forming tendency of the lubricant.

As shown in Figure 9, the lubricant using high-quality base stocks and the advanced, balanced-lubricant technology, achieves improved results over the standard gear lubricant technology.

SKF, the international roller bearing manufacturer, has done extensive work to develop a detailed bearing life equation. The equation considers loads, reliability and life-adjustment factors. The life-adjustment factors include the effects of lubrication and external contamination.

$$L_{naa} = a_1\, a_{SKF}\left(\frac{C}{P}\right)^{10/3} \tag{1}$$

where:

L_{naa}	is adjusted-rating-life in millions of revolutions;
a_1	is life-adjustment-factor for reliability (= 1 for 90% reliability);
a_{SKF}	is life-adjustment factor, including the effects of contamination and lubrication;
C	Basic dynamic load rating, kN (function of bearing type, size, load and speed);
P	Equivalent dynamic bearing load, kN.

Conclusions from Equation 1 are used to increase bearing life and reduction in wear debris through proper lubrication and reduced external contamination. Figure 10 shows the difference in bearing life.

Seals are important to reduce external contamination in the gearbox but are also a common limiting factor to equipment life. Seals should be selected to ensure compatibility with high-performance gear lubricants. Figure 11 shows the test results of two common seal materials used in gearboxes.

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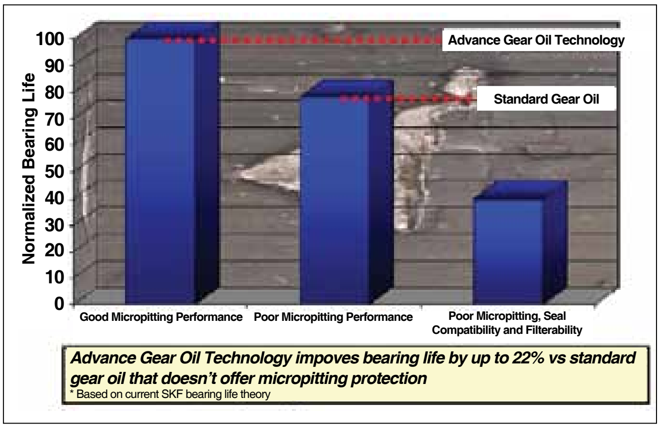

Figure 10—SKF bearing life theory.

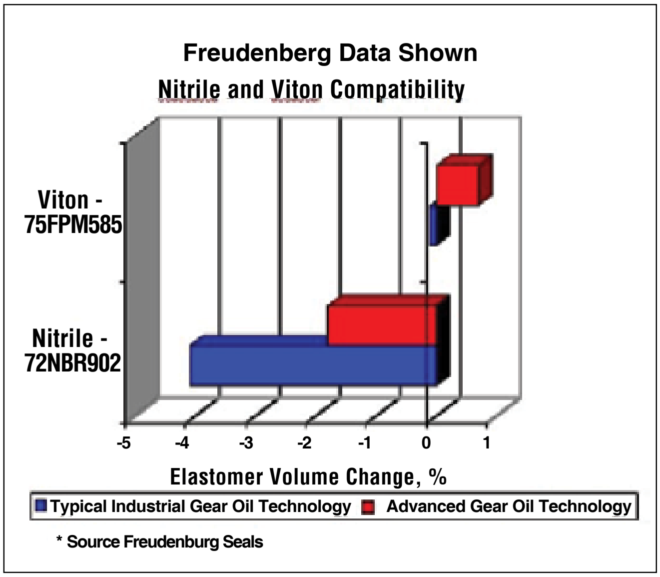

Figure 11—Seal test results.

The figures above show the lubricant using high-quality base stocks and the advanced-balance-lubricant technology achieving improved results over the standard gear lubricant technology.

Oxidation Stability and Corrosion Protection

Oxidation stability is important because as the lubricant oxidizes it will thicken in viscosity and form deposits. Increased viscosity will result in lower efficiencies and higher temperatures in a gearbox. Deposits also cause increased temperatures in a gearbox.

A lubricant containing advanced anti-oxidation technology will have longer oil life in modern gearboxes, versus oils formulated with only conventional gear lubricant additives. This is important because modern gearboxes are designed to operate at higher temperatures than gearboxes of 30 years ago.

Corrosion protection is important because corrosion reduces the life of gears and bearings. Corrosion increases stresses in the contact area of the metals and increases wear debris in the gearbox, thereby decreasing the life of its components. Figures 12 and 13 show oxidation and corrosion test results. These figures show the lubricant using high-quality base stocks and the advanced-balance-lubricant technology achieved improved results over the standard gear lubricant technology.

Table 1—Properties of Gear Lubricants with Polyalphaolefins.

