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| | Engineering and Design<br><br>LUBRICANTS AND HYDRAULIC FLUIDS | |
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**DEPARTMENT OF THE ARMY**
**U.S. Army Corps of Engineers**
**Washington, DC 20314-1000**

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**Engineering and Design**
**LUBRICANTS AND HYDRAULIC FLUIDS**

1. This change to EM 1110-2-1424, 28 February 1999, adds a new Appendix C for the sample procurement specification for turbine oils.

2. Substitute and/or add the attached pages.

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| iv | iv |
| 11-1 | 11-1 |
| | C-1 through C-9 |

3. File this change sheet in front of the publication for reference purposes.

FOR THE COMMANDER:

YVONNE PRETTYMAN-BECK
Colonel, Corps of Engineers
Chief of Staff

CECW-ET

**DEPARTMENT OF THE ARMY**
**U.S. Army Corps of Engineers**
**Washington, DC 20314-1000**

EM 1110-2-1424

Manual
No. 1110-2-1424

28 February 1999

# Engineering and Design
# LUBRICANTS AND HYDRAULIC FLUIDS

**1. Purpose.** This manual provides guidance on lubricants and hydraulic fluids to engineering, operations, maintenance, and construction personnel and other individuals responsible for the U.S. Army Corps of Engineers (USACE) civil works equipment.

**2. Applicability.** This manual applies to all USACE commands having civil works responsibility.

**3. Discussion.** This manual is intended to be a practical guide to lubrication with enough technical detail to allow personnel to recognize and easily discern differences in performance properties specified in manufacturers' product literature so that the proper lubricant for a particular application is selected. It describes basic characteristic properties of oils, hydraulic fluids, greases, solid lubricants, environmentally acceptable lubricants, and their additives. It examines the mechanics of hydrodynamic, boundary, extreme pressure, and elastohydrodynamic lubrication to protect against surface deterioration. Separate chapters are devoted to lubricant specification and selection, and requirements of lubricants for equipment currently in use at USACE civil works facilities. Because conscientious adherence to lubrication schedules is the best prescription for longevity of component parts, operation and maintenance considerations are also addressed.

**4. Distribution Statement.** Approved for public release, distribution is unlimited.

FOR THE COMMANDER:

ALBERT J. GENETTI, JR.
Major General, USA
Chief of Staff

2 Appendices
(See Table of Contents)

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## Engineering and Design
## LUBRICANTS AND HYDRAULIC FLUIDS

### Table of Contents

# Chapter 1
# Introduction

## 1-1. Purpose

This manual provides engineering personnel with design guidance to select, specify, inspect, and approve lubricants and hydraulic fluids used for U.S. Army Corps of Engineers (USACE) equipment. It provides the operation and maintenance staff with guidance for regular and scheduled maintenance. The manual gives broad-based instructions reflecting established criteria and the latest proven state-of-the-art technology and techniques to attain better and more economical lubrication.

## 1-2. Applicability

This manual applies to all USACE commands having civil works responsibility.

## 1-3. References

Required publications are listed below. Related publications are listed in Appendix A.

*a.* 21 CFR 178.3570. Lubricants with Incidental Food Contact

*b.* 29 CFR 1210.1200. Safety and Health Regulations for Workers Engaged in Hazardous Waste

*c.* 29 CFR 1910.1200. OSHA Communication Standard

*d.* 40 CFR 110. Discharge of Oil

*e.* 40 CFR 112. Oil Pollution Prevention

*f.* 40 CFR 113. Liability Limits for Small Onshore Storage Facilities

*g.* 48 CFR 9.2. Federal Acquisition Regulation and Qualification Requirements

*h.* EM 1110-2-3105. Mechanical and Electrical Design of Pumping Stations

*i.* EM 1110-2-3200. Wire Rope Selection

*j.* EM 1110-2-4205. Hydroelectric Power Plants, Mechanical Design

*k.* CEGS 15005. Speed Reducers for Storm Water Pumps

## 1-4. Distribution Statement

Approved for public release, distribution is unlimited.

## 1-5. Scope

*a*. This manual is intended to be a practical guide to lubrication with enough technical detail to allow personnel to recognize and easily discern differences in performance properties specified in manufacturers' product literature so that the proper lubricant for a particular application is selected.

*b*. The manual defines and illustrates friction, wear, and corrosion and how they damage contact surfaces to cause premature equipment failure. It examines the mechanics of hydrodynamic, boundary, extreme pressure, and elastohydrodynamic lubrication to protect against surface deterioration. In practice, manufacturers' laboratories can tailor-make a lubricant for any equipment operating under any conditions by using the right combination of lubricants and additives. This manual describes basic characteristic properties of oils, hydraulic fluids, greases, solid lubricants, environmentally acceptable lubricants, and their additives. Separate chapters are devoted to lubricant specification and selection, and requirements of lubricants for equipment currently in use at USACE civil works facilities. Because conscientious adherence to lubrication schedules is the best prescription for longevity of component parts, operation and maintenance considerations are also addressed.

# Chapter 2
# Lubrication Principles

## 2-1. Friction

*a. Definition of friction.*

(1) Friction is a force that resists relative motion between two surfaces in contact. Depending on the application, friction may be desirable or undesirable. Certain applications, such as tire traction on pavement and braking, or when feet are firmly planted to move a heavy object, rely on the beneficial effects of friction for their effectiveness. In other applications, such as operation of engines or equipment with bearings and gears, friction is undesirable because it causes wear and generates heat, which frequently lead to premature failure.

(2) For purposes of this manual, the energy expended in overcoming friction is dispersed as heat and is considered to be wasted because useful work is not accomplished. This waste heat is a major cause of excessive wear and premature failure of equipment. Two general cases of friction occur: sliding friction and rolling friction.

*b. Sliding friction.*

(1) To visualize sliding friction, imagine a steel block lying on a steel table. Initially a force F (action) is applied horizontally in an attempt to move the block. If the applied force F is not high enough, the block will not move because the friction between the block and table resists movement. If the applied force is increased, eventually it will be sufficient to overcome the frictional resistance force f and the block will begin to move. At this precise instant, the applied force F is equal to the resisting friction force f and is referred to as the force of friction.

(2) In mathematical terms, the relation between the normal load L (weight of the block) and the friction force f is given by the coefficient of friction denoted by the Greek symbol $\mu$. Note that in the present context, "normal" has a different connotation than commonly used. When discussing friction problems, the normal load refers to a load that is perpendicular to the contacting surfaces. For the example used here, the normal load is equal to the weight of the block because the block is resting on a horizontal table. However, if the block were resting on an inclined plane or ramp, the normal load would not equal the weight of the block, but would depend on the angle of the ramp. Since the intent here is to provide a means of visualizing friction, the example has been simplified to avoid confusing readers not familiar with statics.

*c. Laws of sliding friction.* The following friction laws are extracted from the Machinery Handbook, 23rd Revised Edition.

(1) Dry or unlubricated surfaces. Three laws govern the relationship between the frictional force f and the load or weight L of the sliding object for unlubricated or dry surfaces:

(a) "For low pressures (normal force per unit area) the friction force is directly proportional to the normal load between the two surfaces. As the pressure increases, the friction does not rise proportionally; but when the pressure become abnormally high, the friction increases at a rapid rate until seizing takes place."

(b) The value of f/L is defined as the coefficient of friction μ. "The friction both in its total amount and its coefficient is independent of the area of contact, so long as the normal force remains the same. This is true for moderate pressures only. For high pressures, this law is modified in the same way as the first case."

(c) "At very low velocities, the friction force is independent of the velocity of rubbing. As the velocities increase, the friction decreases."

The third law (c) implies that the force required to set a body in motion is the same as the force required to keep it in motion, but this is not true. Once a body is in motion, the force required to maintain motion is less than the force required to initiate motion and there is some dependency on velocity. These facts reveal two categories of friction: static and kinetic. Static friction is the force required to initiate motion ($F_s$). Kinetic or dynamic friction is the force required to maintain motion ($F_k$).

(2) Lubricated surfaces. The friction laws for well lubricated surfaces are considerably different than those for dry surfaces, as follows:

(a) "The frictional resistance is almost independent of the pressure (normal force per unit area) if the surfaces are flooded with oil."

(b) "The friction varies directly as the speed, at low pressures; but for high pressures the friction is very great at low velocities, approaching a minimum at about 2 ft/sec linear velocity, and afterwards increasing approximately as the square root of the speed."

(c) "For well lubricated surfaces the frictional resistance depends, to a very great extent, on the temperature, partly because of the change in viscosity of the oil and partly because, for journal bearings, the diameter of the bearing increases with the rise in temperature more rapidly than the diameter of the shaft, thus relieving the bearing of side pressure."

(d) "If the bearing surfaces are flooded with oil, the friction is almost independent of the nature of the material of the surfaces in contact. As the lubrication becomes less ample, the coefficient of friction becomes more dependent upon the material of the surfaces."

(3) The coefficient of friction. The coefficient of friction depends on the type of material. Tables showing the coefficient of friction of various materials and combinations of materials are available. Common sources for these tables are Marks Mechanical Engineering Handbooks and Machinery's Handbook. The tables show the coefficient of friction for clean dry surfaces and lubricated surfaces. It is important to note that the coefficients shown in these tables can vary.

(4) Asperities. Regardless of how smooth a surface may appear, it has many small irregularities called asperities. In cases where a surface is extremely rough, the contacting points are significant, but when the surface is fairly smooth, the contacting points have a very modest effect. The real or true surface area refers to the area of the points in direct contact. This area is considerably less than the apparent geometric area.

(5) Adhesion. Adhesion occurs at the points of contact and refers to the welding effect that occurs when two bodies are compressed against each other. This effect is more commonly referred to as "cold welding" and is attributed to pressure rather than heat, which is associated with welding in the more familiar sense. A shearing force is required to separate cold-welded surfaces.

(6) Shear strength and pressure. As previously noted, the primary objective of lubrication is to reduce friction and wear of sliding surfaces. This objective is achieved by introducing a material with a low shear strength or coefficient of friction between the wearing surfaces. Although nature provides such materials in the form of oxides and other contaminants, the reduction in friction due to their presence is insufficient for machinery operation. For these conditions, a second relationship is used to define the coefficient of friction: $\mu = S/P$, where S is the shear strength of the material and P is pressure (or force) contributing to compression. This relationship shows that the coefficient of friction is a function of the force required to shear a material.

(7) Stick-slip. To the unaided eye the motion of sliding objects appears steady. In reality this motion is jerky or intermittent because the objects slow during shear periods and accelerate following the shear. This process is continuously repeated while the objects are sliding. During shear periods, the static friction force $F_s$ controls the speed. Once shearing is completed, the kinetic friction force $F_k$ controls the speed and the object accelerates. This effect is known as stick-slip. In well lubricated machinery operated at the proper speed, stick-slip is insignificant, but it is responsible for the squeaking or chatter sometimes heard in machine operation. Machines that operate over long sliding surfaces, such as the ways of a lathe, are subject to stick-slip. To prevent stick-slip, lubricants are provided with additives to make $F_s$ less than $F_k$.

*d. Rolling friction.*

(1) When a body rolls on a surface, the force resisting the motion is termed rolling friction or rolling resistance. Experience shows that much less force is required to roll an object than to slide or drag it. Because force is required to initiate and maintain rolling motion, there must be a definite but small amount of friction involved. Unlike the coefficient of sliding friction, the coefficient of rolling friction varies with conditions and has a dimension expressed in units of length.

(2) Ideally, a rolling sphere or cylinder will make contact with a flat surface at a single point or along a line (in the case of a cylinder). In reality, the area of contact is slightly larger than a point or line due to elastic deformation of either the rolling object or the flat surface, or both. Much of the friction is attributed to elastic hysteresis. A perfectly elastic object will spring back immediately after relaxation of the deformation. In reality, a small but definite amount of time is required to restore the object to original shape. As a result, energy is not entirely returned to the object or surface but is retained and converted to heat. The source of this energy is, in part, the rolling frictional force.

(3) A certain amount of slippage (which is the equivalent of sliding friction) occurs in rolling friction. If the friction of an unhoused rolling object is measured, slippage effects are minimal. However, in practical applications such as a housed ball or roller bearing, slippage occurs and contributes to rolling friction. Neglecting slippage, rolling friction is very small compared to sliding friction.

*e. Laws of rolling friction.* The laws for sliding friction cannot be applied to rolling bodies in equally quantitative terms, but the following generalities can be given:

(1) The rolling friction force F is proportional to the load L and inversely proportional to the radius of curvature r, or $F = \mu_r L/r$, where $\mu_r$ is the coefficient of rolling resistance, in meters (inches). As the radius increases, the frictional force decreases.

(2) The rolling friction force F can be expressed as a fractional power of the load L times a constant k, or $F = kL^n$ where the constant k and the power n must be determined experimentally.

(3) The friction force F decreases as the smoothness of the rolling element improves.

## 2-2. Wear

Wear is defined as the progressive damage resulting in material loss due to relative contact between adjacent working parts. Although some wear is to be expected during normal operation of equipment, excessive friction causes premature wear, and this creates significant economic costs due to equipment failure, cost for replacement parts, and downtime. Friction and wear also generate heat, which represents wasted energy that is not recoverable. In other words, wear is also responsible for overall loss in system efficiency.

*a. Wear and surface damage.* The wear rate of a sliding or rolling contact is defined as the volume of material lost from the wearing surface per unit of sliding length, and is expressed in units of $[\text{length}]^2$. For any specific sliding application, the wear rate depends on the normal load, the relative sliding speed, the initial temperature, and the mechanical, thermal, and chemical properties of the materials in contact.

(1) The effects of wear are commonly detected by visual inspection of surfaces. Surface damage can be classified as follows:

(a) Surface damage without exchange of material:

- Structural changes: aging, tempering, phase transformations, and recrystallization.

- Plastic deformation: residual deformation of the surface layer.

- Surface cracking: fractures caused by excessive contact strains or cyclic variations of thermally or mechanically induced strains.

(b) Surface damage with loss of material (wear):

- Characterized by wear scars of various shapes and sizes.

- Can be shear fracture, extrusion, chip formation, tearing, brittle fracture, fatigue fracture, chemical dissolution, and diffusion.

(c) Surface damage with gain of material:

- Can include pickup of loose particles and transfer of material from the opposing surface.

- Corrosion: Material degradation by chemical reactions with ambient elements or elements from the opposing surface.

(2) Wear may also be classified as mild or severe. The distinguishing characteristics between mild and severe wear are as follows (Williams 1994):

(a) Mild

- Produces extremely smooth surfaces - sometimes smoother than the original.
- Debris is extremely small, typically in the range of 100 nanometers (nm) ($3.28 \times 10^{-13}$ ft) in diameter.
- High electrical contact resistance, but little true metallic contact.

(b) Severe

- Rough, deeply torn surfaces - much rougher than the original.
- Large metallic wear debris, typically up to 0.01 mm ($3.28 \times 10^{-5}$ ft) in diameter.
- Low contact resistance, but true metallic junctions are formed.

*b. Types of wear*. Ordinarily, wear is thought of only in terms of abrasive wear occurring in connection with sliding motion and friction. However, wear also can result from adhesion, fatigue, or corrosion.

(1) Abrasive wear. Abrasive wear occurs when a hard surface slides against and cuts grooves from a softer surface. This condition is frequently referred to as two-body abrasion. Particles cut from the softer surface or dust and dirt introduced between wearing surfaces also contribute to abrasive wear. This condition is referred to as three-body abrasion.

(2) Adhesive wear. Adhesive wear frequently occurs because of shearing at points of contact or asperities that undergo adhesion or cold welding, as previously described. Shearing occurs through the weakest section, which is not necessarily at the adhesion plane. In many cases, shearing occurs in the softer material, but such a comparison is based on shear tests of relatively large pure samples. The adhesion junctions, on the other hand, are very small spots of weakness or impurity that would be insignificant in a large specimen but in practice may be sufficient to permit shearing through the harder material. In some instances the wearing surfaces of materials with different hardness can contain traces of material from the other face. Theoretically, this type of wear does not remove material but merely transfers it between wearing surfaces. However, the transferred material is often loosely deposited and eventually flakes away in microscopic particles; these, in turn, cause wear.

(3) Pitting wear.

(a) Pitting wear is due to surface failure of a material as a result of stresses that exceed the endurance (fatigue) limit of the material. Metal fatigue is demonstrated by bending a piece of metal wire, such as a paper clip, back and forth until it breaks. Whenever a metal shape is deformed repeatedly, it eventually fails. A different type of deformation occurs when a ball bearing under a load rolls along its race. The bearing is flattened somewhat and the edges of contact are extended outward. This repeated flexing eventually results in microscopic flakes being removed from the bearing. Fatigue wear also occurs during sliding motion. Gear teeth frequently fail due to pitting.

(b) While pitting is generally viewed as a mode of failure, some pitting wear is not detrimental. During the break-in period of new machinery, friction wears down working surface irregularities. This condition is considered to be nonprogressive and usually improves after the break-in period. However, parts that are continuously subjected to repeated stress will experience destructive pitting as the material's endurance limit is reached.

(4) Corrosive wear.

(a) Corrosive wear occurs as a result of a chemical reaction on a wearing surface. The most common form of corrosion is due to a reaction between the metal and oxygen (oxidation); however, other chemicals may also contribute. Corrosion products, usually oxides, have shear strengths different from those of the wearing surface metals from which they were formed. The oxides tend to flake away, resulting in the pitting of' wearing surfaces. Ball and roller bearings depend on extremely smooth surfaces to reduce frictional effects. Corrosive pitting is especially detrimental to these bearings.

(b) American National Standards Institute (ANSI) Standard ANSI/AGMA 1010-E95 provides numerous illustrations of wear in gears and includes detailed discussions of the types of wear mentioned above and more. Electric Power Research Institute (EPRI) Report EPRI GS-7352 provides illustrations of bearing failures.

(c) Normal wear is inevitable whenever there is relative motion between surfaces. However, wear can be reduced by appropriate machinery design, precision machining, material selection, and proper maintenance, including lubrication. The remainder of this manual is devoted to discussions on the fundamental principles of lubrication that are necessary to reduce wear.

## 2-3. Lubrication and Lubricants

*a. Purpose of lubrication.* The primary purpose of lubrication is to reduce wear and heat between contacting surfaces in relative motion. While wear and heat cannot be completely eliminated, they can be reduced to negligible or acceptable levels. Because heat and wear are associated with friction, both effects can be minimized by reducing the coefficient of friction between the contacting surfaces. Lubrication is also used to reduce oxidation and prevent rust; to provide insulation in transformer applications; to transmit mechanical power in hydraulic fluid power applications; and to seal against dust, dirt, and water.

*b. Lubricants*. Reduced wear and heat are achieved by inserting a lower-viscosity (shear strength) material between wearing surfaces that have a relatively high coefficient of friction. In effect, the wearing surfaces are replaced by a material with a more desirable coefficient of friction. Any material used to reduce friction in this way is a lubricant. Lubricants are available in liquid, solid, and gaseous forms. Industrial machinery ordinarily uses oil or grease. Solid lubricants such as molybdenum disulfide or graphite are used when the loading at contact points is heavy. In some applications the wearing surfaces of a material are plated with a different metal to reduce friction.

## 2-4. Hydrodynamic or Fluid Film Lubrication

*a. General.* In heavily loaded bearings such as thrust bearings and horizontal journal bearings, the fluid's viscosity alone is not sufficient to maintain a film between the moving surfaces. In these bearings higher fluid pressures are required to support the load until the fluid film is established. If this pressure is supplied by an outside source, it is called hydrostatic lubrication. If the pressure is generated internally, that is, within the bearing by dynamic action, it is referred to as hydrodynamic lubrication. In hydrodynamic lubrication, a fluid wedge is formed by the relative surface motion of the journals or the thrust runners over their respective bearing surfaces. The guide bearings of a vertical hydroelectric generator, if properly aligned, have little or no loading and will tend to operate in the center of the bearing because of the viscosity of the oil.

*b. Thrust bearings.*

(1) In hydrodynamic lubrication, sometimes referred to as fluid film lubrication, the wearing surfaces are completely separated by a film of oil. This type of lubricating action is similar to a speedboat operating on water. When the boat is not moving, it rests on the supporting water surface. As the boat begins to move, it meets a certain amount of resistance or opposing force due to viscosity of the water. This causes the leading edge of the boat to lift slightly and allows a small amount of water to come between it and supporting water surface. As the boat's velocity increases, the wedge-shaped water film increases in thickness until a constant velocity is attained. When the velocity is constant, water entering under the leading edge equals the amount passing outward from the trailing edge. For the boat to remain above the supporting surface there must be an upward pressure that equals the load.

(2) The same principle can be applied to a sliding surface. Fluid film lubrication reduces friction between moving surfaces by substituting fluid friction for mechanical friction. To visualize the shearing effect taking place in the fluid film, imagine the film is composed of many layers similar to a deck of cards. The fluid layer in contact with the moving surface clings to that surface and both move at the same velocity. Similarly, the fluid layer in contact with the other surface is stationary. The layers in between move at velocities directly proportional to their distance from the moving surface. For example, at a distance of ½ h from Surface 1, the velocity would be ½ V. The force F required to move Surface 1 across Surface 2 is simply the force required to overcome the friction between the layers of fluid. This internal friction, or resistance to flow, is defined as the viscosity of the fluid. Viscosity will be discussed in more detail later.

(3) The principle of hydrodynamic lubrication can also be applied to a more practical example related to thrust bearings used in the hydropower industry. Thrust bearing assembly is also known as tilting pad bearings. These bearings are designed to allow the pads to lift and tilt properly and provide sufficient area to lift the load of the generator. As the thrust runner moves over the thrust shoe, fluid adhering to the runner is drawn between the runner and the shoe causing the shoe to pivot, and forming a wedge of oil. As the speed of the runner increases, the pressure of the oil wedge increases and the runner is lifted as full fluid film lubrication takes place. In applications where the loads are very high, some thrust bearings have high pressure-pumps to provide the initial oil film. Once the unit reaches 100 percent speed, the pump is switched off.

*c. Journal bearings.* Although not as obvious as the plate or thrust bearing examples above, the operation of journal or sleeve bearings is also an example of hydrodynamic lubrication. When the journal is at rest, the weight of the journal squeezes out the oil film so that the journal rests on the bearing surface. As rotation starts, the journal has a tendency to roll up the side of the bearing. At the same time fluid adhering to the journal is drawn into the contact area. As the journal speed increases an oil wedge is formed. The pressure of the oil wedge increases until the journal is lifted off the bearing. The journal is not only lifted vertically, but is also pushed to the side by the pressure of the oil wedge. The minimum fluid film thickness at full speed will occur at a point just to the left of center and not at the bottom of the bearing. In both the pivoting shoe thrust bearing and the horizontal journal bearing, the minimum thickness of the fluid film increases with an increase in fluid viscosity and surface speed and decreases with an increase in load.

*d. Film thickness.* The preceding discussion is a very simplified attempt to provide a basic description of the principles involved in hydrodynamic lubrication. For a more precise, rigorous interpretation refer to American Society for Metals Handbook Volume 18, listed in the Appendix A. Simplified equations have been developed to provide approximations of film thickness with a considerable degree of precision. Regardless of how film thickness is calculated, it is a function of viscosity, velocity, and load. As viscosity or velocity increases, the film thickness increases. When these two variables decrease, the film thickness also decreases. Film thickness varies inversely with the load; as the load increases, film thickness decreases. Viscosity, velocity, and operating temperature are also interrelated. If the oil viscosity is increased the operating temperature will increase, and this in turn has a tendency to reduce viscosity. Thus, an increase in viscosity tends to neutralize itself somewhat. Velocity increases also cause temperature increases that subsequently result in viscosity reduction.

*e. Factors influencing film formation.* The following factors are essential to achieve and maintain the fluid film required for hydrodynamic lubrication:

- The contact surfaces must meet at a slight angle to allow formation of the lubricant wedge.

- The fluid viscosity must be high enough to support the load and maintain adequate film thickness to separate the contacting surfaces at operating speeds.

- The fluid must adhere to the contact surfaces for conveyance into the pressure area to support the load.

- The fluid must distribute itself completely within the bearing clearance area.

- The operating speed must be sufficient to allow formation and maintenance of the fluid film.

- The contact surfaces of bearings and journals must be smooth and free of sharp surfaces that will disrupt the fluid film.

Theoretically, hydrodynamic lubrication reduces wear to zero. In reality, the journal tends to move vertically and horizontally due to load changes or other disturbances and some wear does occur. However, hydrodynamic lubrication reduces sliding friction and wear to acceptable levels.

## 2-5. Boundary Lubrication

*a. Definition of boundary lubrication.* When a complete fluid film does not develop between potentially rubbing surfaces, the film thickness may be reduced to permit momentary dry contact between wear surface high points or asperities. This condition is characteristic of boundary lubrication. Boundary lubrication occurs whenever any of the essential factors that influence formation of a full fluid film are missing. The most common example of boundary lubrication includes bearings, which normally operate with fluid film lubrication but experience boundary lubricating conditions during routine starting and stopping of equipment. Other examples include gear tooth contacts and reciprocating equipment.

*b. Oiliness.*

(1) Lubricants required to operate under boundary lubrication conditions must possess an added quality referred to as "oiliness" or "lubricity" to lower the coefficient of friction of the oil between the rubbing surfaces. Oiliness is an oil enhancement property provided through the use of chemical additives

known as antiwear (AW) agents. AW agents have a polarizing property that enables them to behave in a manner similar to a magnet. Like a magnet, the opposite sides of the oil film have different polarities. When an AW oil adheres to the metal wear surfaces, the sides of the oil film not in contact with the metal surface have identical polarities and tend to repel each other and form a plane of slippage. Most oils intended for use in heavier machine applications contain AW agents.

(2) Examples of equipment that rely exclusively on boundary lubrication include reciprocating equipment such as engine and compressor pistons, and slow-moving equipment such as turbine wicket gates. Gear teeth also rely on boundary lubrication to a great extent.

## 2-6. Extreme Pressure (EP) Lubrication

*a.* Definition. AW agents are effective only up to a maximum temperature of about 250 °C (480 °F). Unusually heavy loading will cause the oil temperature to increase beyond the effective range of the antiwear protection. When the load limit is exceeded, the pressure becomes too great and asperities make contact with greater force. Instead of sliding, asperities along the wear surfaces experience shearing, removing the lubricant and the oxide coating. Under these conditions the coefficient of friction is greatly increased and the temperature rises to a damaging level.

*b. Extreme pressure additives.* Applications under extreme pressure conditions rely on additives. Lubricants containing additives that protect against extreme pressure are called EP lubricants, and oils containing additives to protect against extreme pressure are classified as EP oils. EP lubrication is provided by a number of chemical compounds. The most common are compounds of boron, phosphorus, sulfur, chlorine, or combinations of these. The compounds are activated by the higher temperature resulting from extreme pressure, not by the pressure itself. As the temperature rises, EP molecules become reactive and release derivatives of phosphorus, chlorine, or sulfur (depending on which compound is used) to react with only the exposed metal surfaces to form a new compound such as iron chloride or iron sulfide. The new compound forms a solid protective coating that fills the asperities on the exposed metal. Thus, the protection is deposited at exactly the sites where it is needed. AW agents in the EP oil continue to provide antiwear protection at sites where wear and temperature are not high enough to activate the EP agents.

## 2-7. Elastohydrodynamic (EHD) Lubrication

*a. Definition of EHD lubrication.* The lubrication principles applied to rolling bodies, such as ball or roller bearings, is known as elastohydrodynamic (EHD) lubrication.

*b. Rolling body lubrication.* Although lubrication of rolling objects operates on a considerably different principle than sliding objects, the principles of hydrodynamic lubrication can be applied, within limits, to explain lubrication of rolling elements. An oil wedge, similar to that which occurs in hydrodynamic lubrication, exists at the lower leading edge of the bearing. Adhesion of oil to the sliding element and the supporting surface increases pressure and creates a film between the two bodies. Because the area of contact is extremely small in a roller and ball bearing, the force per unit area, or load pressure, is extremely high. Roller bearing load pressures may reach 34,450 kPa (5000 lb/sq in) and ball bearing load pressures may reach 689,000 kPa (1,000,000 lb/sq in). Under these pressures, it would appear that the oil would be entirely squeezed from between the wearing surfaces. However, viscosity increases that occur under extremely high pressure prevent the oil from being entirely squeezed out. Consequently, a thin film of oil is maintained.

*c. Effect of film thickness and roughness.*

(1) The roughness of the wearing surfaces is an important consideration in EHD lubrication. Roughness is defined as the arithmetic average of the distance between the high and low points of a surface, and is sometimes called the centerline average (CLA).

(2) As film thickness increases in relation to roughness fewer asperities make contact. Engineers use the ratio of film thickness to surface roughness to estimate the life expectancy of a bearing system. The relation of bearing life to this ratio is very complex and not always predictable. In general, life expectancy is extended as the ratio increases. Full film thickness is considered to exist when the value of this ratio is between 2 and 4. When this condition prevails, fatigue failure is due entirely to subsurface stress. However, in most industrial applications, a ratio between 1 and 2 is achieved. At these values surface stresses occur, and asperities undergo stress and contribute to fatigue as a major source of failure in antifriction bearings.

# Chapter 3
# Lubricating Oils

## 3-1. Oil Refining

Most lubricating oils are currently obtained from distillation of crude petroleum. Due to the wide variety of petroleum constituents, it is necessary to separate petroleum into portions (fractions) with roughly the same qualities.

*a.* General scheme of the refining process. The refining process can be briefly described as follows:

(1) Crudes are segregated and selected depending on the types of hydrocarbons in them.

(2) The selected crudes are distilled to produce fractions. A fraction is a portion of the crude that falls into a specified boiling point range.

(3) Each fraction is processed to remove undesirable components. The processing may include:

- Solvent refining to remove undesirable compounds.
- Solvent dewaxing to remove compounds that form crystalline materials at low temperature.
- Catalytic hydrogenation to eliminate compounds that would easily oxidize.
- Clay percolation to remove polar substances.

(4) The various fractions are blended to obtain a finished product with the specified viscosity. Additives may be introduced to improve desired characteristics. The various types of and uses for additives are discussed in Chapter 7.

*b. Separation into fractions.* Separation is accomplished by a two-stage process: crude distillation and residuum distillation.

(1) Crude distillation. In the first stage the crude petroleum is mixed with water to dissolve any salt. The resulting brine is separated by settling. The remaining oil is pumped through a tubular furnace where it is partially vaporized. The components that have a low number of carbon atoms vaporize and pass into a fractionating column or tower. As the vapors rise in the column, cooling causes condensation. By controlling the temperature, the volatile components may be separated into fractions that fall within particular boiling point ranges. In general, compounds with the lowest boiling points have the fewest carbon atoms and compounds with the highest boiling points have the greatest number of carbon atoms. This process reduces the number of compounds within each fraction and provides different qualities. The final products derived from this first-stage distillation process are raw gasoline, kerosene, and diesel fuel.

(2) Residuum distillation. The second-stage process involves distilling the portion of the first-stage that did not volatilize. Lubricating oils are obtained from this portion, which is referred to as the residuum. To prevent formation of undesired products, the residuum is distilled under vacuum so it will boil at a lower temperature. Distillation of the residuum produces oils of several boiling point ranges. The higher

the boiling point, the higher the carbon content of the oil molecules in a given range. More importantly, viscosity also varies with the boiling point and the number of carbon atoms in the oil molecules.

*c. Impurity removal.* Once the oil is separated into fractions, it must be further treated to remove impurities, waxy resins, and asphalt. Oils that have been highly refined are usually referred to as premium grades to distinguish them from grades of lesser quality in the producer's line of products. However, there are no criteria to establish what constitutes premium grade.

## 3-2. Types of Oil

Oils are generally classified as refined and synthetic. Paraffinic and naphthenic oils are refined from crude oil while synthetic oils are manufactured. Literature on lubrication frequently makes references to long-chain molecules and ring structures in connection with paraffinic and naphthenic oils, respectively. These terms refer to the arrangement of hydrogen and carbon atoms that make up the molecular structure of the oils. Discussion of the chemical structure of oils is beyond the scope of this manual, but the distinguishing characteristics between these oils are noted below.

*a. Paraffinic oils.* Paraffinic oils are distinguished by a molecular structure composed of long chains of hydrocarbons, i.e., the hydrogen and carbon atoms are linked in a long linear series similar to a chain. Paraffinic oils contain paraffin wax and are the most widely used base stock for lubricating oils. In comparison with naphthenic oils, paraffinic oils have:

- Excellent stability (higher resistance to oxidation).
- Higher pour point.
- Higher viscosity index.
- Low volatility and, consequently, high flash points.
- Low specific gravities.

*b. Naphthenic oils.* In contrast to paraffinic oils, naphthenic oils are distinguished by a molecular structure composed of “rings” of hydrocarbons, i.e., the hydrogen and carbon atoms are linked in a circular pattern. These oils do not contain wax and behave differently than paraffinic oils. Naphthenic oils have:

- Good stability.
- Lower pour point due to absence of wax.
- Lower viscosity indexes.
- Higher volatility (lower flash point).
- Higher specific gravities.

Naphthenic oils are generally reserved for applications with narrow temperature ranges and where a low pour point is required.

*c. Synthetic oils.*

(1) Synthetic lubricants are produced from chemical synthesis rather than from the refinement of existing petroleum or vegetable oils. These oils are generally superior to petroleum (mineral) lubricants in most circumstances. Synthetic oils perform better than mineral oils in the following respects:

- Better oxidation stability or resistance.

- Better viscosity index.

- Much lower pour point, as low as -46 °C (-50 °F).

- Lower coefficient of friction.

(2) The advantages offered by synthetic oils are most notable at either very low or very high temperatures. Good oxidation stability and a lower coefficient of friction permits operation at higher temperatures. The better viscosity index and lower pour points permit operation at lower temperatures.

(3) The major disadvantage to synthetic oils is the initial cost, which is approximately three times higher than mineral-based oils. However, the initial premium is usually recovered over the life of the product, which is about three times longer than conventional lubricants. The higher cost makes it inadvisable to use synthetics in oil systems experiencing leakage.

(4) Plant Engineering magazine's "Exclusive Guide to Synthetic Lubricants," which is revised every three years, provides information on selecting and applying these lubricants. Factors to be considered when selecting synthetic oils include pour and flash points; demulsibility; lubricity; rust and corrosion protection; thermal and oxidation stability; antiwear properties; compatibility with seals, paints, and other oils; and compliance with testing and standard requirements. Unlike Plant Engineering magazine's "Chart of Interchangeable Lubricants," it is important to note that synthetic oils are as different from each other as they are from mineral oils. Their performance and applicability to any specific situation depends on the quality of the synthetic base-oil and additive package, and the synthetic oils listed in Plant Engineering are not necessarily interchangeable.

*d. Synthetic lubricant categories.*

(1) Several major categories of synthetic lubricants are available including:

(a) Synthesized hydrocarbons. Polyalphaolefins and dialkylated benzenes are the most common types. These lubricants provide performance characteristics closest to mineral oils and are compatible with them. Applications include engine and turbine oils, hydraulic fluids, gear and bearing oils, and compressor oils.

(b) Organic esters. Diabasic acid and polyol esters are the most common types. The properties of these oils are easily enhanced through additives. Applications include crankcase oils and compressor lubricants.

(c) Phosphate esters. These oils are suited for fire-resistance applications.

(d) Polyglycols. Applications include gears, bearings, and compressors for hydrocarbon gases.

(e) Silicones. These oils are chemically inert, nontoxic, fire-resistant, and water repellant. They also have low pour points and volatility, good low-temperature fluidity, and good oxidation and thermal stability at high temperatures.

(2) Table 3-1 identifies several synthetic oils and their properties.

## 3-3. Characteristics of Lubricating Oils

*a. Viscosity.* Technically, the viscosity of an oil is a measure of the oil's resistance to shear. Viscosity is more commonly known as resistance to flow. If a lubricating oil is considered as a series of fluid layers superimposed on each other, the viscosity of the oil is a measure of the resistance to flow between the individual layers. A high viscosity implies a high resistance to flow while a low viscosity indicates a low resistance to flow. Viscosity varies inversely with temperature. Viscosity is also affected by pressure; higher pressure causes the viscosity to increase, and subsequently the load-carrying capacity of the oil also increases. This property enables use of thin oils to lubricate heavy machinery. The load-carrying capacity also increases as operating speed of the lubricated machinery is increased. Two methods for measuring viscosity are commonly employed: shear and time.

(1) Shear. When viscosity is determined by directly measuring shear stress and shear rate, it is expressed in centipoise (cP) and is referred to as the absolute or dynamic viscosity. In the oil industry, it is more common to use kinematic viscosity, which is the absolute viscosity divided by the density of the oil being tested. Kinematic viscosity is expressed in centistokes (cSt). Viscosity in centistokes is conventionally given at two standard temperatures: 40 °C and 100 °C (104 °F and 212 °F ).

(2) Time. Another method used to determine oil viscosity measures the time required for an oil sample to flow through a standard orifice at a standard temperature. Viscosity is then expressed in SUS (Saybolt Universal Seconds). SUS viscosities are also conventionally given at two standard temperatures: 37 °C and 98 °C (100 °F and 210 °F). As previously noted, the units of viscosity can be expressed as centipoise (cP), centistokes (cST), or Saybolt Universal Seconds (SUS), depending on the actual test method used to measure the viscosity.

*b. Viscosity index.* The viscosity index, commonly designated VI, is an arbitrary numbering scale that indicates the changes in oil viscosity with changes in temperature. Viscosity index can be classified as follows: low VI - below 35; medium VI - 35 to 80; high VI - 80 to 110; very high VI - above 110. A high viscosity index indicates small oil viscosity changes with temperature. A low viscosity index indicates high viscosity changes with temperature. Therefore, a fluid that has a high viscosity index can be expected to undergo very little change in viscosity with temperature extremes and is considered to have a stable viscosity. A fluid with a low viscosity index can be expected to undergo a significant change in viscosity as the temperature fluctuates. For a given temperature range, say -18 to 370°C ( 0 - 100 °F), the viscosity of one oil may change considerably more than another. An oil with a VI of 95 to 100 would change less than one with a VI of 80. Knowing the viscosity index of an oil is crucial when selecting a lubricant for an application, and is especially critical in extremely hot or cold climates. Failure to use an oil with the proper viscosity index when temperature extremes are expected may result in poor lubrication and equipment failure. Typically, paraffinic oils are rated at 38 °C ( 100 °F) and naphthenic oils are rated at -18 °C (0 °F). Proper selection of petroleum stocks and additives can produce oils with a very good VI.