Viscosity Index	130–160+
Low temperature fluidity	–40˚C range
Oxidation and thermal stability	Excellent
Hydrolytic stability - add shear stability	Excellent
Compatibility to mineral oils	Excellent
Compatibility to seals/paints	Good in balanced formulation
Additive solubility	Good in balanced formulation
Traction coefficient	Very good
Viscosities range	Wide range available

Table 2—Properties of Gear Lubricants with Polyglycols.

Viscosity Index	200+
Low temperature fluidity	–20/–50˚C
Oxidation and thermal stability	Excellent (No Coke)
Hydrolytic stability	Good, but can be hygroscopic
Compatibility to mineral oils	Poor – miscible to immiscible
Compatibility to seals/paints	Fair
Additive solubility	Good
Traction coefficient	Excellent
Viscosities range	Wide range available

Synthetic Gear Lubricants

A synthetic lubricant is formulated with synthetic base fluids. Most synthetic base fluids are products derived from chemical synthesis, which creates consistent uniformity in appearance and performance. Some severely hydro-processed mineral oils, which have undergone chemical rearrangement, are now marketed and recognized as synthetic oils.

Synthetic gear lubricants can be made from many base fluids, each with various properties. Depending on the application, one type of synthetic base fluid may have advantages over other synthetic base fluids and mineral oils. These various base fluids can be PAO (polyalphaolefins), PAG (polyglycols), organic esters, phosphate esters, polybutenes, silicone, flourocarbon and others. PAOs and PAGs are common synthetic-based fluids used in industrial gear oils.

Features of synthetic lubricants.

Synthetic gear lubricants are proven in the most extreme conditions. They provide enhanced performance versus standard gear oil technology in the areas of:

- Thermal and oxidative stability (Figs. 12–14)
- Low volatility
- Shear stability
- Low-temperature performance
- Improved traction properties (lower energy requirements)

Properties of synthetic lubricants. See Table 1 for synthetic gear lubricants with PAO-based fluids, and Table 2 for synthetic gear lubricants with PAG-based fluids. Synthetic lubricants offer the following benefits:

- Synthetic lubricants offer a potentially wider range of operating temperatures.
- Reduced energy requirements. When energy consumption is reduced, waste heat is less. Figure 15 shows the thermographic images on identical gearboxes that result from lower energy consumption.
- Table 3 lists additional benefits of the synthetic lubricant.

Comments on Synthetic Gear Lubricants

Synthetic gear lubricants have various benefits that potentially can lower operating and maintenance costs while creating higher revenue through increased production. synthetic gear lubricants may be the solution to your equipment concerns. An engineering analysis can identify the potential savings and may lower your total cost of ownership (TCO).

Balanced Formulations

Industrial gear lubricants are formulated to meet the demands of today's competitive gearbox market. The formulator must consider many factors in developing the gear lubricant. Proper viscosity through high-quality base stocks is still the key factor in performance of the lubricant, and will only be enhanced by the selection of the proper balance of additives.

Today's high-quality lubricants contain many different additives to protect equipment and provide long oil life. Each additive has been designed to offer a particular performance benefit, but with it, more often than not, come detriments to the performance of other lubricant additives. Take rust inhibitors and anti-wear additives for example. These additives work on the metal surface, bonding and interacting with the surface to form a protective film. Figure 16 shows how, individually, (a) a rust inhibitor and (b) an anti-wear additive, form a protective film. However, combining such additives forces them to compete against each other for the metal surface. Incorrect selection of chemistries and/or failure to balance additive concentrations properly can result in one additive dominating the metal surface. The rust inhibitor (c) adequately protects the metal surface, but the anti-wear additive, being blocked from bonding with the surface, is unable to protect the surface from wear. A lubricant formulated in the (c) example would be prone to causing premature equipment failure.

Alternatively, with the right chemistries at the optimum and balanced concentrations, a lubricant can achieve good performance in both features. A balanced, formulated gear lubricant shown in Figure 16d enables both additives to share the surface and thus offers optimum rust and anti-wear protection. The trade-off between rust and anti-wear additives is just one of many formulating hurdles faced by lubricant developers.

Care should be taken when selecting a lubricant to ensure that the best overall balance and optimized performance for the application have been designed into the product. Check that any perceived "extra protection" is appropriate and is not achieved at the expense of other important properties. The selection of an unbalanced lubricant may lead to unwarranted maintenance requirements, downtime and premature equipment failure and higher operating costs.

There are many concerns in formulating an industrial gear lubricant, and a properly balanced formulation is key to productivity. Depending on the application, a synthetic lubricant may be the best choice for your operations.

Summary of Gear Lubricants

Industrial gear lubricant formulations have changed over the past few years to meet the demands of new gearbox designs. The formulator must consider many factors in the gear lubricant.