**Table 3-1**
**Synthetic Oils**

| Fluid Property | Di-ester | Typical Phosphate Ester | Inhibited Esters | Typical Methyl Silicone | Typical Phenyl Methyl Silicone | Chlorinated Phenyl Methyl Silicone | Polyglycol (inhibited) | Perfluorinate Polyether |
|---|---|---|---|---|---|---|---|---|
| Maximum temperature in absence of oxygen (°C) | 250 | 300 | 110 | 220 | 320 | 305 | 260 | 370 |
| Maximum temperature in presence of oxygen (°C) | 210 | 240 | 110 | 180 | 250 | 230 | 200 | 310 |
| Maximum temperature due to decrease in viscosity (°C) | 150 | 180 | 100 | 200 | 250 | 280 | 200 | 300 |
| Minimum temperature due to increase in viscosity (°C) | -35 | -65 | -55 | -50 | -30 | -65 | -20 | -60 |
| Density (g/ml) | 0.91 | 1.01 | 1.12 | 0.97 | 1.06 | 1.04 | 1.02 | 1.88 |
| Viscosity index | 145 | 140 | 0 | 200 | 175 | 195 | 160 | 100-300 |
| Flash point (°C) | 230 | 255 | 200 | 310 | 290 | 270 | 180 | |
| Spontaneous ignition temperature | Low | Medium | Very high | High | High | Very high | Medium | Very high |
| Thermal conductivity (W/M °C) | 0.15 | 0.14 | 0.13 | 0.16 | 0.15 | 0.15 | 0.15 | |
| Thermal capacity (J/kg °C) | 2,000 | 1,700 | 1,600 | 1,550 | 1,550 | 1,550 | 2,000 | |
| Bulk modulus | Medium | Medium | Medium | Very low | Low | Low | Medium | Low |
| Boundary lubrication | Good | Good | Very good | Fair, but poor for steel on steel | Fair, but poor for steel on steel | Good | Very good | Poor |
| Toxicity | Slight | Slight | Some toxicity | Nontoxic | Nontoxic | Nontoxic | Believed to be low | Low |
| Suitable rubbers | Nitrile, silicone | Silicone | Butyl, EPR | Neoprene, viton | Neoprene, viton | Viton, fluoro-silicone | Nitrile | Many |
| Effect on plastics | May act as plasticizers | | Powerful solvent | Slight, but may leach out plasticizers | Slight, but may leach out plasti-cizers | Slight, but may leach out plasticizers | Generally mild | Mild |
| Resistance to attack by water | Good | Good | Fair | Very good | Very good | Good | Good | Very good |
| Resistance to chemicals | Attacked by alkali | Attacked by alkali | Attacked by many chemicals | Attacked by strong alkali | Attacked by strong alkali | Attacked by alkali | Attacked by oxidants | Very good |
| Effect on metals | Slightly corrosive to Non-ferrous metals | Corrosive to some Non-ferrous metals when hot | Enhanced corrosion in presence of water | Non-corrosive | Non-corrosive | Corrosive in presence of water to ferrous metals | Non-corrosive | Removes oxide films at elevated temperatures |
| Cost (relative to mineral oil) | 4 | 6 | 6 | 15 | 25 | 40 | 4 | 500 |

Note: Application data for a variety of synthetic oils are given in this table. The list is not complete, but most readily available synthetic oils are included. The data are generalizations, and no account has been taken of the availability and property variations of different viscosity grades in each chemical type. Reference: Neale, M.J., Lubrication: A Tribology Handbook

(Continued)

**Table 3-1 (Continued)**

| Fluid Property | Chlorinated Diphenyl | Silicate Ester or Disiloxame | Polyphenyl Ether | Fluorocarbon | Mineral Oil (for comparison) | Remark |
|---|---|---|---|---|---|---|
| Maximum temperature in absence of oxygen (°C) | 315 | 300 | 450 | 300 | 200 | For esters this temperature will be higher in the absence of metals |
| Maximum temperature in absence of oxygen (°C) | 145 | 200 | 320 | 300 | 150 | This limit is arbitrary. It will be higher if oxygen concentration is low and life is short |
| Maximum temperature due to decrease in viscosity (°C) | 100 | 240 | 150 | 140 | 200 | With external pressurization or low loads this limit will be higher |
| Minimum temperature due to decrease in viscosity (°C) | -10 | -60 | 0 | -50 | 0 to -50 | This limit depends on the power available to overcome the effect of increased viscosity |
| Density (g/ml) | 1.42 | 1.02 | 1.19 | 1.95 | 0.88 | |
| Viscosity index | -200 to +25 | 150 | -60 | -25 | 0 to 140 | A high viscosity index is desirable |
| Flash point (°C) | 180 | 170 | 275 | None | 150 to 200 | Above this temperature the vapor of the fluid may be ignited by an open flame |
| Spontaneous ignition temperature | Very high | Medium | High | Very high | Low | Above this temperature the fluid may ignite without any flame being present |
| Thermal conductivity (W/m° C) | 0.12 | 0.15 | 0.14 | 0.13 | 0.13 | A high thermal conductivity and high thermal capacity are desirable for effective cooling |
| Thermal capacity (J/kg° C) | 1,200 | 1,700 | 1,750 | 1,350 | 2,000 | |
| Bulk modulus | Medium | Low | Medium | Low | Fairly high | There are four different values of bulk modulus for each fluid but the relative qualities are consistent |
| Boundary lubrication | Very good | Fair | Fair | Very good | Good | This refers primarily to antiwear properties when some metal contact is occurring |
| Toxicity | Irritant vapor when hot | Slight | Believed to be low | Nontoxic unless overheated | Slight | Specialist advice should always be taken on toxic hazards |
| Suitable rubbers | Viton | Viton nitrile, floro-silicone | (None for very high tempera-tures) | Silicone | Nitrile | |
| Effect on plastics | Powerful solvent | Generally mild | Polyimides satisfactory | Some soften-ing when hot | Generally slight | |
| Resistance to attack by water | Excellent | Poor | Very good | Excellent | Excellent | This refers to breakdown of the fluid itself and not the effect of water on the system |
| Resistance to chemicals | Very resistant | Generally poor | Resistant | Resistant but attacked by alkali and amines | Very resistant | |
| Effect on metals | Some corrosion of copper alloys | Noncorrosive | Noncorrosive | Noncorrosive, but unsafe with aluminum and magnesium | Noncorrosive when pure | |
| Cost (relative to mineral oil) | 10 | 8 | 100 | 300 | 1 | These are rough approximations and vary with quality and supply position |

*c. Pour point*. The pour point is the lowest temperature at which an oil will flow. This property is crucial for oils that must flow at low temperatures. A commonly used rule of thumb when selecting oils is to ensure that the pour point is at least 10 °C (20 °F) lower than the lowest anticipated ambient temperature.

*d. Cloud point*. The cloud point is the temperature at which dissolved solids in the oil, such as paraffin wax, begin to form and separate from the oil. As the temperature drops, wax crystallizes and becomes visible. Certain oils must be maintained at temperatures above the cloud point to prevent clogging of filters.

*e. Flash point and fire point.* The flash point is the lowest temperature to which a lubricant must be heated before its vapor, when mixed with air, will ignite but not continue to burn. The fire point is the temperature at which lubricant combustion will be sustained. The flash and fire points are useful in determining a lubricant's volatility and fire resistance. The flash point can be used to determine the transportation and storage temperature requirements for lubricants. Lubricant producers can also use the flash point to detect potential product contamination. A lubricant exhibiting a flash point significantly lower than normal will be suspected of contamination with a volatile product. Products with a flash point less than 38 °C (100 °F) will usually require special precautions for safe handling. The fire point for a lubricant is usually 8 to 10 percent above the flash point. The flash point and fire point should not be confused with the auto-ignition temperature of a lubricant, which is the temperature at which a lubricant will ignite spontaneously without an external ignition source.

*f. Acid number or neutralization number.* The acid or neutralization number is a measure of the amount of potassium hydroxide required to neutralize the acid contained in a lubricant. Acids are formed as oils oxidize with age and service. The acid number for an oil sample is indicative of the age of the oil and can be used to determine when the oil must be changed.

## 3-4 Oil Classifications and Grading Systems

*a.* Professional societies classify oils by viscosity ranges or grades. The most common systems are those of the SAE (Society of Automotive Engineers), the AGMA (American Gear Manufacturers Association), the ISO (International Standards Organization), and the ASTM (American Society for Testing and Materials). Other systems are used in special circumstances.

*b.* The variety of grading systems used in the lubrication industry can be confusing. A specification giving the type of oil to be used might identify an oil in terms of its AGMA grade, for example, but an oil producer may give the viscosity in terms of cSt or SUS. Conversion charts between the various grading systems are readily available from lubricant suppliers. Conversion between cSt and SUS viscosities at standard temperatures can also be obtained from ASTM D 2161.

# Chapter 4
# Hydraulic Fluids

## 4-1. Purpose of Hydraulic Fluids

*a. Power transmission.* The primary purpose of any hydraulic fluid is to transmit power mechanically throughout a hydraulic power system. To ensure stable operation of components, such as servos, the fluid must flow easily and must be incompressible.

*b. Lubrication.* Hydraulic fluids must provide the lubricating characteristics and qualities necessary to protect all hydraulic system components against friction and wear, rust, oxidation, corrosion, and demulsibility. These protective qualities are usually provided through the use of additives.

*c. Sealing.* Many hydraulic system components, such as control valves, operate with tight clearances where seals are not provided. In these applications hydraulic fluids must provide the seal between the low-pressure and high-pressure side of valve ports. The amount of leakage will depend on the closeness or the tolerances between adjacent surfaces and the fluid viscosity.

*d. Cooling.* The circulating hydraulic fluid must be capable of removing heat generated throughout the system.

## 4-2. Physical Characteristics

The physical characteristics of hydraulic fluids are similar to those already discussed for lubricating oils. Only those characteristics requiring additional discussion are addressed below.

*a. Viscosity.* As with lubricating oils, viscosity is the most important characteristic of a hydraulic fluid and has a significant impact on the operation of a hydraulic system. If the viscosity is too high then friction, pressure drop, power consumption, and heat generation increase. Furthermore, sluggish operation of valves and servos may result. If the viscosity is too low, increased internal leakage may result under higher operating temperatures. The oil film may be insufficient to prevent excessive wear or possible seizure of moving parts, pump efficiency may decrease, and sluggish operation may be experienced.

*b. Compressibility.* Compressibility is a measure of the amount of volume reduction due to pressure. Compressibility is sometimes expressed by the “bulk modulus,” which is the reciprocal of compressibility. Petroleum fluids are relatively incompressible, but volume reductions can be approximately 0.5 percent for pressures ranging from 6900 kPa (1000 lb/sq in) up to 27,600 kPa (4000 lb/sq in). Compressibility increases with pressure and temperature and has significant effects on high-pressure fluid systems. Problems directly caused by compressibility include the following: servos fail to maintain static rigidity and experience adverse effects in system amplification or gain; loss in efficiency, which is counted as power loss because the volume reduction due to compressibility cannot be recovered; and cavitation, which may cause metal fracture, corrosive fatigue, and stress corrosion.

*c. Stability.* The stability of a hydraulic fluid is the most important property affecting service life. The properties of a hydraulic fluid can be expected to change with time. Factors that influence the changes include: mechanical stress and cavitation, which can break down the viscosity improvers and cause reduced viscosity; and oxidation and hydrolysis which cause chemical changes, formation of volatile components, insoluble materials, and corrosive products. The types of additives used in a fluid must be selected carefully to reduce the potential damage due to chemical breakdown at high temperatures.

## 4-3. Quality Requirements

The quality of a hydraulic fluid is an indication of the length of time that the fluid's essential properties will continue to perform as expected, i.e., the fluid's resistance to change with time. The primary properties affecting quality are oxidation stability, rust prevention, foam resistance, water separation, and antiwear properties. Many of these properties are achieved through use of chemical additives. However, these additives can enhance one property while adversely affecting another. The selection and compatibility of additives is very important to minimize adverse chemical reactions that may destroy essential properties.

*a. Oxidation stability.* Oxidation, or the chemical union of oil and oxygen, is one of the primary causes for decreasing the stability of hydraulic fluids. Once the reactions begin, a catalytic effect takes place. The chemical reactions result in formation of acids that can increase the fluid viscosity and can cause corrosion. Polymerization and condensation produce insoluble gum, sludge, and varnish that cause sluggish operation, increase wear, reduce clearances, and plug lines and valves. The most significant contributors to oxidation include temperature, pressure, contaminants, water, metal surfaces, and agitation.

(1) Temperature. The rate of chemical reactions, including oxidation, approximately doubles for every 10 °C (18 °F) increase in temperature. The reaction may start at a local area where the temperature is high. However, once started, the oxidation reaction has a catalytic effect that causes the rate of oxidation to increase.

(2) Pressure. As the pressure increases, the fluid viscosity also increases, causing an increase in friction and heat generation. As the operating temperature increases, the rate of oxidation increases. Furthermore, as the pressure increases, the amount of entrained air and associated oxygen also increases. This condition provides additional oxygen to accelerate the oxidation reaction.

(3) Contaminants. Contaminants that accelerate the rate of oxidation may be dirt, moisture, joint compounds, insoluble oxidation products, or paints. A 1 percent sludge concentration in a hydraulic fluid is sufficient to cause the fluid to oxidize in half the time it would take if no sludge were present. Therefore the contaminated fluid's useful life is reduced by 50 percent.

(4) Water and metal. Certain metals, such as copper, are known to be catalysts for oxidation reactions, especially in the presence of water. Due to the production of acids during the initial stages of oxidation, the viscosity and neutralization numbers increase. The neutralization number for a fluid provides a measure of the amount of acid contained in a fluid. The most commonly accepted oxidation test for hydraulic fluids is the ASTM Method D 943 Oxidation Test. This test measures the neutralization number of oil as it is heated in the presence of pure oxygen, a metal catalyst, and water. Once started the test continues until the neutralization number reaches a value of 2.0. One series of tests provides an indication of how the neutralization number is affected by contaminants. With no water or metal contaminants, the neutralization number reached 0.17 in 3500 hours. When the test was repeated with copper contaminant, the neutralization number reached a value of 0.89 after 3000 hours. The test was subsequently repeated with copper and water contamination and the neutralization number reached 11.2 in approximately 150 hours.

(5) Agitation. To reduce the potential for oxidation, oxidation inhibitors are added to the base hydraulic fluid. Two types of inhibitors are generally used: chain breakers and metal deactivators. Chain breaker inhibitors interrupt the oxidation reaction immediately after the reaction is initiated. Metal deactivators reduce the effects of metal catalysts.

*b. Rust and corrosion prevention.* Rust is a chemical reaction between water and ferrous metals. Corrosion is a chemical reaction between chemicals (usually acids) and metals. Water condensed from entrained air in a hydraulic system causes rust if the metal surfaces are not properly protected. In some cases water reacts with chemicals in a hydraulic fluid to produce acids that cause corrosion. The acids attack and remove particles from metal surfaces allowing the affected surfaces to leak, and in some cases to seize. To prevent rust, hydraulic fluids use rust inhibitors that deposit a protective film on metal surfaces. The film is virtually impervious to water and completely prevents rust once the film is established throughout the hydraulic system. Rust inhibitors are tested according to the ASTM D 665 Rusting Test. This test subjects a steel rod to a mixture of oil and salt water that has been heated to 60 °C (140 °F). If the rod shows no sign of rust after 24 hours the fluid is considered satisfactory with respect to rust-inhibiting properties. In addition to rust inhibitors, additives must be used to prevent corrosion. These additives must exhibit excellent hydrolytic stability in the presence of water to prevent fluid breakdown and the acid formation that causes corrosion.

*c. Air entrainment and foaming.* Air enters a hydraulic system through the reservoir or through air leaks within the hydraulic system. Air entering through the reservoir contributes to surface foaming on the oil. Good reservoir design and use of foam inhibitors usually eliminate surface foaming.

(1) Air entrainment is a dispersion of very small air bubbles in a hydraulic fluid. Oil under low pressure absorbs approximately 10 percent air by volume. Under high pressure, the percentage is even greater. When the fluid is depressurized, the air produces foam as it is released from solution. Foam and high air entrainment in a hydraulic fluid cause erratic operation of servos and contribute to pump cavitation. Oil oxidation is another problem caused by air entrainment. As a fluid is pressurized, the entrained air is compressed and increases in temperature. This increased air temperature can be high enough to scorch the surrounding oil and cause oxidation.

(2) The amount of foaming in a fluid depends upon the viscosity of the fluid, the source of the crude oil, the refinement process, and usage. Foam depressants are commonly added to hydraulic fluid to expedite foam breakup and release of dissolved air. However, it is important to note that foam depressants do not prevent foaming or inhibit air from dissolving in the fluid. In fact, some antifoamants, when used in high concentrations to break up foam, actually retard the release of dissolved air from the fluid.

*d. Demulsibility or water separation.* Water that enters a hydraulic system can emulsify and promote the collection of dust, grit, and dirt, and this can adversely affect the operation of valves, servos, and pumps, increase wear and corrosion, promote fluid oxidation, deplete additives, and plug filters. Highly refined mineral oils permit water to separate or demulsify readily. However, some additives such as antirust treatments actually promote emulsion formation to prevent separated water from settling and breaking through the antirust film.

*e. Antiwear properties.*

(1) Conventional hydraulic fluids are satisfactory for low-pressure and low-speed applications. However, hydraulic fluids for high-pressure (over 6900 kPa or 1000.5 lb/sq in) and high-speed (over 1200 rpm) applications that use vane or gear pumps must contain antiwear additives. These applications

do not permit the formation of full fluid film lubrication to protect contacting surfaces--a condition known as boundary lubrication. Boundary lubrication occurs when the fluid viscosity is insufficient to prevent surface contact. Antiwear additives provide a protective film at the contact surfaces to minimize wear. At best, use of a hydraulic fluid without the proper antiwear additives will cause premature wear of the pumps and cause inadequate system pressure. Eventually the pumps will be destroyed.

(2) Quality assurance of antiwear properties is determined through standard laboratory testing. Laboratory tests to evaluate antiwear properties of a hydraulic fluid are performed in accordance with ASTM D 2882. This test procedure is generally conducted with a variety of high-speed, high-pressure pump models manufactured by Vickers or Denison. Throughout the tests, the pumps are operated for a specified period. At the end of each period the pumps are disassembled and specified components are weighed. The weight of each component is compared to its initial weight; the difference reflects the amount of wear experienced by the pumps for the operating period. The components are also inspected for visual signs of wear and stress.

## 4-4. Use of Additives

Many of the qualities and properties discussed above are achieved by the product manufacturer's careful blending of additives with base oil stocks. Because of incompatibility problems and the complex interactions that can occur between various additives, oil producers warn users against attempting to enhance oil properties through indiscriminate use of additives. The various types of additives and their use are discussed in Chapter 7.

## 4-5. Types of Hydraulic Fluids

*a. Petroleum.* Petroleum-based oils are the most commonly used stock for hydraulic applications where there is no danger of fire, no possibility of leakage that may cause contamination of other products, no wide temperature fluctuations, and no environmental impact.

*b. Fire resistant.* In applications where fire hazards or environmental pollution are a concern, water-based or aqueous fluids offer distinct advantages. The fluids consist of water-glycols and water-in-oil fluids with emulsifiers, stabilizers, and additives. Due to their lower lubricity, piston pumps used with these fluids should be limited to 20,670 kPa (3000 lb/sq in.) Furthermore, vane pumps should not be used with water-based fluid unless they are specifically designed to use such fluids.

(1) Water-glycol. Water-glycol fluids contain from 35 to 60 percent water to provide the fire resistance, plus a glycol antifreeze such as ethylene, diethylene, or propylene which is nontoxic and biodegradable, and a thickener such as polyglycol to provide the required viscosity. These fluids also provide all the important additives such as antiwear, foam, rust, and corrosion inhibitors. Operating temperatures for water-glycol fluids should be maintained below 49 °C (120 °F) to prevent evaporation and deterioration of the fluid. To prevent separation of fluid phases or adverse effects on the fluid additives, the minimum temperature should not drop below 0 $^0$C (32 $^0$F).

(a) Viscosity, pH, and water hardness monitoring are very important in water-glycol systems. If water is lost to evaporation, the fluid viscosity, friction, and operating temperature of the fluid will increase. The end result is sluggish operation of the hydraulic system and increased power consumption. If fluid viscosity is permitted to drop due to excessive water, internal leakage at actuators will increase and cause sluggish operation. A thin fluid is also more prone to turbulent flow which will increase the potential for erosion of system components.

(b) Under normal use, the fluid pH can be expected to drop due to water evaporation, heat, and loss of corrosion inhibitors. The fluid pH should be slightly alkaline (i.e., above pH8) to prevent rust. However, because of their volatility and toxicity, handling of the amine additives that stabilize the pH is not recommended. Therefore, these essential additives are not usually replenished. Fluids with pH levels that drop below 8 should be removed and properly discarded.

(c) Make-up water added to the system must be distilled or soft deionized. The calcium and magnesium present in potable water will react with lubricant additives causing them to floc or come out of solution and compromise the fluid's performance. When this condition occurs the fluid is permanently damaged and should be replaced. To prolong the fluid and component life, water added to the system should have a maximum hardness of 5 parts per million (ppm).

(2) Water-oil emulsions

(a) Oil-in-water. These fluids consist of very small oil droplets dispersed in a continuous water phase. These fluids have low viscosities, excellent fire-resistance, and good cooling capability due to the large proportion of water. Additives must be used to improve their inherently poor lubricity and to protect against rust.

(b) Water-in-oil. The water content of water-in-oil fluids may be approximately 40 percent. These fluids consist of very small water droplets dispersed in a continuous oil phase. The oil phase provides good to excellent lubricity while the water content provides the desired level of fire-resistance and enhances the fluid cooling capability. Emulsifiers are added to improve stability. Additives are included to minimize rust and to improve lubricity as necessary. These fluids are compatible with most seals and metals common to hydraulic fluid applications. The operating temperature of water-in-oil fluids must be kept low to prevent evaporation and oxidation. The proportion of oil and water must be monitored to ensure that the proper viscosity is maintained especially when adding water or concentrated solutions to the fluid to make up for evaporation. To prevent phase separation, the fluid should be protected from repeated cycles of freezing and thawing.

(c) Synthetic fire-resistant fluids. Three types of synthetic fire-resistant fluids are manufactured: phosphate esters, chlorinated (halogenated) hydrocarbons, and synthetic base (a mixture of these two). These fluids do not contain water or volatile materials, and they provide satisfactory operation at high temperatures without loss of essential elements (in contrast to water-based fluids). The fluids are also suitable for high-pressure applications. Synthetic fluids have a low viscosity index, anywhere from 80 to -400, so their use should be restricted to relatively constant operating temperatures. When required to operate at low temperatures, these fluids may require auxiliary heating. Synthetic fluids also have high specific gravities so pump inlet conditions must be carefully selected to prevent cavitation. Phosphate esters have flash points above 204 °C (400 °F) and auto-ignition temperatures above 483 °C (900 °F), making these fluids less likely to ignite and sustain burning. Halogenated hydrocarbon fluids are inert, odorless, nonflammable, noncorrosive, and have low toxicity. Seal compatibility is very important when using synthetic fluids. Most commonly used seals such as Nitrile (Buna) and Neoprene are not compatible with these fluids.

*c. Environmentally acceptable hydraulic fluids.* The requirements for biodegradable fluids are discussed in Chapter 8.

## 4-6. Cleanliness Requirements

Due to the very small clearances and critical nature of hydraulic systems, proper maintenance and cleanliness of these systems is extremely important. Hydraulic system cleanliness codes, oil purification, and filtration are discussed in Chapter 12.

# Chapter 5
# Grease

## 5-1. Description

Grease is a semifluid to solid mixture of a fluid lubricant, a thickener, and additives. The fluid lubricant that performs the actual lubrication can be petroleum (mineral) oil, synthetic oil, or vegetable oil. The thickener gives grease its characteristic consistency and is sometimes thought of as a “three-dimensional fibrous network” or “sponge” that holds the oil in place. Common thickeners are soaps and organic or inorganic nonsoap thickeners. The majority of greases on the market are composed of mineral oil blended with a soap thickener. Additives enhance performance and protect the grease and lubricated surfaces. Grease has been described as a temperature-regulated feeding device: when the lubricant film between wearing surfaces thins, the resulting heat softens the adjacent grease, which expands and releases oil to restore film thickness.

## 5-2. Function

“The function of grease is to remain in contact with and lubricate moving surfaces without leaking out under gravity or centrifugal action, or be squeezed out under pressure. Its major practical requirement is that it retain its properties under shear at all temperatures that it is subjected to during use. At the same time, grease must be able to flow into the bearing through grease guns and from spot to spot in the lubricated machinery as needed, but must not add significantly to the power required to operate the machine, particularly at startup.” (Boehringer 1992)

*a. Applications suitable for grease.* Grease and oil are not interchangeable. Grease is used when it is not practical or convenient to use oil. The lubricant choice for a specific application is determined by matching the machinery design and operating conditions with desired lubricant characteristics. Grease is generally used for:

(1) Machinery that runs intermittently or is in storage for an extended period of time. Because grease remains in place, a lubricating film can instantly form.

(2) Machinery that is not easily accessible for frequent lubrication. High-quality greases can lubricate isolated or relatively inaccessible components for extended periods of time without frequent replenishing. These greases are also used in sealed-for-life applications such as some electrical motors and gearboxes.

(3) Machinery operating under extreme conditions such as high temperatures and pressures, shock loads, or slow speed under heavy load. Under these circumstances, grease provides thicker film cushions that are required to protect and adequately lubricate, whereas oil films can be too thin and can rupture.

(4) Worn components. Grease maintains thicker films in clearances enlarged by wear and can extend the life of worn parts that were previously oil lubricated. Thicker grease films also provide noise insulation.

*b. Functional properties of grease.*

(1) Functions as a sealant to minimize leakage and to keep out contaminants. Because of its consistency, grease acts as a sealant to prevent lubricant leakage and also to prevent entrance of corrosive

contaminants and foreign materials. It also acts to keep deteriorated seals effective (whereas an oil would simply seep away).

(2) Easier to contain than oil. Oil lubrication can require an expensive system of circulating equipment and complex retention devices. In comparison, grease, by virtue of its rigidity, is easily confined with simplified, less costly retention devices.

(3) Holds solid lubricants in suspension. Finely ground solid lubricants, such as molybdenum disulfide (moly) and graphite, are mixed with grease in high temperature service (over 315 °C [599 °F]) or in extreme high-pressure applications. Grease holds solids in suspension while solids will settle out of oils.

(4) Fluid level does not have to be controlled and monitored.

c. Notable disadvantages of grease:

(1) Poor cooling. Due to its consistency, grease cannot dissipate heat by convection like a circulating oil.

(2) Resistance to motion. Grease has more resistance to motion at start-up than oil, so it is not appropriate for low torque/high speed operation.

(3) More difficult to handle than oil for dispensing, draining, and refilling. Also, exact amounts of lubricant cannot be as easily metered.

## 5-3. Grease Characteristics

Common ASTM tests for the grease characteristics listed below are shown in Table 5-3.

*a. Apparent viscosity.* At start-up, grease has a resistance to motion, implying a high viscosity. However, as grease is sheared between wearing surfaces and moves faster, its resistance to flow reduces. Its viscosity decreases as the rate of shear increases. By contrast, an oil at constant temperature would have the same viscosity at start-up as it has when it is moving. To distinguish between the viscosity of oil and grease, the viscosity of a grease is referred to as “apparent viscosity.” Apparent viscosity is the viscosity of a grease that holds only for the shear rate and temperature at which the viscosity is determined.

*b. Bleeding, migration, syneresis.* Bleeding is a condition when the liquid lubricant separates from the thickener. It is induced by high temperatures and also occurs during long storage periods. Migration is a form of bleeding that occurs when oil in a grease migrates out of the thickener network under certain circumstances. For example, when grease is pumped though a pipe in a centralized lubrication system, it may encounter a resistance to the flow and form a plug. The oil continues to flow, migrating out of the thickener network. As the oil separates from the grease, thickener concentration increases, and plugging gets worse. If two different greases are in contact, the oils may migrate from one grease to the other and change the structure of the grease. Therefore, it is unwise to mix two greases. Syneresis is a special form of bleeding caused by shrinking or rearrangement of the structure due to physical or chemical changes in the thickener.

*c. Consistency, penetration, and National Lubricating Grease Institute (NLGI) numbers.* The most important feature of a grease is its rigidity or consistency. A grease that is too stiff may not feed into areas requiring lubrication, while a grease that is too fluid may leak out. Grease consistency depends on the type and amount of thickener used and the viscosity of its base oil. A grease's consistency is its resistance to deformation by an applied force. The measure of consistency is called penetration. Penetration depends on whether the consistency has been altered by handling or working. ASTM D 217 and D 1403 methods measure penetration of unworked and worked greases. To measure penetration, a cone of given weight is allowed to sink into a grease for 5 seconds at a standard temperature of 25 °C (77 °F). The depth, in tenths of a millimeter, to which the cone sinks into the grease is the penetration. A penetration of 100 would represent a solid grease while one of 450 would be semifluid. The NLGI has established consistency numbers or grade numbers, ranging from 000 to 6, corresponding to specified ranges of penetration numbers. Table 5.1 lists the NLGI grease classifications along with a description of the consistency of each classification.

**Table 5.1**
**NLGI Grease Classification**

| NLGI Number | ASTM Worked Penetration 0.1 mm ($3.28 \times 10^{-4}$ ft) at 25 °C (77 °F) | Consistency |
|---|---|---|
| 000 | 445 - 475 | Semifluid |
| 00 | 400 - 430 | Semifluid |
| 0 | 355 - 385 | Very soft |
| 1 | 310 - 340 | Soft |
| 2 | 265 - 295 | Common grease |
| 3 | 220 - 250 | Semihard |
| 4 | 175 - 205 | Hard |
| 5 | 130 - 160 | Very hard |
| 6 | 85 - 115 | Solid |

*d. Contaminants.* Greases tend to hold solid contaminants on their outer surfaces and protect lubricated surfaces from wear. If the contamination becomes excessive or eventually works its way down to the lubricated surfaces the reverse occurs -- the grease retains abrasive materials at the lubricated surface and wear occurs.

*e. Corrosion- and rust-resistance.* This denotes the ability of grease to protect metal parts from chemical attack. The natural resistance of a grease depends upon the thickener type. Corrosion-resistance can be enhanced by corrosion and rust inhibitors.

*f. Dropping point.* Dropping point is an indicator of the heat resistance of grease. As grease temperature rises, penetration increases until the grease liquefies and the desired consistency is lost. Dropping point is the temperature at which a grease becomes fluid enough to drip. The dropping point indicates the upper temperature limit at which a grease retains its structure, not the maximum temperature at which a grease may be used. A few greases have the ability to regain their original structure after cooling down from the dropping point.

*g. Evaporation.* The mineral oil in a grease evaporates at temperatures above 177 °C (350 °F). Excessive oil evaporation causes grease to harden due to increased thickener concentration. Therefore, higher evaporation rates require more frequent relubrication.

*h. Fretting wear and false brinelling.* Fretting is friction wear of components at contact points caused by minute oscillation. The oscillation is so minute that grease is displaced from between parts but is not allowed to flow back in. Localized oxidation of wear particles results and wear accelerates. In bearings, this localized wear appears as a depression in the race caused by oscillation of the ball or roller. The depression resembles that which occurs during Brinell hardness determination, hence the term "false brinelling." An example would be fretting wear of automotive wheel bearings when a car is transported by train. The car is secured, but the vibration of the train over the tracks causes minute oscillation resulting in false brinelling of the bearing race.

*i. Oxidation stability.* This is the ability of a grease to resist a chemical union with oxygen. The reaction of grease with oxygen produces insoluble gum, sludges, and lacquer-like deposits that cause sluggish operation, increased wear, and reduction of clearances. Prolonged high-temperature exposure accelerates oxidation in greases.

*j. Pumpability and slumpability.* Pumpability is the ability of a grease to be pumped or pushed through a system. More practically, pumpability is the ease with which a pressurized grease can flow through lines, nozzles, and fittings of grease-dispensing systems. Slumpability, or feedability, is its ability to be drawn into (sucked into) a pump. Fibrous greases tend to have good feedability but poor pumpability. Buttery-textured greases tend to have good pumpability but poor feedability.

*k. Shear stability.* Grease consistency may change as it is mechanically worked or sheared between wearing surfaces. A grease's ability to maintain its consistency when worked is its shear stability or mechanical stability. A grease that softens as it is worked is called thixotropic. Greases that harden when worked are called rheopectic.

*l. High-temperature effects.* High temperatures harm greases more than they harm oils. Grease, by its nature, cannot dissipate heat by convection like a circulating oil. Consequently, without the ability to transfer away heat, excessive temperatures result in accelerated oxidation or even carbonization where grease hardens or forms a crust. Effective grease lubrication depends on the grease's consistency. High temperatures induce softening and bleeding, causing grease to flow away from needed areas. The mineral oil in grease can flash, burn, or evaporate at temperatures above 177 °C (350 °F). High temperatures, above 73-79 °C (165-175 °F), can dehydrate certain greases such as calcium soap grease and cause structural breakdown. The higher evaporation and dehydration rates at elevated temperatures require more frequent grease replacement.

*m. Low-temperature effects.* If the temperature of a grease is lowered enough, it will become so viscous that it can be classified as a hard grease. Pumpability suffers and machinery operation may become impossible due to torque limitations and power requirements. The temperature at which this occurs depends on the shape of the lubricated part and the power being supplied to it. As a guideline, the base oil's pour point is considered the low-temperature limit of a grease.

*n. Texture.* Texture is observed when a small sample of grease is pressed between thumb and index finger and slowly drawn apart. Texture can be described as:

- Brittle: the grease ruptures or crumbles when compressed.

- Buttery: the grease separates in short peaks with no visible fibers.

- Long fiber: the grease stretches or strings out into a single bundle of fibers.

- Resilient: the grease can withstand moderate compression without permanent deformation or rupture.

- Short fiber: the grease shows short break-off with evidence of fibers.

- Stringy: the grease stretches or strings out into long, fine threads, but with no visible evidence of fiber structure.

*o. Water resistance.* This is the ability of a grease to withstand the effects of water with no change in its ability to lubricate. A soap/water lather may suspend the oil in the grease, forming an emulsion that can wash away or, to a lesser extent, reduce lubricity by diluting and changing grease consistency and texture. Rusting becomes a concern if water is allowed to contact iron or steel components.

## 5-4. Fluid Lubricants

Fluid lubricants used to formulate grease are normally petroleum or synthetic oils. For petroleum oils in general, naphthenic oils tend to chemically mix better with soaps and additives and form stronger structures than paraffinic oils. Synthetic oils are higher in first cost but are effective in high-temperature and low-temperature extremes. With growing environmental concerns, vegetable oils and certain synthetic oils are also being used in applications requiring nontoxic or biodegradable greases. Separate chapters in this manual are devoted to lubricating oils and environmentally acceptable oils. They describe the characteristics that each type of oil brings to grease. The base oil selected in formulating a grease should have the same characteristics as if the equipment is to be lubricated by oil. For instance, lower-viscosity base oils are used for grease applications at lower temperatures or high speeds and light loads, whereas higher-viscosity base oils are used for higher temperatures or low speed and heavy load applications.

## 5-5. Soap Thickeners

*a.* Dispersed in its base fluid, a soap thickener gives grease its physical character. Soap thickeners not only provide consistency to grease, they affect desired properties such as water and heat resistance and pumpability. They can affect the amount of an additive, such as a rust inhibitor, required to obtain a desired quality. The soap influences how a grease will flow, change shape, and age as it is mechanically worked and at temperature extremes. Each soap type brings its own characteristic properties to a grease.

*b.* The principal ingredients in creating a soap are a fatty acid and an alkali. Fatty acids can be derived from animal fat such as beef tallow, lard, butter, fish oil, or from vegetable fat such as olive, castor, soybean, or peanut oils. The most common alkalies used are the hydroxides from earth metals such as aluminum, calcium, lithium, and sodium. Soap is created when a long-carbon-chain fatty acid reacts with the metal hydroxide. The metal is incorporated into the carbon chain and the resultant compound develops a polarity. The polar molecules form a fibrous network that holds the oil. Thus, a somewhat rigid gel-like material "grease" is developed. Soap concentration can be varied to obtain different grease thicknesses. Furthermore, viscosity of the base oil affects thickness as well. Since soap qualities are also determined by the fatty acid from which the soap is prepared, not all greases made from soaps containing the same metals are identical. The name of the soap thickener refers to the metal (calcium, lithium, etc.) from which the soap is prepared.

## 5-6. Complex Soap

*a.* The high temperatures generated by modern equipment necessitated an increase in the heat-resistance of normal soap-thickened greases. As a result, "complex" soap greases were developed. The dropping point of a complex grease is at least 38 °C (100 °F) higher than its normal soap-thickened counterpart, and its maximum usable temperature is around 177 °C (350 °F). Complex soap greases are limited to this temperature because the mineral oil can flash, evaporate, or burn above that temperature. Generally, complex greases have good all-around properties and can be used in multipurpose applications. For extreme operating conditions, complex greases are often produced with solid lubricants and use more highly refined or synthetic oils.

*b.* A "complexing agent" made from a salt of the named metal is the additional ingredient in forming a complex grease. A complex soap is formed by the reaction of a fatty acid and alkali to form a soap, and the simultaneous reaction of the alkali with a short-chain organic or inorganic acid to form a metallic salt (the complexing agent). Basically, a complex grease is made when a complex soap is formed in the presence of a base oil. Common organic acids are acetic or lactic, and common inorganic acids are carbonates or chlorides.

## 5-7. Additives

Surface-protecting and performance-enhancing additives that can effectively improve the overall performance of a grease are described in Chapter 7. Solid lubricants such as molybdenum disulfide and graphite are added to grease in certain applications for high temperatures (above 315 °C or 599 °F) and extreme high-pressure applications. Incorporating solid additives requires frequent grease changes to prevent accumulation of solids in components (and the resultant wear). Properties of solid lubricants are described in Chapter 6. Not mentioned in other chapters are dyes that improve grease appearance and are used for identification purposes.

## 5-8. Types of Greases

The most common greases are described below.

*a. Calcium grease.*

(1) Calcium or lime grease, the first of the modern production greases, is prepared by reacting mineral oil with fats, fatty acids, a small amount of water, and calcium hydroxide (also known as hydrated lime). The water modifies the soap structure to absorb mineral oil. Because of water evaporation, calcium grease is sensitive to elevated temperatures. It dehydrates at temperatures around 79 °C (175 °F) at which its structure collapses, resulting in softening and, eventually, phase separation. Greases with soft consistencies can dehydrate at lower temperatures while greases with firm consistencies can lubricate satisfactorily to temperatures around 93 °C (200 °F). In spite of the temperature limitations, lime grease does not emulsify in water and is excellent at resisting "wash out." Also, its manufacturing cost is relatively low. If a calcium grease is prepared from 12-hydroxystearic acid, the result is an anhydrous (waterless) grease. Since dehydration is not a concern, anhydrous calcium grease can be used continuously to a maximum temperature of around 110 °C (230 °F).

(2) Calcium complex grease is prepared by adding the salt calcium acetate. The salt provides the grease with extreme pressure characteristics without using an additive. Dropping points greater than 260 °C (500 °F) can be obtained and the maximum usable temperature increases to approximately 177 °C (350 °F). With the exception of poor pumpability in high-pressure centralized systems, where caking and hardening sometimes occur calcium complex greases have good all-around characteristics that make them desirable multipurpose greases.

*b. Sodium grease.* Sodium grease was developed for use at higher operating temperatures than the early hydrated calcium greases. Sodium grease can be used at temperatures up to 121 °C (250 °F), but it is soluble in water and readily washes out. Sodium is sometimes mixed with other metal soaps, especially calcium, to improve water resistance. Although it has better adhesive properties than calcium grease, the use of sodium grease is declining due to its lack of versatility. It cannot compete with water-resistant, more heat-resistant multipurpose greases. It is, however, still recommended for certain heavy-duty applications and well-sealed electric motors.

*c. Aluminum grease.*

(1) Aluminum grease is normally clear and has a somewhat stringy texture, more so when produced from high-viscosity oils. When heated above 79 °C (175 °F), this stringiness increases and produces a rubberlike substance that pulls away from metal surfaces, reducing lubrication and increasing power consumption. Aluminum grease has good water resistance, good adhesive properties, and inhibits rust without additives, but it tends to be short-lived. It has excellent inherent oxidation stability but relatively poor shear stability and pumpability.

(2) Aluminum complex grease has a maximum usable temperature of almost 100 °C (212 °F) higher than aluminum-soap greases. It has good water-and-chemical resistance but tends to have shorter life in high-temperature, high-speed applications.

*d. Lithium grease.*

(1) Smooth, buttery-textured lithium grease is by far the most popular when compared to all others. The normal grease contains lithium 12-hydroxystearate soap. It has a dropping point around 204 °C (400 °F) and can be used at temperatures up to about 135 °C (275 °F). It can also be used at temperatures as low as -35 °C (-31 °F) . It has good shear stability and a relatively low coefficient of friction, which permits higher machine operating speeds. It has good water-resistance, but not as good as that of calcium or aluminum. Pumpability and resistance to oil separation are good to excellent. It does not naturally inhibit rust, but additives can provide rust resistance. Anti-oxidants and extreme pressure additives are also responsive in lithium greases.

(2) Lithium complex grease and lithium soap grease have similar properties except the complex grease has superior thermal stability as indicated by a dropping point of 260 °C (500 °F). It is generally considered to be the nearest thing to a true multipurpose grease.