An understanding of the lubricating film classifications and their effects on the equipment are required for the properly formulated industrial gear oil. The knowledge of gear types, speeds, operating temperatures, loads, drive type, ambient conditions, maintenance accessibility, industry specifications and OEM specifications are important to the gear oil formulation. This enables the formulator to achieve the correct lubricant characteristics to optimize gear protection in the application.

It is equally important to formulate not only with the concerns of gears and gearing in mind, but the bearings and seals as well. Bearings and seals are important factors in the reliability of enclosed gearboxes.

Synthetic lubricants are important when the application and/or gearbox design requires the advantages of synthetic lubricants to achieve the desirable equipment reliability. Synthetic lubricants have a comprehensive range of scientifically engineered molecules that offer performance beyond the capabilities of conventional mineral oils.

The understanding of the application and design of the gearbox will enable the user of industrial gears to select the proper lubricant to achieve the maximum productivity.

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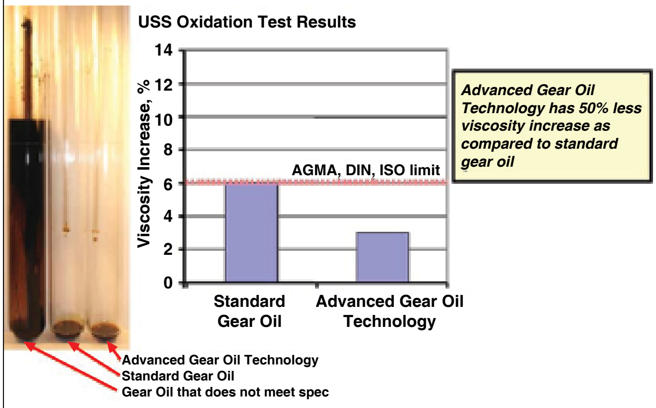

Figure 12—Oxidation test results.

Advanced gear oil technology | Standard gear oil technology

Figure 13—Emcor rust test with 0.5% NaCl water.

Table 3—Features and Benefits of Synthetic Gear Lubricants versus Mineral Oils.	
Thermal and oxidation stability	Longer drain intervals
Low volatility	Lower oil consumption
High viscosity index	Better wear protection
High temperature performance	Better equipment protection
Low temperature performance	Less wear under cold starting conditions
Low traction properties	Reduced energy consumption

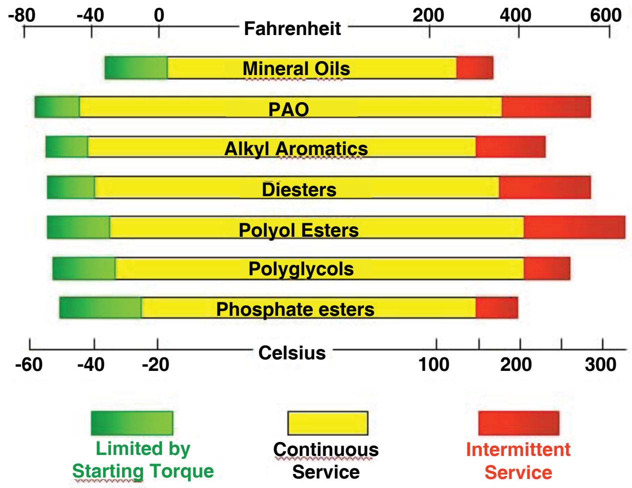

Figure 14—Operating temperature ranges.

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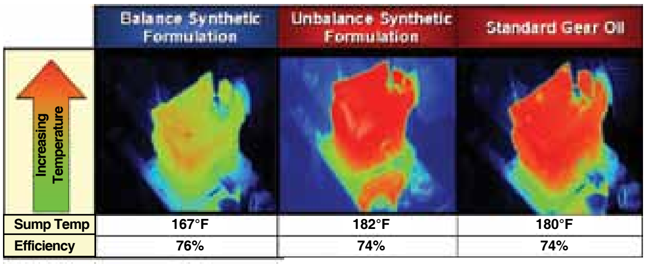

Figure 15—Thermographic images of gearboxes.