*e. Other greases.* Thickeners other than soaps are available to make greases. Although most of these are restricted to very special applications, two nonsoap greases are worthy of mention. One is organic, the other inorganic.

(1) Polyurea grease.

(a) Polyurea is the most important organic nonsoap thickener. It is a low-molecular-weight organic polymer produced by reacting amines (an ammonia derivative) with isocyanates, which results in an oil-soluble chemical thickener. Polyurea grease has outstanding resistance to oxidation because it contains no metal soaps (which tend to invite oxidation). It effectively lubricates over a wide temperature range of -20 to 177 °C (-4 to 350 °F) and has long life. Water-resistance is good to excellent, depending on the grade. It works well with many elastomer seal materials. It is used with all types of bearings but has been particularly effective in ball bearings. Its durability makes it well suited for sealed-for-life bearing applications.

(b) Polyurea complex grease is produced when a complexing agent, most commonly calcium acetate or calcium phosphate, is incorporated into the polymer chain. In addition to the excellent properties of normal polyurea grease, these agents add inherent extreme pressure and wear protection properties that increase the multipurpose capabilities of polyurea greases.

(2) Organo-clay. Organo-clay is the most commonly used inorganic thickener. Its thickener is a modified clay, insoluble in oil in its normal form, but through complex chemical processes, converts to platelets that attract and hold oil. Organo-clay thickener structures are amorphous and gel-like rather than the fibrous, crystalline structures of soap thickeners. This grease has excellent heat-resistance since clay does not melt. Maximum operating temperature is limited by the evaporation temperature of its mineral oil, which is around 177 °C (350 °F). However, with frequent grease changes, this multipurpose grease can operate for short periods at temperatures up to its dropping point, which is about 260 °C (500 °F). A disadvantage is that greases made with higher-viscosity oils for high thermal stability will have poor low-temperature performance. Organo-clay grease has excellent water-resistance but requires additives for oxidation and rust resistance. Work stability is fair to good. Pumpability and resistance to oil separation are good for this buttery textured grease.

## 5-9. Compatibility

*a*. Greases are considered incompatible when the physical or performance characteristics of the mixed grease falls below original specifications. In general, greases with different chemical compositions should not be mixed. Mixing greases of different thickeners can form a mix that is too firm to provide sufficient lubrication or more commonly, a mix that is too soft to stay in place.

*b*. Combining greases of different base oils can produce a fluid component that will not provide a continuous lubrication film. Additives can be diluted when greases with different additives are mixed. Mixed greases may become less resistant to heat or have lower shear stability. If a new brand of grease must be introduced, the component part should be disassembled and thoroughly cleaned to remove all of the old grease. If this is not practical, the new grease should be injected until all traces of the prior product are flushed out. Also, the first grease changes should be more frequent than normally scheduled.

## 5-10. Grease Application Guide

When selecting a grease, it is important to determine the properties required for the particular application and match them to a specific grease. A grease application guide is shown in Table 5-2. It shows the most common greases, their usual properties, and important uses. Some of the ratings given are subjective and can vary significantly from supplier to supplier. Common ASTM tests for the grease characteristics described in paragraph 5-3 are shown in Table 5-3.

**Table 5-2**
**Grease Application Guide**

| Properties | Aluminum | Sodium | Calcium-Conventional | Calcium - Anhydrous | Lithium | Aluminum Complex | Calcium Complex | Lithium Complex | Polyurea | Organo-Clay |
|---|---|---|---|---|---|---|---|---|---|---|
| Dropping point (°C) | 110 | 163-177 | 096-104 | 135-143 | 177-204 | 260+ | 260+ | 260+ | 243 | 260+ |
| Dropping point (°F) | 230 | 325-350 | 205-220 | 275-290 | 350-400 | 500+ | 500+ | 500+ | 470 | 500+ |
| Maximum usable temperature (°C) | 79 | 121 | 93 | 110 | 135 | 177 | 177 | 177 | 177 | 177 |
| Maximum usable temperature (°F) | 175 | 350 | 200 | 230 | 275 | 350 | 350 | 350 | 350 | 350 |
| Water resistance | Good to excellent | Poor to fair | Good to excellent | Excellent | Good | Good to excellent | Fair to excellent | Good to excellent | Good to excellent | Fair to excellent |
| Work stability | Poor | Fair | Fair to good | Good to excellent | Good to excellent | Good to excellent | Fair to good | Good to excellent | Poor to good | Fair to good |
| Oxidation stability | Excellent | Poor to good | Poor to excellent | Fair to excellent | Fair to excellent | Fair to excellent | Poor to good | Fair to excellent | Good to excellent | Good |
| Protection against rust | Good to excellent | Good to excellent | Poor to excellent | Poor to excellent | Poor to excellent | Good to excellent | Fair to excellent | Fair to excellent | Fair to excellent | Poor to excellent |
| Pumpability (in centralized system) | Poor | Poor to fair | Good to excellent | Fair to excellent | Fair to excellent | Fair to good | Poor to fair | Good to excellent | Good to excellent | Good |
| Oil separation | Good | Fair to good | Poor to good | Good | Good to excellent | Good to excellent | Good to excellent | Good to excellent | Good to excellent | Good to excellent |
| Appearance | Smooth and clear | Smooth to fibrous | Smooth and buttery | Smooth and buttery | Smooth and buttery | Smooth and buttery | Smooth and buttery | Smooth and buttery | Smooth and buttery | Smooth and buttery |
| Other properties | | Adhesive & cohesive | EP grades available | EP grades available | EP grades available, reversible | EP grades available, reversible | EP grades antiwear inherent | EP grades available | EP grades available | |
| Principal Uses | Thread lubricants | Rolling contact economy | General uses for economy | Military multiservice | Multi-service[1] automotive & industrial | Multi-service industrial | Multi-service automotive & industrial | Multi-service automotive & industrial | Multi-service automotive & industrial | High temp. (frequent relube) |

[1] Multiservice includes rolling contact bearings, plain bearings, and others.
Reference: NLGI Lubricating Grease Guide, 4th ed.

**Table 5-3**
**ASTM Tests for Grease Characteristics**

| Grease Characteristic | ASTM Test Method | Description |
|---|---|---|
| Apparent viscosity / pumpability | D 1092 - Measuring Apparent Viscosity of Lubricating Greases | Apparent viscosities at 16 shear rates are determined by measuring the hydraulic pressure on a floating piston which forces grease through a capillary tube. Eight different capillary tubes and a 2-speed hydraulic gear pump are used. |
| Consistency and shear stability | D 217 - Cone Penetration of Lubricating Grease<br>D 1403 - Cone Penetration of Lubricating Grease Using One-Quarter and One-Half Scale Cone Equipment | Depth, in tenths of a millimeter, a 150-g (0.33-lb) cone penetrates the surface of worked and unworked grease at 25 °C (77 °F) in 5 seconds. D 1403 is used when only a small amount of grease is available. |
| | D 1831- Roll Stability of Lubricating Grease | A 5- kg (11-lb) roller and 50 g (0.11 lb) of grease are put into a 165-rpm revolving chamber for 2 hours at room temperature. The difference in penetrations measured before and after rolling is an indicator of shear stability. |
| Corrosion and rust resistance | D 1743 - Determining Corrosion Preventive Properties of Lubricating Greases | A grease-packed bearing is spun for 1-minute at 1750 rpm. Excess grease is thrown off and a thin layer remains on bearing surfaces. The bearing is exposed to water and stored for 48 hours at 52 °C (125 °F) and 100% humidity. It is then cleaned and examined for corrosion. |
| | D 4048 - Detection of Copper Corrosion from Lubricating Grease | A copper strip is immersed in grease inside a covered jar and heated in an oven or liquid bath for a specified time. The strip is removed, washed, and compared and classified using the ASTM Copper Strip Corrosion Standards. |
| Dropping point | D 566 - Dropping Point of Lubricating Grease<br>D 2265 - Dropping Point of Lubricating Grease over Wide-Temperature Range | Grease and a thermometer are placed in a cup inside a test tube and heated until a drop falls through the cup. That temperature is the dropping point. The test tube assembly is heated in an oil bath for D 566 and inside an aluminum block oven for D 2265. |
| Evaporation | D 972 - Evaporation Loss of Lubricating Greases and Oils<br>D 2595 - Evaporation Loss of Lubricating Greases over Wide-Temperature Range | Two liters per minute of heated air is passed over grease inside a chamber for 22 hours. Temperature range is 100 - 150 °C (212 - 302 °F) for D 972 and 93 - 315 °C (200 - 599 °F) for D 2595. Evaporation is calculated from grease weight loss, in percent. |
| Heat resistance / Consistency | D 3232 - Measurement of Consistency of Lubricating Greases at High Temperatures | Can also indicate flow at high temperatures. Grease in a cylindrical opening in an aluminum block is heated at a rate of 5 °C (10 °F)/min while a trident probe turns at 20 rpm in the grease. A Brookfield viscometer attached to the probe measures torque at temperature increments. From this, apparent viscosities are determined at different temperatures. |
| Leakage | D 1263 - Leakage Tendencies of Automotive Wheel Bearing Greases | A seal-less, grease-packed wheel bearing encircled by a collector ring is spun for 6 hours at 660 rpm at 105 °C (221 °F). Grease thrown off into the ring is weighed and leakage is determined. |

(Continued)

**Table 5-3 (Concluded)**

| Grease Characteristic | ASTM Test Method | Description |
|---|---|---|
| Oxidation Stability | D 942 - Oxidation Stability of Lubricating Greases by the Oxygen Bomb Method | Indicates oxidation from storage when grease charged with oxygen at 758 kPa (110 psi) is sealed in a "bomb" at 99 °C (210 °F). As grease oxidizes, it absorbs oxygen. Pressure is recorded at time intervals and degree of oxidation is determined by the corresponding drop in oxygen pressure. |
| | D 3336 - Performance Characteristics of Lubricating Greases in Ball-Bearings at Elevated Temperatures | There are no ASTM tests for oxidation in service, but this test relates oxidation stability to failure rate of bearings at desired elevated temperatures. |
| Water Resistance | D 1264 - Determining the Water Washout Characteristics of Lubricating Greases | Measures grease washout of a bearing turning at 600 rpm with water flowing at 5 mL/sec for 1 hour at 38 °C (100 °F) and 79 °C (175 °F). |
| | D 4049 - Determining the Resistance of Lubricating Grease to Water Spray | Measures removal of grease 0.8 mm (1/32 in) thick on a plate by water through a nozzle for 5 minutes at 38 °C (100 °F) and 275 kPa (40 psi). |
| Wear Resistance | D 2266 - Wear Preventive Characteristics of Lubricating Grease (Four-Ball Method) | A rotating steel ball is pressed against three, grease-coated, stationary steel balls for 60 minutes. Scar diameters on the three stationary balls are relative measures of wear. Balls are 12.7 mm (0.5 inch). Applied load is 40 kgf (392 N) rotating at 1200 rpm. Temperature is 75 °C (167 °F). |
| | D 2596 - Measurement of Extreme-Pressure Properties of Lubricating Grease (Four-Ball Method) | Same steel ball setup as above, but load is incrementally increased every 10 seconds until seizure occurs. This is the weld point. Load wear index is then calculated. Maximum load is 800 kgf (7845 N) rotating at 1770 rpm. Temperature is 27 °C (80 °F). |
| | D 2509 - Measurement of Extreme Pressure Properties of Lubricating Grease (Timken Method) | The outer edge of a continuously grease-fed bearing race rotates at 800 rpm and rubs against a fixed steel block for 10 minutes. Successive runs are made with increasingly higher loads and any surface scoring is reported. Grease is applied at 25 °C (77 °F). The Timken OK load is the highest load in which no scoring occurs. |

# Chapter 6
# Nonfluid Lubrication

## 6-1. Solid Lubrication

*a. Definition of solid lubricant.* A solid lubricant is a material used as powder or thin film to provide protection from damage during relative movement and to reduce friction and wear. Other terms commonly used for solid lubrication include dry lubrication, dry-film lubrication, and solid-film lubrication. Although these terms imply that solid lubrication takes place under dry conditions, fluids are frequently used as a medium or as a lubricant with solid additives. Perhaps the most commonly used solid lubricants are the inorganic compounds graphite and molybdenum disulfide ($MoS_2$) and the polymer material polytetrafluoroethylene (PTFE).

*b. Characteristics.* The properties important in determining the suitability of a material for use as a solid lubricant are discussed below.

(1) Crystal structure. Solid lubricants such as graphite and $MoS_2$ possess a lamellar crystal structure with an inherently low shear strength. Although the lamellar structure is very favorable for materials such as lubricants, nonlamellar materials also provide satisfactory lubrication.

(2) Thermal stability. Thermal stability is very important since one of the most significant uses for solid lubricants is in high temperature applications not tolerated by other lubricants. Good thermal stability ensures that the solid lubricant will not undergo undesirable phase or structural changes at high or low temperature extremes.

(3) Oxidation stability. The lubricant should not undergo undesirable oxidative changes when used within the applicable temperature range.

(4) Volatility. The lubricant should have a low vapor pressure for the expected application at extreme temperatures and in low-pressure conditions.

(5) Chemical reactivity. The lubricant should form a strong, adherent film on the base material.

(6) Mobility. The life of solid films can only be maintained if the film remains intact. Mobility of adsorbates on the surfaces promotes self-healing and prolongs the endurance of films.

(7) Melting point. If the melting point is exceeded, the atomic bonds that maintain the molecular structure are destroyed, rendering the lubricant ineffective.

(8) Hardness. Some materials with suitable characteristics, such as those already noted, have failed as solid lubricants because of excessive hardness. A maximum hardness of 5 on the Mohs' scale appears to be the practical limit for solid lubricants.

(9) Electrical conductivity. Certain applications, such as sliding electric contacts, require high electrical conductivity while other applications, such as insulators making rubbing contact, require low conductivity.

*c. Applications.* Generally, solid lubricants are used in applications not tolerated by more conventional lubricants. The most common conditions requiring use of solid lubricants are discussed below. Specific Corps of Engineers and Bureau of Reclamation facilities where solid lubricant bearings have been used are discussed in paragraph 6-3 of this chapter.

(1) Extreme temperature and pressure conditions. These are defined as high-temperature applications up to 1926 °C ( 3500 °F), where other lubricants are prone to degradation or decomposition; extremely low temperatures, down to -212 °C (-350 °F), where lubricants may solidify or congeal; and high-to-full-vacuum applications, such as space, where lubricants may volatilize.

(2) As additives. Graphite, $MoS_2$, and zinc oxide are frequently added to fluids and greases. Surface conversion coatings are often used to supplement other lubricants.

(3) Intermittent loading conditions. When equipment is stored or is idle for prolonged periods, solids provide permanent, noncorrosive lubrication.

(4) Inaccessible locations. Where access for servicing is especially difficult, solid lubricants offer a distinct advantage, provided the lubricant is satisfactory for the intended loads and speeds.

(5) High dust and lint areas. Solids are also useful in areas where fluids may tend to pick up dust and lint with liquid lubricants; these contaminants more readily form a grinding paste, causing damage to equipment.

(6) Contamination. Because of their solid consistency, solids may be used in applications where the lubricant must not migrate to other locations and cause contamination of other equipment, parts, or products.

(7) Environmental. Solid lubricants are effective in applications where the lubricated equipment is immersed in water that may be polluted by other lubricants, such as oils and greases.

*d. Advantages of solid lubricants.*

(1) More effective than fluid lubricants at high loads and speeds.

(2) High resistance to deterioration in storage.

(3) Highly stable in extreme temperature, pressure, radiation, and reactive environments.

(4) Permit equipment to be lighter and simpler because lubrication distribution systems and seals are not required.

*e. Disadvantages of solid lubricants*.

(1) Poor self-healing properties. A broken solid film tends to shorten the useful life of the lubricant.

(2) Poor heat dissipation. This condition is especially true with polymers due to their low thermal conductivities.

(3) Higher coefficient of friction and wear than hydrodynamically lubricated bearings.

(4) Color associated with solids may be undesirable.

*f. Types of solid lubricants*.

(1) Lamellar solids. The most common materials are graphite and molybdenum disulfide.

(a) Graphite. Graphite has a low friction coefficient and very high thermal stability (2000 °C [3632 °F] and above). However, practical application is limited to a range of 500 to 600 °C (932 to 1112 °F) due to oxidation. Furthermore, because graphite relies on adsorbed moisture or vapors to achieve low friction, use may be further limited. At temperatures as low as 100 °C (212 °F), the amount of water vapor adsorbed may be significantly reduced to the point that low friction cannot be maintained. In some instances sufficient vapors may be extracted from contaminants in the surrounding environment or may be deliberately introduced to maintain low friction. When necessary, additives composed of inorganic compounds may be added to enable use at temperatures to 550 °C ( 1022 °F). Another concern is that graphite promotes electrolysis. Graphite has a very noble potential of + 0.25V, which can lead to severe galvanic corrosion of copper alloys and stainless steels in saline waters.

(b) Molybdenum disulfide ($MoS_2$). Like graphite, $MoS_2$ has a low friction coefficient, but, unlike graphite, it does not rely on adsorbed vapors or moisture. In fact, adsorbed vapors may actually result in a slight, but insignificant, increase in friction. $MoS_2$ also has greater load-carrying capacity and its manufacturing quality is better controlled. Thermal stability in nonoxidizing environments is acceptable to 1100 °C (2012 °F), but in air it may be reduced to a range of 350 to 400 °C (662 to 752 °F).

(2) Soft metal films. Many soft metals such as lead, gold, silver, copper, and zinc, possess low shear strengths and can be used as lubricants by depositing them as thin films on hard substrates. Deposition methods include electroplating, evaporating, sputtering, and ion plating. These films are most useful for high temperature applications up to 1000 °C (1832 °F) and roller bearing applications where sliding is minimal.

(3) Surface treatments. Surface treatments commonly used as alternatives to surface film depositions include thermal diffusion, ion implantation, and chemical conversion coatings.

(a) Thermal diffusion. This is a process that introduces foreign atoms into a surface for various purposes such as increasing wear-resistance by increasing surface hardness; producing low shear strength to inhibit scuffing or seizure; and in combination with these to enhance corrosion-resistance.

(b) Ion implantation. This is a recently developed method that bombards a surface with ions to increase hardness, which improves wear- and fatigue-resistance.

(c) Chemical conversion coatings. Frequently, solid lubricants will not adhere to the protected metal surface. A conversion coating is a porous nonlubricating film applied to the base metal to enable adherence of the solid lubricant. The conversion coating by itself is not a suitable lubricant.

(4) Polymers. Polymers are used as thin films, as self-lubricating materials, and as binders for lamellar solids. Films are produced by a process combining spraying and sintering. Alternatively, a coating can be produced by bonding the polymer with a resin. Sputtering can also be used to produce films. The most common polymer used for solid lubrication is PTFE The main advantages of PTFE are low friction coefficient, wide application range of -200 to 250 °C (-328 to 418 °F), and lack of chemical

reactivity. Disadvantages include lower load-carrying capacity and endurance limits than other alternatives. Low thermal conductivity limits use to low speed sliding applications where $MoS_2$ is not satisfactory. Common applications include antistick coatings and self-lubricating composites.

*g. Methods of applying solids.* There are several methods for applying solid lubricants.

(1) Powdered solids. The oldest and simplest methods of applying solid lubricants are noted below.

(a) Burnishing. Burnishing is a rubbing process used to apply a thin film of dry powdered solid lubricant such as graphite, $MoS_2$, etc., to a metal surface. This process produces a highly polished surface that is effective where lubrication requirements and wear-life are not stringent, where clearance requirements must be maintained, and where wear debris from the lubricant must be minimized. Surface roughness of the metal substrate and particle size of the powder are critical to ensure good application.

(b) Hand rubbing. Hand rubbing is a procedure for loosely applying a thin coating of solid lubricant.

(c) Dusting. Powder is applied without any attempt to evenly spread the lubricant. This method results in a loose and uneven application that is generally unsatisfactory.

(d) Tumbling. Parts to be lubricated are tumbled in a powdered lubricant. Although adhesion is not very good, the method is satisfactory for noncritical parts such as small threaded fasteners and rivets.

(e) Dispersions. Dispersions are mixtures of solid lubricant in grease or fluid lubricants. The most common solids used are graphite, $MoS_2$ , PTFE, and Teflon®. The grease or fluid provides normal lubrication while the solid lubricant increases lubricity and provides extreme pressure protection. Addition of $MoS_2$ to lubricating oils can increase load-carrying capacity, reduce wear, and increase life in roller bearings, and has also been found to reduce wear and friction in automotive applications. However, caution must be exercised when using these solids with greases and lubricating fluids. Grease and oil may prevent good adhesion of the solid to the protected surface. Detergent additives in some oils can also inhibit the wear-reducing ability of $MoS_2$ and graphite, and some antiwear additives may actually increase wear. Solid lubricants can also affect the oxidation stability of oils and greases. Consequently, the concentration of oxidation inhibitors required must be carefully examined and controlled. Aerosol sprays are frequently used to apply solid lubricant in a volatile carrier or in an air-drying organic resin. However, this method should be limited to short-term uses or to light- or moderate-duty applications where thick films are not necessary. Specifications for solid lubricant dispersions are not included in this manual. Readers interested in specifications for solid dispersions are referred to Appendix A. Before using dispersions, users should become familiar with their applications and should obtain information in addition to that provided in this manual. The information should be based on real-world experiences with similar or comparable applications.

(2) Bonded coatings. Bonded coatings provide greater film thickness and increased wear life and are the most reliable and durable method for applying solid lubricants. Under carefully controlled conditions, coatings consisting of a solid lubricant and binding resin agent are applied to the material to be protected by spraying, dipping, or brushing. Air-cured coatings are generally limited to operating temperatures below 260 °C ( 500 °F) while heat-cured coatings are generally used to 370 °C (698 °F). The most commonly used lubricants are graphite, $MoS_2$ , and PTFE. Binders include organic resins, ceramics, and metal salts. Organic resins are usually stable below 300°C (572 °F). Inorganic binders such as metal salts or ceramics permit bonded films to be used in temperatures above 650 °C (1202 °F). The choice of binder is also influenced by mechanical properties, environmental compatibility, and facility of processing.

Air-cured coatings applied by aerosol are used for moderate-duty applications; however, thermosetting resin binders requiring heat-cure generally provide longer wear-life. The most common method of applying bonded coatings is from dispersions in a volatile solvent by spraying, brushing, or dipping. Spraying provides the most consistent cover, but dipping is frequently used because it is less expensive. Surface preparation is very important to remove contaminants and to provide good surface topography for lubricant adhesion. Other pretreatments used as alternatives or in conjunction with roughness include phosphating for steels and analogous chemical conversion treatments for other metals. Specifications for solid film bonded coating are not included in this manual. Readers interested in specifications for solid film bonded coatings are referred to the references in Appendix A.

(3) Self-lubricating composites. The primary applications for self-lubricating composites include dry bearings, gears, seals, sliding electrical contacts, and retainers in roller bearings. Composites may be polymer, metal-solid, carbon and graphite, and ceramic and cermets.

(a) Polymer. The low thermal conductivity of polymers inhibits heat dissipation, which causes premature failure due to melting. This condition is exacerbated if the counterface material has the same or similar thermal conductivity. Two polymers in sliding contact will normally operate at significantly reduced speeds than a polymer against a metal surface. The wear rate of polymer composites is highly dependent upon the surface roughness of the metal counterfaces. In the initial operating stages, wear is significant but can be reduced by providing smooth counterfaces. As the run-in period is completed, the wear rate is reduced due to polymer film transfer or by polishing action between the sliding surfaces. Environmental factors also influence wear rate. Increased relative humidity inhibits transfer film formation in polymer composites such as PTFE, which rely on transfer film formation on counterfaces. The presence of hydrocarbon lubricants may also produce similar effects. Composites such as nylons and acetals, which do not rely on transfer film formation, experience reduced wear in the presence of small amounts of hydrocarbon lubricants.

(b) Metal-solid. Composites containing lamellar solids rely on film transfer to achieve low friction. The significant amount of solids required to improve film transfer produces a weak composite with reduced wear life. Addition of nonlamellar solids to these composites can increase strength and reduce wear. Various manufacturing techniques are used in the production of metal-solid composites. These include powder metallurgy, infiltration of porous metals, plasma spraying, and electrochemical codeposition. Another fabrication technique requires drilling holes in machine parts and packing the holes with solid lubricants. One of the most common applications for these composites is self-lubricating roller bearing retainers used in vacuum or high temperatures up to 400 °C (752 °F). Another application is in fail-safe operations, where the bearing must continue to operate for a limited time following failure of the normal lubrication system.

(c) Carbon and graphites. The primary limitations of bulk carbon are low tensile strength and lack of ductility. However, their high thermal and oxidation stabilities at temperatures of 500 to 600 °C (932 to 1112 °F) (higher with additives) enable use at high temperatures and high sliding speeds. For graphitic carbons in dry conditions, the wear rate increases with temperature. This condition is exacerbated when adsorbed moisture inhibits transfer film formation. Furthermore, dusting may also cause failure at high temperatures and sliding speeds. However, additives are available to inhibit dusting.

(d) Ceramics and cermets. Ceramics and cermets can be used in applications where low wear rate is more critical than low friction. These composites can be used at temperatures up to 1000 °C (1832 °F). Cermets have a distinct advantage over ceramics in terms of toughness and ductility. However, the metal content tends to reduce the maximum temperature limit. Solid lubricant use with bulk ceramics is limited to insertion in machined holes or recesses.

## 6-2. Self-Lubricating Bearings

*a. Self-lubricating bearing research.* The Corps of Engineers Hydroelectric Design Center (HDC) has developed a standardized test specification for evaluating self-lubricating bearings for wicket gate applications in hydroelectric turbines. Although the test criteria, procedures, and equipment were established based on the requirements from hydropower applications, there is potential for other applications such as bushings for miter and tainter gates. The tests are used as benchmarks to measure and compare the performance of competing products. During the tests, bearings are subjected to accelerated wear under the worst operating conditions possible. Testing is divided into three sections: initial set and creep, accelerated wear, and edge loading.

(1) Initial set and creep. In this test the bushings and sleeves are subjected to static loads to 229.6 bar (3300 lb/in$^2$). The shaft is rotated at periodic intervals, and the shaft displacement wear relative to the test block is continuously monitored.

(2) Accelerated wear test. In this test a radial load of 227.6 bar (3300 lb/in$^2$) is superimposed by a dynamic load of 68.9 bar (1000 lb/in$^2$) at 2 Hz. The shaft is rotated according to established criteria, and temperatures, static load, dynamic load to rotate (friction), stroke displacement, and wear are recorded.

(3) Edge load test. This test is similar to the accelerated wear test except that the sleeve is machined to simulate shaft misalignment.

*b. Application of self-lubricated bearings.* Table 6-1 identifies Corps facilities using self-lubricating bearings and their specific applications.

**Table 6-1**
**Corps of Engineers and Bureau of Reclamation Facilities Using Self-lubricating Bearings**

| Location | Facility | Application |
|---|---|---|
| **Corps Facilities** | | |
| Portland, OR | Little Goose | Wicket gate, linkage bushing, operating rings |
| Portland, OR | Lower Monumental | Wicket gate, linkage bushing, operating rings |
| Portland, OR | Bonneville Lock | Swing bridge pivot bearing |
| Portland, OR | Bonneville Lock | Mooring rollers |
| Portland, OR | Bonneville Lock | Miter gate bushings |
| St. Paul, MN | Lock No. 10, MS River | Gate chain bushings |
| Louisville, KY | Cannelton Lock | Lock gate drive bushings |
| Little Rock, AK | Dardanelles Dam | Wicket gate, linkage bushing, operating rings |
| Nashville, TN | Kentucky Lock Project | Mooring rollers |
| Walla Walla, WA | McNary Lock and Dam | Fish screen sphericals |
| Rock Island, IL | Rock Island Dam | Wicket gate, linkage bushing, operating rings |
| **Bureau of Reclamation Facilities** | | |
| Grand Coulee, WA | Grand Coulee | Linkage bearing evaluation, sole plate keys |
| Denver, CO | NA | Bearing evaluation |

## 6-3. Self-Lubricating Bearings for Olmsted Wicket Gates Prototype Tests

*a. Introduction.* Applicable to this manual is a discussion of the self-lubricating bearings used in the Olmsted Locks and Dams prototype hydraulically operated wicket gates, including lessons learned from the testing of the bearings and monitoring of the hydraulic fluid used in operating the wickets. The discussion is assembled from a report entitled *"Olmsted Prototype Hydraulically Operated Navigable Pass Wicket Dam, Final Report August 1997,"* prepared by the Corps of Engineers Louisville District. The report details project development, design, construction, testing, material evaluation, and lessons learned.

*b. General.*

(1) The Olmsted project has undergone numerous conceptual changes throughout its development. One approved design included 220 remotely operated, hydraulically actuated wicket gates. Each wicket was to be 2.74 m (9 ft, 2 in.) wide and 7.77 m (25 ft, 6 in.) long with a design lift of 6.7 m (22 ft). A full-scale model (prototype) was constructed with five wickets to test the design, materials, and components developed by Louisville District. New and unique materials and components were developed and tested, such as self-lubricating bearings and biodegradable hydraulic fluid.

(2) Self-lubricating bearings by five different manufacturers were tested and evaluated. The manufacturers are Merriman, Thordon, Lubron, Kamatics, and Rowend. Each wicket was installed with a complete set of bearings from one manufacturer. The size of the bearings and corresponding pins were determined based on load data collected on a 1:25 model of the wicket at the U.S. Army Engineer Waterways Experiment Station Vicksburg, MS. The contact area/diameter and length of bearings were designed to have a maximum distributed load of 552.7 bar (8000 psi). No seals were installed on any of the bearings. The manufacturers were given the option to use whatever lubrication they chose for the conditions specified. The conditions were that the bearings were to be in the Ohio River operating at slow speeds under a minimum of 6.7 m (22 ft) of head. The bearings were installed dry and each was operated approximately 50 times during the shake-down test before the site was flooded. Each set of bearings, except Wicket #1, received 400 cycles of operation. The 400 cycles corresponded to the number of operations the wickets would have been subjected to over a 25-year service life at the Olmsted facility. Because of a wicket malfunction, Wicket #1 received only 255 cycles, but was exposed to the same conditions throughout the test. The bearings were subjected to extended periods in which the wickets were left in a fixed position and the river current was allowed to flow past. Each hinge bearing on each of the wickets was subjected to the same loads and experienced the same conditions.

*c. Test summary.*

(1) Wicket #1, Lubron. The manufacturer of the bearings installed on Wicket #1 was Lubron Bearing Systems, Huntington Beach, CA. Lubron used a bearing manufactured with a manganese bronze housing with an inner lubricating coating of PTFE, trade name AQ100 ™. The material is a combination of PTFE, fluorocarbons and epoxy resin, hardeners, and metallic and fibrous fillers.

- Hinge sleeve bushings and pins. Evaluation of the hinge sleeve bushings after operation indicated no wear of the lubricated surface. The lubricating material inside the bushing was in good condition. The hinge pins were in good condition with no sign of wear.

- Prop spherical bearing. The spherical bearing in the prop was designed with a stainless steel ball mounted in a manganese bronze race. The race was coated with the AQ100 ™ lubricant material.

After testing, the ball and housing were in good condition with no indication of wear. The lubricant material was well coated on the ball and not worn off the race.

(2) Wicket #2, Kamatics. The manufacturer of the bearings installed on Wicket #2 was Kamatics Corporation (Kaman), Bloomfield, CT. Kamatics used a bearing manufactured with a fiberglass/epoxy housing incorporating an inner lubricating liner (Karon V™) of PTFE. Each of the bearings Kamatics provided were designed for swell caused by the inherent absorption of water into the fiberglass bushing housing.

- Hinge sleeve bushings and pins. Evaluation of the hinge sleeve bushings after operation indicated that the lubricating liner (Karon V™) material was ground and flaked off both the left and right side sleeve bushings. Kamatics sent a letter to the Corps explaining that the company believed contamination entering the bushing through unnecessarily large clearances was the reason the bushings failed. The hinge pins were in good condition with no sign of wear.

- Prop spherical bearing. The spherical bearing on the prop was designed with a stainless steel ball mounted in a stainless steel race. Observation of the prop after testing revealed the bearing applied side loads on the cover plate caused bolts to shear off. Wear marks were evident on the stainless steel ball where contact had been made between the ball and the stainless steel race. The Karon V™ lubricating liner material was removed along the contact area of the race. Wear marks were evident on the race where the ball and race had been rubbing steel-on-steel. Kamatics sent a letter to the Corps explaining that improper location of the split of the outer race resulted in nonuniform contact between ball and liner which caused chipping of the liner. The Kamatics letter stated that with a properly located split line for the outer race, the Karon V™ lined spherical bearing would function without difficulty.

- Direct-connect cylinder to gate connection pin. Wicket #2 was a direct-connected cylinder. Therefore, the connection between the piston rod and the gate used two sleeve bushings. Evaluation of the bushings after operation indicated the lubricating liner (Karon V™) material was worn away from the nonload side of the bushing. Material from the Kamatics lubricant used in the bushing was present on the stainless steel pin. No scoring was present on the pin.

- Cylinder trunnion bushings. Evaluation of the bushings after operation indicated the lubricating liner (Karon V™) material was in good condition, with minor wear on the load-bearing surface of the bushing. Lubricant material from the Kamatics bushings was deposited on the stainless steel pins and from the thrust surface of the bushing on the side of the trunnion. The area where contact was made between the cylinder trunnion pins and the bushings could be seen, but the pins were not damaged.

(3) Wicket #3, Merriman. The manufacturer of the bearings installed on Wicket #3 was Merriman, Hingham, MA. Merriman's product, Lubrite™, used a bushing machined from manganese bronze. A series of $6.35 \times 10^{-3}$ m (1/4-in.) holes were drilled in a designated pattern in the housings and filled with Merriman G12 lubricant. The inner lubricating liner used in the housings was G12 lubricant. G12 is an epoxy-based graphite-free lubricant.

- Hinge sleeve bushings and pins. Evaluation of the bushings after operation indicated the final inner surface coating layer of Gl2 was removed and the G12 plugs were exposed. On the inside of the left bushing, a couple of the plugs had begun to wear or wash out. Approximately 250 microns (10 mils) of material was removed from the plugs and the manganese bronze had begun to show wear in a 13-$cm^2$ (2-$in.^2$) area of the bushing. The pins were in good condition with no sign of wear. There was little to no lubricant material present on the pins.

- Prop spherical bearing. The spherical ball of the bearing was machined from manganese bronze. Lubrite™ lubricant G12 was added to the ball by means of a series of machined rings and holes and by inserting the lubricant into the voids. A 175-micron (7-mil) layer of G12 lubricant was applied over the face of the ball for break-in purposes. The surface of the ball was rough with pits where the G12 lubricant had worn or washed out. Observation of the ball indicated galvanic corrosive action between the lubricant material and stainless steel could have caused the pitting of the material. The noncontact surface of the ball still had signs of the initial break-in surface coat of G12 lubricant on it. The race was in good condition.

- Cylinder trunnion bushing. Evaluation of the bushings after operation indicated the 200-micron (8-mil) thick inner break-in surface layer of G12 was removed on the bottom, along the load area of the bushings. The stainless steel trunnion pins had G12 lubricant deposited on the pins. The load areas where the bushing contacted the pins showed no signs of wear. The pins were in good condition with no signs of wear.

(4) Wicket #4, Thordon. The manufacturer of the bearings installed on Wicket #4 was Thordon Bearings, Inc., of Burlington, Ontario, Canada. Thordon used a bushing machined from bronze. The inner lubricating liner used in the bushing was Thordon SXL TRAXL™. SXL is a polyurethane-based material with multiple proprietary additives that the manufacturer will not disclose.

- Hinge sleeve bushings and pins. Evaluation of the bushings after operation indicated that the final inner surface coating was in good condition, with minor deposits of black debris impregnated into the material. The stainless steel hinge pins were in good condition with no signs of wear.

- Cylinder trunnion bushing. Evaluation of the bushings after operation indicated that the loads caused the lubricating material to compress approximately 125 to 250 microns (5 to10 mils).

The manufacturer of the bushings provided the Corps of Engineers an overview of their interpretation of the cause of dark areas observed in the bushing. They stated the discoloration most probably was iron oxide from mild steel that was trapped between the bottom of the shaft and the bearing, subsequently pressed into the bearing surface. The stainless steel trunnion pins showed no signs of wear and were in good condition.

(5) Wicket #5, Rowend. The manufacturer of the bearings installed on Wicket #5 was Rowend, Liberty Center, OH. Rowend used a bushing machined from manganese bronze. A series of 6.3-mm (1/4-in.) holes were drilled in the bushing and filled with R-8 lubricant in a designated pattern around the bushing. The inner lubricating material used was R-8™, a proprietary material.

- Hinge sleeve bushings and pins. Evaluation of the bushings after operation indicated that galvanic corrosion occurred between the manganese bronze bushing and the stainless steel pin. The noncontact surface of the left hinge bushings had pits. The thrust surface of the left hinge bearing also had pitting and the R-8™ lubricant was beginning to wash out of the plug area. The right hinge bushing side thrust surface experienced the majority of the side loading and was grooved and worn from the rotation. The R-8 lubricant washed out of the plug area as much as 0.79 mm

(1/32 in.) on the thrust surface. Pitting was not present on the load side of the right hinge bushing. There were no indications of galvanic action found on the stainless steel hinge pins.

- Direct-connect cylinder to gate connection pin. Wicket #5 was a direct-connected cylinder; therefore, the connection between the piston rod and the gate used two sleeve bushings. Evaluation of the bushings after operation indicated the lubricating material fully coated the bushing surface as required. There were minor traces of galvanic corrosion in the manganese bronze material. Overall, the bushings were in good condition. Lubricant material used in the bushing was on the pin. No scoring was present on the pin.

- Cylinder trunnion bushings. Evaluation of the bushings indicated that foreign material had gotten into the bushing and damaged the manganese housing. Some grooves were in the base metal. The R-8™ material was distributed around the bushing, as is normal.

*d. Lessons learned. Lessons learned in this study were.*

(1) Bearing materials. Of the five self-lubricating bearing materials tested, each performed differently. Four of the manufacturers made the housings of the bearings from manganese bronze into which a specific lubricant was applied. The fifth manufacturer, Kamatics, used a fiberglass housing onto which a lubricant was applied. Rowend used lubricant plugs with no break-in surface, and pitting occurred in the manganese bronze. It is believed that galvanic action between the material and the stainless steel pin caused the pitting. Merriman and Lubron used a break-in layer of lubricant which seemed to protect the bronze from the galvanic action. Thordon used a material that was laminated to the bronze and absorbed fine debris into the material. Kamatics used a PTFE-based lubricant that delaminated and flaked off the housing of the bearings. Based on the testing conducted, the Lousville District rated the products in the following order: Lubron and Thordon (equal) > Merriman > Rowend > Kamatics. The reason for the low rating of the Kamatics bearing was the observed damage.

(2) Biodegradable hydraulic fluid. The fluid performed well once the proper size filters were determined. Originally a 10-micron- ($3.28 \times 10^{-5}$ ft) filter was installed in the return line from the cylinders and on the supply line. In October and November, when the site was not in use, the cylinders were exposed to cold weather. The cold fluid would not pass through the 10-micron filter fast enough, activating an alarm in the control system. To correct the problem, the 10-micron filter in the return line was replaced with a 20-micron ($6.56 \times 10^{-5}$ ft) filter, and the heater inside the reservoir was turned on. These actions solved the problem.

(3) Hydraulic fluid filters. It is important to position the filters on the reservoir in a location where they are easily accessible for routine maintenance.

(4) Cleaning of hydraulic system. Initial cleaning of the system was performed by the mechanical contractor. After operating the hydraulic system for a period of time, metal shavings were discovered in the return filter. It was determined that the shavings came from the manifolds. It was believed that the shock to the piping system from engaging of the alignment cylinder solenoids dislodged the shavings from the manifold. Each manifold was removed and recleaned, and the problem no longer occurred.