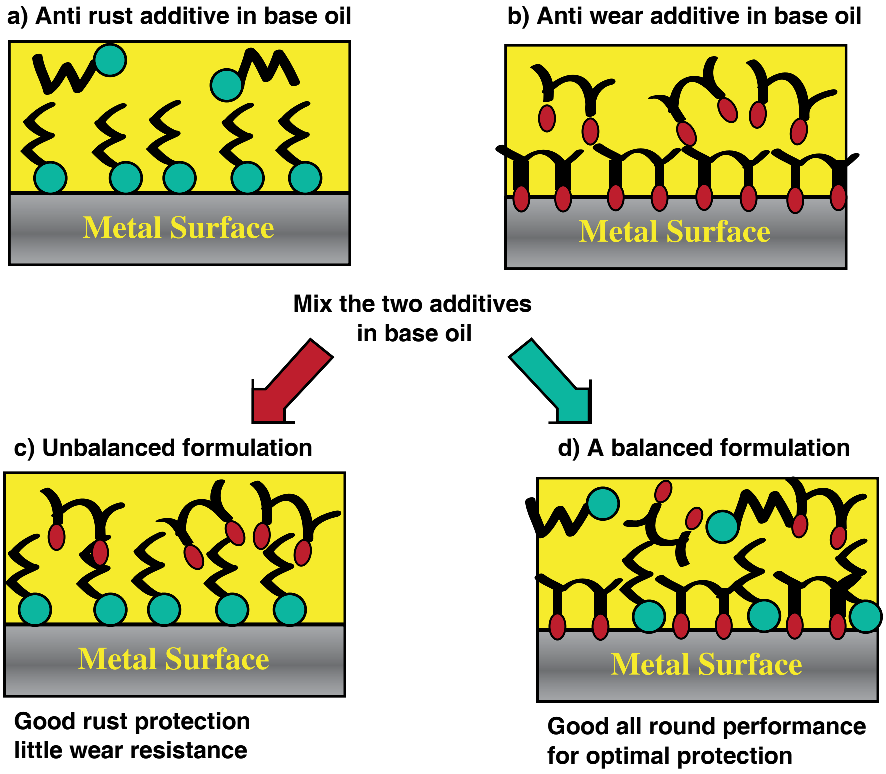

Figure 16—Additives at work.

Facts versus Myths

Myth—If I have micropitting on my gear teeth, a lubricant with a higher level of sulfur-phosphorous package will reduce this failure mode.
Fact—Sulfur-phosphorous additive packages have been known to increase the sub-surface fatigue—which leads to micropitting—by aggravating the cracks at the stress point.

Myth—If I have wear on my gear teeth, a higher level of anti-wear or anti-scuffing additive will solve the problem.
Fact—You need the proper amount of anti-wear and/or anti-scuffing additive in the lubricant to achieve optimum wear protection. If the gear oil has been over-treated with one type of additive to improve one performance dimension, measured by results in a single laboratory test, it is likely that the gear oil will have reduced performance in another key property of the lubricant that may cause another concern. For example, increasing extreme-pressure additive levels can also decrease the oxidative stability of the lubricant.

Myth—Proper viscosity of lubricant is important and so a lubricant with a higher viscosity index (VI) is better. (Author's note: Viscosity index is defined as the change in lubricant viscosity with the change in lubricant temperature. As the temperature increases, the viscosity will decrease, and as the temperature decreases, the viscosity will decrease.)
Fact—If you take into account the viscosity of the lubricant at the gearbox operating temperature, the first part of this statement is true. However, higher VI is not necessarily better; it depends on how the higher VI is achieved. If it is achieved through use of viscosity index improvers, then a higher viscosity index is not a true benefit in an industrial gearbox. Viscosity index improvers are typically large molecules that will shear down in a relatively short time under the high-shear conditions in industrial gearboxes. After shearing of the VI improvers, the lubricant will provide lower film thickness, leading to increased stresses in the contact areas. These increased stresses will lead to increased wear rates and reduced efficiencies in the gearbox. Another concern is that a very high viscosity index may result in a too-high viscosity for the gears and/or bearings that may cause other type of failures. Always check for proper viscosity for the operating temperatures for the application.

Myth—Viscosity determines the lubricity, or "oiliness," of oil.
Fact—Heavier oils (higher viscosity) do form thicker lubricating films, but that's not the whole story. In current gear lubricants, the inherent properties of the base fluids and additives also provide lubricity. Synthetic base fluids can provide lower traction under sliding conditions, and additives, such as fatty materials or friction modifiers, can increase lubricity without necessarily increasing viscosity.

Myth—Used oil condition is the primary cause of lubricant-related equipment breakdowns.
Fact—The two most prevalent causes of lubricant-related equipment breakdowns are: 1) use of the wrong lubricant, and 2) high concentrations of contaminants in the lubricant.

Myth—When it comes to lubrication, nothing is new.
Fact—Industrial machines have been getting more powerful, smaller and more complicated, and industrial lubrication has had to keep in step with technology. For example, synthetic lubricants have been developed to meet the demands of high load- carrying capacity for high-output equipment, while also delivering improved energy efficiency versus conventional gear lubricants. Today's lubricants offer improved performance, lower total cost of ownership and improved productivity.