# Chapter 7
# Lubricant Additives

## 7-1. General

Oil quality is established by the refining processes and additives are most effective if the oil is well refined. Although the overall performance of an oil can be improved by introducing additives, a poor quality oil cannot be converted into a premium quality oil by introducing additives. Furthermore, there are limits to the amount of additives that can be introduced to improve performance. Beyond these limits, the benefits are minimal or may provide no gains in performance. They also may increase the cost of lubricants and, in some cases, may even be harmful. An additive may function in any of the following three ways:

- Protecting lubricated surfaces. Extreme pressure (EP) additives and rust inhibitors are included in this category. These additives coat the lubricated surfaces and prevent wear or rust.

- Improving performance. Viscosity index improvers and antifoaming agents are examples. They make the oil perform in a desired manner for specific applications.

- Protecting the lubricant itself. Antioxidants reduce the tendency of oil to oxidize and form sludge and acids.

The most common additives are listed in Table 7-1, and they are discussed individually in the following paragraphs.

## 7-2. Surface Additives

The primary purpose of surface additives is to protect lubricated surfaces. Extreme pressure additives, rust and corrosion inhibitors, tackiness agents, antiwear additives, and oiliness additives are included in this category. These additives coat the lubricated surfaces to prevent wear or rust.

*a. Rust inhibitors.* Rust inhibitors are added to most industrial lubricants to minimize rusting of metal parts, especially during shipment, storage, and equipment shutdown. Although oil and water do not mix very well, water will emulsify--especially if the oil contains polar compounds that may develop as the oil ages. In some instances the water will remain either suspended by agitation or will rest beneath the oil on machine surfaces when agitation is absent. Rust inhibitors form a surface film that prevents water from making contact with metal parts. This is accomplished by making the oil adhere better or by emulsifying the water if it is in a low concentration.

*b. Corrosion inhibitors.* Corrosion inhibitors suppress oxidation and prevent formation of acids. These inhibitors form a protective film on metal surfaces and are used primarily in internal combustion engines to protect alloy bearings and other metals from corrosion.

*c. Extreme pressure (EP) agents.* Extreme pressure agents react with the metal surfaces to form compounds that have a lower shear strength than the metal. The reaction is initiated by increased temperature caused by pressure between asperities on wearing surfaces. The reaction creates a protective coating at the specific points where protection is required. This coating reduces friction, wear, scoring,

**Table 7-1**
**Types of Additives**

| Main Type | Function and Subtypes |
|---|---|
| Acid neutralizers | Neutralize contaminating strong acids formed, e.g., by combustion of high sulfur fuels or by decomposition of active EP additives. |
| Antifoam | Reduce surface foam. |
| Antioxidants | Reduce oxidation. Various types are: oxidation inhibitors, retarders; anticatalyst metal deactivators, metal passivators. |
| Antirust | Reduce rusting of ferrous surfaces swept by oil. |
| Antiwear agents | Reduce wear and prevent scuffing of rubbing surfaces under steady load operating conditions |
| Corrosion inhibitors | Type (a) reduces corrosion of lead; type (b) reduces corrosion of cuprous metals. |
| Detergents | Reduce or prevent deposits formed at high temperatures, e.g., in internal combustion engines. |
| Dispersant | Prevent deposition of sludge by dispersing a finely divided suspension of the insoluble material formed at low temperature. |
| Emulsifiers | Form emulsions; either water-in-oil or oil-in-water, according to type. |
| Extreme pressure | Prevent scuffing of rubbing surfaces under severe operating conditions, e.g., heavy shock load, by formation of a mainly inorganic surface film. |
| Oiliness enhancers | Reduce friction under boundary lubrication conditions; increase load-carrying capacity where limited by temperature rise by formation of mainly organic surface films. |
| Pour- point depressants | Reduce pour point of paraffinic oils. |
| Tackiness agents | Reduce loss of oil by gravity, e.g., from vertical sliding surfaces, or by centrifugal force. |
| Viscosity index improvers | Reduce the decrease in viscosity due to increase of temperature |

Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

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seizure, and galling of wear surfaces. Extreme pressure additives are used in heavy loading or shock loading applications such as turbines, gears, and ball and roller bearings.

*d. Tackiness agents.* In some cases, oils must adhere to surfaces extremely well. Adding polymers composed of long-chain molecules or aluminum soaps of long-chain fatty acids increases the tackiness or adhesiveness of oils.

*e. Antiwear (AW) agents.* Additives that cause an oil to resist wear by coating the metal surfaces are called antiwear agents. Molecules of the antiwear compound are polar and attach (adsorb) themselves to metal surfaces or react mildly with the metal. When boundary lubrication conditions (direct contact between metal asperities) occur, such as in starting and stopping of machinery, these molecules resist removal more than ordinary oil molecules. This reduces friction and wear. However, they are effective only up to about 250 °C (480 °F ).

*f. Detergents and dispersant.* Detergents and dispersant are used primarily in internal combustion engines to keep metal surfaces clean by preventing deposition of oxidation products.

*g. Compounded oil.* A small amount of animal fat or vegetable oil added to a mineral oil will reduce the coefficient of friction without affecting the viscosity. The ability of an oil to provide a lower coefficient of friction at a given viscosity is often called oiliness or lubricity. When fatty oil is added to obtain this quality of oiliness, the lubricant is called a compounded oil. Fatty oil adheres to metal more strongly than mineral oil and provides a protective film. Compounded oils are generally used in worm gears.

## 7-3. Performance-Enhancing Additives

These additives improve the performance of lubricants. Viscosity index improvers, antifoaming agents, emulsifiers, demulsifiers, and pour-point depressants are examples.

*a. Pour-point depressants.* An oil's pour point is the temperature at which the oil ceases to flow under the influence of gravity. In cold weather, oil with a high pour point makes machinery startup difficult or impossible. The stiffness of cold oil is due to paraffin waxes that tend to form crystal structures. Pour-point depressants reduce the size and cohesiveness of the crystal structures, resulting in reduced pour point and increased flow at reduced temperatures.

*b. Viscosity index (VI) improvers.* The viscosity index is an indicator of the change in viscosity as the temperature is changed. The higher the VI, the less the viscosity of an oil changes for a given temperature change. Viscosity index improvers are used to limit the rate of change of viscosity with temperature. These improvers have little effect on oil viscosity at low temperatures. However, when heated, the improvers enable the oil viscosity to increase within the limited range permitted by the type and concentration of the additive. This quality is most apparent in the application of multigrade motor oils.

*c. Emulsifiers.* In most industrial applications it is undesirable to have emulsified water in the oil. However, soluble oils require emulsifiers to promote rapid mixing of oil and water and to form stable emulsions. Soluble oils are used as lubricants and coolants for cutting, grinding, and drilling applications in machine shops.

*d. Demulsifiers.* Demulsifiers promote separation of oil and water in lubricants exposed to water.

## 7-4. Lubricant Protective Additives

Lubricant protective additives are employed to protect the lubricant instead of the equipment. Oxidation inhibitors and foam inhibitors are examples.

*a. Oxidation inhibitors.* Over time, hydrocarbon molecules will react to incorporate oxygen atoms into their structure This reaction produces acids, sludge, and varnish that foul or damage metal parts. At low temperatures and under minimal exposure to oxygen, this process is very slow. At temperatures above 82 °C (180 °F) the oxidation rate is doubled for every -7.78 to -6.67 °C (18 to 20 °F) rise in temperature. Oxidation of hydrocarbons is a very complex chemical process and depends on the nature of the oil. Oxidation inhibitors reduce the quantity of oxygen reacting with oil by forming inactive soluble compounds and by passivating metal-bearing surfaces to retard the oxidation rate. As previously noted, oxidation inhibitors are consumed as the oil ages. Oil condition should be monitored periodically to ensure that essential additives are maintained at safe levels. Oxidation inhibitors are used in most industrial lubricant applications where oil is continuously circulated or contained in a housing.

*b. Foam inhibitors.* In many applications, air or other gases may become entrained in oil. Unless these gases are released, a foam is produced. Foaming can result in insufficient oil delivery to bearings, causing premature failure. Foam may also interfere with proper operation of equipment such as lubricating pumps and may result in false oil level readings. Under some circumstances foam may overflow from oil reservoirs. Foam inhibitors such as silicone polymers or polyacrylates are added to reduce foaming.

## 7-5. Precautions

*a.* Additives alone do not establish oil quality with respect to oxidation resistance, emulsification, pour point, and viscosity index. Lubricant producers do not usually state which compounds are used to enhance the lubricant quality, but only specify the generic function such as antiwear, EP agents, or oxidation inhibitors. Furthermore, producers do not always use the same additive to accomplish the same goal. Consequently, any two brands selected for the same application may not be chemically identical. Users must be aware of these differences and that they may be significant when mixing different products.

(1) Additive depletion. Certain precautions must be observed with regard to lubricant additives. Some additives are consumed during use. As these additives are consumed, lubricant performance for the specific application is reduced and equipment failure may result under continued use. Oil monitoring programs should be implemented to periodically test oils and verify that the essential additives have not been depleted to unacceptable levels.

(2) Product incompatibility. Another important consideration is incompatibility of lubricants. Some oils, such as those used in turbine, hydraulic, motor, and gear applications are naturally acidic. Other oils, such as motor oils and transmission fluids, are alkaline. Acidic and alkaline lubricants are incompatible.

*b.* When servicing an oil lubricating system, the existing and new oils must be compatible. Oils for similar applications but produced by different manufacturers may be incompatible due to the additives used. When incompatible fluids are mixed, the additives may be consumed due to chemical reaction with one another. The resulting oil mixture may be deficient of essential additives and therefore unsuitable for the intended application. When fresh supplies of the oil in use are not available, the lubricant manufacturer should be consulted for recommendation of a compatible oil. Whenever oil is added to a system, the oil and equipment should be checked frequently to ensure that there are no adverse reactions between the new and existing oil. Specific checks should include bearing temperatures and signs of foaming, rust, or corrosion.

# Chapter 8
# Environmentally Acceptable Lubricants

## 8-1. General

Mineral-oil-based lubricating oils, greases, and hydraulic fluids are found in widespread use throughout Corps of Engineers facilities. However, these products are usually toxic and not readily biodegradable. Because of these characteristics, if these materials escape to the environment, the impacts tend to be cumulative and consequently harmful to plant, fish, and wildlife. Due to these potential hazards, the Environmental Protection Agency (EPA) and other government regulators have imposed increasingly stringent regulations on the use, containment, and disposal of these materials. For instance, the EPA requires that no visible oil sheen be evident downstream from facilities located in or close to waterways. Another regulation requires that point discharges into waterways should not exceed 10 parts per million (ppm) of mineral-based oils. Corps facilities such as hydropower plants, flood-control pumping plants, and lock-and-dam sites either are or have the potential to become polluters due to the use of mineral-oil-based materials in these facilities. Grease, hydraulic fluids, and oil leaking from equipment may be carried into the waterway. Because of the difficulty in completely eliminating spills and discharges of these mineral-oil-based materials, and to alleviate concerns about their impact on the environment, a new class of environmentally acceptable (EA) materials is becoming available and starting to find increasing use in sensitive locations. EA lubricants, as contrasted to mineral-oil-based equivalents, are nontoxic and decompose into water and carbon dioxide ($CO_2$). EA fluids are frequently made from renewable resources, which reduces dependency on mineral oils.

## 8-2. Definition of Environmentally Acceptable (EA) Lubricants

*a.* The lubrication industry uses a variety of terms to address “environmental” lubricants. A few of these terms, all preceded by the term “environmentally,” are: “acceptable,” “aware,” “benign,” “friendly,” “harmless,” “safe,” “sensitive,” and “suitable.” Two other commonly used terms are “green fluids” and “food grade” lubricants. The term green fluid is mostly used for lubricants manufactured from vegetable oil. Food grade lubricants are rated by the U.S. Department of Agriculture (USDA) and generally are used in the food industry where incidental food contact may occur. Food grade lubricants may or may not qualify as EA lubricants. Indeed, most food grade lubricants are made of U.S.P. White Mineral Oil which is not toxic but does not meet the biodegradability criteria commonly required of EA lubricants. “Environmentally acceptable” is the most commonly used term and is used by some ASTM committees to address environmental lubricants. This manual uses the term EA.

*b.* At the present time there are no standards for EA lubricants or hydraulic fluids. Manufacturers and end users agree that for a lubricant to be classified as an EA type it should be biodegradable and nontoxic. This means that if a small quantity of EA fluid is inadvertently spilled into the environment, such as a waterway, it should readily break down and not cause harm to fish, plants, or wildlife.

*c.* U.S. standards-writing organizations are currently working to develop nationally recognized tests and procedures for demonstrating compliance with various environmental criteria such as biodegradability and toxicity. The ASTM Committee on Petroleum Products and Lubricants has formed a subcommittee, referred to as the Subcommittee on Environmental Standards for Lubricants, which is tasked with developing test methods for determining aerobic aquatic biodegradation and aquatic toxicity of lubricants. The methodology developed by this subcommittee, ASTM D 5864, for determining the aerobic aquatic biodegradation of the lubricants, was accepted for standard use by the ASTM in December 1995. The subcommittee is also developing a test method for determining the aquatic toxicity of lubricants. With approval of these standards, it is expected that these methods will be used by industry for evaluating and specifying EA fluids.

*d.* However, lacking formally approved U.S. test procedures, suppliers of EA lubricants frequently use established European standards to demonstrate their products' compliance with U.S. criteria. In this manual, references are made to these European standards.

*e.* The base fluids discussed herein may be used for preparation of hydraulic fluids, lubrication fluids, or greases. Environmental tests referred to in this manual are applicable to all three types of products.

## 8-3. Biodegradation

*a. Definition.*

(1) *Biodegradation* is defined as the chemical breakdown or transformation of a substance caused by organisms or their enzymes.

(2) *Primary biodegradation* is defined as a modification of a substance by microorganisms that causes a change in some measurable property of the substance.

(3) *Ultimate biodegradation* is the degradation achieved when a substance is totally utilized by microorganisms resulting in the production of carbon dioxide, methane, water, mineral salts, and new microbial cellular constituents.

*b. Tests.*

(1) ASTM test method D 5864 determines lubricant biodegradation. This test determines the rate and extent of aerobic aquatic biodegradation of lubricants when exposed to an inoculum under laboratory conditions. The inoculum may be the activated sewage-sludge from a domestic sewage-treatment plant, or it may be derived from soil or natural surface waters, or any combination of the three sources. The degree of biodegradability is measured by calculating the rate of conversion of the lubricant to $CO_2$. A lubricant, hydraulic fluid, or grease is classified as readily biodegradable when 60 percent or more of the test material carbon is converted to $CO_2$ in 28 days, as determined using this test method.

(2) The most established test methods used by the lubricant industry for evaluating the biodegradability of their products are Method CEC-L-33-A-94 developed by the Coordinating European Council (CEC); Method OECD 301B, the Modified Sturm Test, developed by the Organization for Economic Cooperation and Development (OECD); and Method EPA 560/6-82-003, number CG-2000, the Shake Flask Test, adapted by the U.S. Environmental Protection Agency (EPA). These tests also determine the rate and extent of aerobic aquatic biodegradation under laboratory conditions. The Modified Sturm Test and Shake Flask Test also calculate the rate of conversion of the lubricant to $CO_2$ . The CEC test measures the disappearance of the lubricant by analyzing test material at various incubation times through infrared spectroscopy. Laboratory tests have shown that the degradation rates may vary widely among the various test methods indicated above.

## 8-4. Toxicity

Toxicity of a substance is generally evaluated by conducting an acute toxicity test. While awaiting acceptance of the ASTM test method for determining the aquatic toxicity of lubricants, the most common test methods used by the lubricant industry for evaluating the acute toxicity of their products are EPA 560/6-82-002, Sections EG-9 and ES-6; and OECD 203. These tests determine the concentration of a substance that produces a toxic effect on a specified percentage of test organisms in 96 hours. The acute toxicity test is normally conducted using rainbow trout. Toxicity is expressed as concentration in parts per million (ppm) of the test material that results in a 50 percent mortality rate after 96 hours (LC50). A substance is generally considered acceptable if aquatic toxicity (LC50) exceeds 1000 ppm. That is, a lubricant or a hydraulic fluid is generally considered acceptable if a concentration of greater than 1000 ppm of the material in an aqueous solution is needed to achieve a 50 percent mortality rate in the test organism.

## 8-5. EA Base Fluids and Additives

Base fluids are mixed with additives to form the final products. These additives are necessary because they provide the resulting end product with physical and chemical characteristics such as oxidation stability, foaming, etc., required for successful application. However, most additives currently used for mineral-based oil are toxic and nonbiodegradable. Therefore, they cannot be used with EA fluids. Furthermore, since the physical and chemical properties of EA fluids are quite different than those of mineral oil, EA fluids will require entirely different additives. Several additive manufacturers are working with the lubricant industry to produce environmentally suitable additives for improving the properties of EA base fluids. Additives that are more than 80 percent biodegradable (CEC-L33-T82) are available. Sulfurized fatty materials (animal fat or vegetable oils) are used to formulate extreme pressure/antiwear additives, and succinic acid derivatives are used to produce ashless (no metal) additives for corrosion protection. Suppliers are using a variety of base fluids to formulate EA hydraulic fluids, lubricating oils, and greases. The base fluid may be the same for all three products. For example a biodegradable and nontoxic ester may be used as the base fluid for production of hydraulic fluid, lubricating oil, and grease. The most popular base fluids are vegetable oils, synthetic esters, and polyglycols.

*a. Vegetable oils.*

(1) Vegetable oil production reaches the billions of gallons in the United States. However, due to technical complexity and economic reasons, few are usable for formulating EA fluids. The usable vegetable oils offer excellent lubricating properties, and they are nontoxic and highly biodegradable, relatively inexpensive compared to synthetic fluids, and are made from natural renewable resources.

(2) Rapeseed oil (RO), or canola oil, appears to be the base for the most popular of the biodegradable hydraulic fluids. The first RO-based hydraulic fluids were commercially available in 1985. Laboratory tests have identified limits to the use of this oil, but extensive practical experience has yielded relatively few problems. The quality of RO has improved over time, and it has become increasingly popular, but it has problems at both high and low temperatures and tends to age rapidly. Its cost, about double that of mineral oil, still makes it more affordable than many alternative EA fluids.

(3) The benefits of RO include its plentiful supply, excellent lubricity, and high viscosity index and flash point. RO is highly biodegradable. One popular RO achieves its maximum biodegradation after only 9 days. RO possesses good extreme pressure and antiwear properties, and readily passes the Vickers 35VQ25 vane pump wear tests. It offers good corrosion protection for hydraulic systems and does not

attack seal materials, varnish, or paint. Mixing with mineral oil is acceptable and has no influence on oil performance. RO is not water soluble and is lighter than water. Escaped oil can be skimmed off the surface of water. Molecular weight is high, indicating low volatility and low evaporation loss.

(4) Concerns about RO include poor low-temperature fluidity and rapid oxidation at high temperatures. Vegetable oil lubricants, including rapeseed, castor, and sunflower oils, tend to age quickly. At high temperatures, they become dense and change composition; at low temperatures, they thicken and gel. Some RO products are not recommended for use in ambient temperatures above 32°C (90 °F) or below -6°C (21°F), but other products gel only after extended periods below -18°C (0°F) and will perform well up to 82°C (180°F). The major problem with RO is its high content of linoleic and linolenic fatty acids. These acids are characterized by two and three double bonds, respectively. A greater number of these bonds in the product results in a material more sensitive to and prone to rapid oxidation. These problems can be only partially controlled by antioxidants. Refining the base oil to reduce these acids results in increased stability. Testing indicates that vegetable oils with higher oleic content have increased oxidative stability. Genetic engineering has produced rapeseed and sunflower oils with high oleic content for applications requiring better oxidation stability.

(5) Conversion to vegetable-oil-based fluids should present few problems, as all are mixable with mineral oil. However, contamination with mineral oil should be kept to a minimum so that biodegradability will not be affected. Special filter elements are not required. Filters should be checked after 50 hours of operation, as vegetable oils tend to remove mineral-oil deposits from the system and carry these to the filters. Filter-clogging indicators should be carefully monitored, as filter-element service life may be reduced in comparison to mineral-oil operation.

*b. Synthetic esters (SE).*

(1) Synthetic esters have been in use longer than any other synthetic-based fluid. They were originally used as aircraft jet engine lubricants in the 1950s and still are used as the base fluid for almost all aircraft jet engine lubricants. For EA base lubricants, the most commonly used synthetic esters are polyol esters; the most commonly used polyol esters are trimethylolpropane and pentaerithritol.

(2) Synthetic esters are made from modified animal fat and vegetable oil reacted with alcohol. While there are similarities between RO and SEs, there are important differences. Esters are more thermally stable and have much higher oxidative stability.

(3) SE fluids can be regarded as one of the best biodegradable hydraulic fluids. Synthetic esters with suitable additives can also be nontoxic. They perform well as lubricants. They have excellent lubrication properties: high viscosity index and low friction characteristics. Their liquidity at low and high temperatures is excellent, as is their aging stability. Although they mix well with mineral oils, this characteristic negatively influences their biodegradability. SE fluids offer good corrosion protection and lubricity and usually can be used under the same operating conditions as mineral oils. They are applicable for extreme temperature-range operations and appear to be the best biodegradable fluids for heavy-duty or severe applications. Synthetic esters do have higher first cost and are incompatible with some paints, finishes, and some seal materials. However, it may be possible to extend oil-change intervals and partially offset the higher cost.

(4) Since SE fluids are miscible with mineral oil, conversion may be accomplished by flushing the system to reduce the residual mineral-oil content to a minimum. Special filter elements are not required.

Filters should be checked after 50 hours of operation, as vegetable oil tends to remove mineral-oil deposits from the system and carry them to the filters.

*c. Polyglycols (PG).*

(1) The use of polyglycols is declining due to their aquatic toxicity when mixed with lubricating additives and their incompatibility with mineral oils and seal materials.

(2) Polyglycol hydraulic fluids have been available for several decades and are widely used, particularly in the food-processing industry. They also have been used since the mid-1980s in construction machinery (primarily excavators) and a variety of stationary installations. They were the first biodegradable oils on the market.

(3) PG fluids have the greatest stability with a range from -45 to 250 °C (-49 to 482 °F). Polyglycols excel where fire hazard is a concern. Oil-change intervals are similar to those for a mineral oil: 2000 hours or once a year.

(4) PG oils are not compatible with mineral oils and may not be compatible with common coatings, linings, seals, and gasket materials. They must be stored in containers free of linings. Some PG oils do not biodegrade well. The rate and degree of biodegradation are controlled by the ratio of propylene to ethylene oxides, with polyethylene glycols being the more biodegradable. The rate and extent of biodegradability diminish with increasing molecular weight.

(5) When a hydraulic system is converted from mineral oil to PG, it is essential that the oil supplier's recommendations are followed. Normally, total system evacuation and one or two flushing procedures are required to avoid any mixing with previously used mineral oil. Mineral oil is less dense than PG fluids, so any residual mineral oil will float to the top and must be skimmed off. According to the manufacturer's recommendations, the final residual quantity of mineral oil may not exceed 1 percent of the total fluid volume. Mineral oil must not be used to replace lost PG fluid, and other contamination of PG with mineral oil must be avoided. Compatibility with varnish, seal, and filter materials also must be considered. Paper filters may need to be replaced with glass-fiber or metal-mesh filters, and these should be checked after the first 50 hours of operation. The filters will retain any residual mineral oil and may become clogged. Because of their excellent wetting properties, PG fluids tend to remove deposits left from operation with mineral oil, and these deposits are carried to the filter. Polyglycols are soluble in water, so water must be excluded from the system.

*d. Water.*

(1) With the prospect of increasingly stringent environmental restrictions on the use of mineral-oil-based hydraulic fluids, water may become a practical alternative. Pure water has poor lubricity and cannot function as a lubricant in the traditional sense, but water has been used as hydraulic fluid in specialty applications where leakage contamination and fire hazard are major concerns. New designs and use of highly wear-resistant materials have opened up possibilities for new water hydraulic applications. Reasons to use water include the following:

(a) Water costs a fraction of mineral oils and other EA fluids.

(b) Water disposal has little or no impact on the environment.

(c) Water is nonflammable and can be used where high temperatures and oils could create fire hazards.

(d) Water has better thermal conductivity than oil and can transfer heat better allowing smaller heat exchanger to be used.

(e) Water's incompressibility makes it ideal for accurate actuator positioning, whereas oil may be sluggish and imprecise.

(2) Water does have several performance drawbacks, however. Conventional hydraulic oil system components will not work with water, and modifying oil system components for water has had poor results. Component manufacturers are now designing parts specifically for water and are having good results. The following list describes performance drawbacks of water and solutions for overcoming them:

(a) Water has low viscosity, so leakage is a concern. Components with tighter clearances are being manufactured to compensate for this.

(b) Water has low viscosity and low film strength, which means lower lubricity and higher wear. Also, water corrodes metal parts. Stainless steel and high-strength plastic and ceramic bearings and component parts designed for high wear resistance are being developed.

(c) Water has higher vapor pressure than mineral oil which makes it more prone to cause cavitation. Pumps are being manufactured with smoother and larger flow areas and throttling valves are being redesigned with innovative flow geometries to mitigate the cavitation potential.

(d) Water freezes. Nontoxic antifreezes have been developed to lower water's "pour point."

(3) The rate and extent to which water hydraulics are adopted depends on the motivation for further technical development and EA additive development by lubricant producers. The driving factor would be legislation regarding toxic and nonbiodegradable hydraulic fluids.

## 8-6. Properties of Available EA Products

The ecotoxicological properties, physical properties, and relative costs of the most widely used EA fluids, as compared with conventional mineral-based oils, are shown in Table 8-1. The cost figures do not include the expenses for changing over to the EA oils, which may be substantial. PG may require total evacuation of the system plus one or two flushes. Disposal costs for EA oils may be greater than for mineral oils because recyclers will not accept them. As previously noted, laboratory tests have shown that the degradation rates may vary widely among the various biodegradation test methods. Table 8-1 indicates that the vegetable oil and synthetic-ester-based fluids, if formulated properly, are readily biodegradable. The toxicity tests show that the base stocks of most EA lubricants are nontoxic. The wide range of toxicity in Table 8-1 is caused by additives in the formulated products. The following discussion summarizes important properties of EA fluids.

*a. Oxidation stability*. One of the most important properties of lubricating oils and hydraulic fluids is their oxidation stability. Oils with low values of oxidation stability will oxidize rapidly in the presence of water at elevated temperatures. When oil oxidizes it will undergo a complex chemical reaction that will produce acid and sludge. Sludge may settle in critical areas of the equipment and interfere with the lubrication and cooling functions of the fluid. The oxidized oil will also corrode the equipment.

**Table 8-1**
**Comparison of Ecotoxicological and Physical Properties of Lubricants**

| Properties | Conventional Mineral Oil | Polyglycol | Vegetable Oil | Synthetic Ester |
|---|---|---|---|---|
| % Biodegradability EPA 560/6-82-003 | 42 - 49 | 6 - 38 | 72 - 80 | 55 - 84 |
| Toxicity[1], LC50, Trout, EPA 560/6-82-002 | 389 - >5000 | 80 - >5000 | 633 - >5000 | >5000 |
| Oxidation Stability[1], TOST, hours, ASTM D 943 | 1000 - 2000 | <500 | <75 | <500 |
| Lubricity[2] ASTM D 2266 | Good | Good | Good | Good |
| Viscosity Index[2] ASTM D 2270 | 90 - 100 | 100 - 200 | 100 - 250 | 120 - 200 |
| Foaming[2], ASTM D 892 | Pass | Pass | Pass | Pass |
| Pour Point[2] °C (°F) ASTM D 97 | -54 to -15 (-65 to 5) | -40 to 20 (-40 to 68) | -20 to 10 (-4 to 50) | -60 to 20 (-76 to 68) |
| Compatibility with Mineral Oil[2] | - | Not miscible | Good | Good |
| Relative Cost[2] | 1 | 2 - 4 | 2 - 3 | 5 - 20 |

[1] Cheng et al., 1994
[2] Rhee 1996

Oxidation stability is normally measured by test method ASTM D 943. This test, which is commonly known as Turbine Oil Stability Test (TOST), is used to evaluate the oxidation stability of oils in the presence of oxygen, water, and iron-copper catalyst at an elevated temperature. As Table 8-1 shows the TOST life of mineral oil is more than 1000 hours. Synthetic esters and polyglycols are hydrolytically less stable than mineral oils at elevated temperatures, resulting in lower TOST lives. It has been shown that formulated synthetic esters with proper additives will produce high TOST values. Vegetable oils, on the other hand, have a TOST life of less than 75 hours. To improve the TOST life of vegetable oil products, more research must be done on formulating a proper mixture of base oil with a suitable additive package. Until acceptable commercial formulations are demonstrated, vegetable oils should be confined to applications involving very dry conditions and low temperatures.

*b. Lubricity.* Lubricity is the degree to which an oil or grease lubricates moving parts and minimizes wear. Lubricity is usually measured by test method ASTM D 2266, commonly known as the Four-Ball Method. Laboratory tests have shown that EA lubricants normally produce good wear properties.

*c. Pour point.* Pour point defines the temperature at which an oil solidifies. When oil solidifies, its performance is greatly compromised. Pour point is normally evaluated by test method ASTM D 97. The low-temperature fluidity of vegetable-based fluids is poor compared to other fluids listed in Table 8-1. However, the pour point of vegetable-based hydraulic fluids and lubricants may be acceptable for many applications.

*d. Viscosity index.* Viscosity index (VI) is a measure of the variation in the kinematic viscosity of oils as the temperature changes. The higher the viscosity index, the less the effect of temperature on its kinematic viscosity. VI is measured by test method ASTM D 2270. As Table 8-1 shows, the VI of most EA fluids meets or exceeds the VI of petroleum-based fluids.

*e. Foaming.* The tendency of oils to foam can be a serious problem in lubricating and hydraulic systems. The lubrication and hydraulic properties of oils are greatly impeded by excessive foaming. Foaming characteristics of oils are usually determined by test method ASTM D 892. Laboratory tests have shown that most formulated EA fluids do not have foaming problems.

*f. Paint compatibility.* Some common paints used in fluid systems are incompatible with many EA fluids. When it is anticipated that EA fluids may be used in a fluid system, the use of epoxy resin paints should be used to eliminate potential compatibility problems.

*g. Elastomeric seal compatibility.* Polyurethane seals should not be used with EA fluids. Instead, the use of Viton and Buna N (low to medium nitrile) is recommended. EA fluids are compatible with steel and copper alloys and provide excellent rust protection. The fluid manufacturer must be consulted for specific compatibility data for each material encountered in the application.

*h. Degradability.* Since EA fluids are biodegradable they will break down in the presence of water and bacteria. Moisture traps in breather intakes and other equipment modifications which will keep moisture out of the system should be considered. EA fluids should be periodically monitored to insure that biodegradation is not occurring.

## 8-7. Environmentally Acceptable Guidelines

At present there are no industry or guide specifications for EA fluids and greases. However, several manufacturers have developed biodegradable and nontoxic fluids for limited applications. In addition, several hydroelectric facilities operated by the Bureau of Reclamation and the Corps of Engineers are testing these products and are obtaining good results. Until specific standards and specifications are developed, it is recommended that the following guidance be used for qualifying the fluids to be environmentally acceptable:

*a. They must be nontoxic.* That is, using test method EPA 560/6-82-002, concentrations greater than 1000 ppm of the test material are necessary to kill 50 percent of the test organisms in 96 hours (LC50>1000).

*b. They must be readily biodegradable.* That is, using the ASTM test method D 5864, 60 percent or more of the test material carbon must be converted to $CO_2$ in 28 days.

## 8-8. Changing from Conventional to EA Lubricants

Plant owners and operators considering a change to biodegradable lubricants and hydraulic fluids should, above all, be aware that these products are not identical to conventional mineral oil products. Furthermore, the EA fluids are not necessarily equal to one another. It is important to make a thorough assessment of the requirements of the specific application to determine whether a substitution can be made, and whether any compromises in quality or performance will be compatible with the needs of the user. Switching to EA - products may require special considerations, measures, or adaptations to the system. Depending on the application and the product chosen, these could include the following:

*a.* Some commercially available synthetic ester and vegetable-oil-based lubricants meet the requirements of nontoxicity and biodegradability. However, the compatibility of these fluids with existing materials encountered in the application, such as paints, filters, and seals, must be considered. The fluid manufacturer must be consulted for specific compatibility data for each material of construction. The manufacturer of the existing equipment must be consulted, especially when the equipment is still under warranty.

*b.* Extreme care must be taken when selecting an EA oil or grease for an application. Product availability may be impacted due to the dynamic nature of developing standards and environmental requirements. EA lubricating oils should not be used in hydroelectric turbine applications, such as bearing oil, runner hub oil, or governor oil, until extensive tests are performed. It is recommended that the Corps of Engineers Hydroelectric Design Center be consulted prior to the initial purchase of any EA fluids and greases for hydropower applications (see paragraph 8-10).

*c.* Accelerated fluid degradation at high temperature, change of performance characteristics at low temperature, and possible new filtration requirements should be investigated carefully. The oxidation rate of vegetable-based EA lubricants increases markedly above 82 °C (179.6 °F), and lengthy exposure at the low temperature can cause some products to gel.

*d.* On a hydraulic power system, when changing over to EA lubricants, the system should be thoroughly drained of the mineral oil and, if possible, flushed. Flushing is mandatory if diesel engine oil was the previous hydraulic fluid. This will avoid compromising the biodegradability and low toxicity of the EA fluids. Disposal of the used fluids should be in accordance with applicable environmental regulations and procedures.

*e.* More frequent filter changes may be necesary.

*f.* Moisture scavengers may be necessary on breather intakes to keep water content in the lubricant low.

*g.* Temperature controls for both upper and lower extremes may need to be added to the system.

*h.* Redesign of hydraulic systems to include larger reservoirs may be necessary to deal with foaming problems.

*i.* The use of stainless steel components to protect against corrosion may be necessary.

*j.* The number of manufacturers who produce EA hydraulic fluids, lubricating oils, and greases continues to expand. Names of the manufacturers include some well known companies that have marketed lubricants for many years as well as a large number of smaller companies that appear to specialize in EA products. Some of these companies also market specialty EA products such as gear oils, wire rope lubricants, air tool lubricants and cutting and tapping fluids. EA turbine oils exist; however, to date, none of the oil suppliers has recommended these products for hydroelectric power plants.

## 8-9. Survey of Corps Users

*a.* A survey of all Army Corps of Engineers districts was conducted to determine how extensively alternative lubricants are being used, and with what results. A follow-up with manufacturers of some of the products revealed that many installations that reported using environmentally acceptable products actually were using food-grade lubricants made from synthetic oils or mineral oils. Neither of these base materials is readily biodegradable.

*b.* The use of environmentally friendly lubricants at Corps of Engineers installations still is far from widespread. Six Corps districts reported using biodegradable oils in one or more applications. The longest use to date has been about 5 years.

*c.* Several installations reported using rapeseed-based oils as hydraulic fluids. The products are being used in Nashville District in hydraulic power units operating at 53.06 l/min (14 gpm) and 172.4 bar (2500 psi), in lock gate operating machinery in Huntington District and in pressure-activated pitch controls in a pumping plant in Little Rock District. The Wilmington District has converted almost all of the hydraulics in waterfront and floating plant applications to rapeseed oil products, and the Alaska District reports using rapeseed oils in excavators, cranes, and dredges.

*d.* Nashville District also reported using rapeseed-based lubricants in gate and valve machinery, while Rock Island District uses them to lubricate gate lift chains. Other districts reported having specified EA - oils for specific applications, but have not yet put the new equipment in operation.

*e.* Operators of installations using the EA products generally are satisfied with their performance and are considering expanding their use. Some operators who installed heaters or coolers to accommodate fluids with limited temperature ranges report increased equipment life because the moderate temperatures reduce stress on the pumps. Although the same environmental regulations apply to reporting and cleanup of all spills, an environmental agency's response to a spill sometimes does take the “environmentally acceptable” nature of the fluid into account. One user observed that a spill in quiet water gelled on the surface “like chicken fat,” making cleanup easy. Finally, most operators report that installation of rapeseed-based oil in a mineral-oil system is as easy as any other complete oil change.

*f.* Overall, the most positive reports on EA fluids were applications in closed hydraulic systems. In systems open to the environment, degradation and temperature sensitivity cause problems. Exposure to water also can spur biodegradation of the lubricant while in service, a problem of particular significance in hydropower applications. The only two failures of the fluids reported in the Corps of Engineers survey were cases of contamination that caused the fluids to biodegrade while in use.

## 8-10. USACE Contacts

*a.* Additional information on hydropower applications can be obtained from the Hydroelectric Design Center, CENPP-HDC, at P.O. Box 2870, Portland, OR 97208.

*b.* Information on the survey, other EA applications, and associated new lubricants and technologies can be obtained from the U.S. Army Construction Engineering Research Laboratories, CECER-FL-M, P. 0. Box 9005, Champaign, IL 61826-9005.

# Chapter 9
# Gears

## 9-1. General

*a.* Energy is transmitted from a power source to a terminal point, through gears that change speeds, directions, and torque. Gear lubricants are formulated and applied to prevent premature component failure, assure reliable operation, reduce operating cost, and increase service life. The important objectives accomplished by these lubricants include: reduction of friction and wear, corrosion prevention, reduction of operating noise, improvement in heat transfer, and removal of foreign or wear particles from the critical contact areas of the gear tooth surfaces.

*b.* Gears vary greatly in their design and in their lubrication requirements. Proper lubrication is important to prevent premature wear of gear tooth surfaces. When selecting a lubricant for any gear application the following issues must be considered: type and materials of gear; operating conditions, including rolling or sliding speed, type of steady load, and temperature; method of lubricant application; environment; and type of service. Enclosed gears -- those encased in an oil-tight housing -- usually require an oil with various additives, depending on the operating conditions. Rust, oxidation, and foam inhibitors are common. Extreme pressure (EP) additives are also used when loads are severe.

*c.* Worm gears are special because the action between the worm and the mating bull gear is sliding rather than the rolling action common in most gears. The sliding action allows fluid film lubrication to take place. Another significant difference is that worm gears are usually made of dissimilar materials, which reduces the chance of galling and reduces friction. EP additives usually are not required for worm gears and may actually be detrimental to a bronze worm gear. Lubrication can be improved by oiliness additives.

*d.* In open gear applications, the lubricant must resist being thrown off by centrifugal force or being scraped off by the action of the gear teeth. A highly adhesive lubricant is required for most open gear applications. Most open gear lubricants are heavy oils, asphalt-based compounds, or soft greases. Depending on the service conditions, oxidation inhibitors or EP additives may be added. Caution must be exercised when using adhesive lubricants because they may attract and retain dust and dirt, which can act as abrasives. To minimize damage, gears should be periodically cleaned.

## 9-2. Gear Types

*a. Spur gears.* Spur gears are the most common type used. Tooth contact is primarily rolling, with sliding occurring during engagement and disengagement. Some noise is normal, but it may become objectionable at high speeds.

*b. Rack and pinion.* Rack and pinion gears are essentially a variation of spur gears and have similar lubrication requirements.

*c. Helical.* Helical gears operate with less noise and vibration than spur gears. At any time, the load on helical gears is distributed over several teeth, resulting in reduced wear. Due to their angular cut, teeth meshing results in thrust loads along the gear shaft. This action requires thrust bearings to absorb the thrust load and maintain gear alignment.

*d. Herringbone.* Herringbone gears are essentially two side-by-side opposite-hand helical gears. This design eliminates thrust loads, but alignment is very critical to ensure correct teeth engagement.

*e. Bevel.* Bevel gears are used to transmit motion between shafts with intersecting center lines. The intersecting angle is normally 90 deg but may be as high as 180 deg. When the mating gears are equal in size and the shafts are positioned at 90 degrees to each other, they are referred to as miter gears. The teeth of bevel gears can also be cut in a curved manner to produce spiral bevel gears, which produce smoother and quieter operation than straight cut bevels.

*f. Worm.* Operation of worm gears is analogous to a screw. The relative motion between these gears is sliding rather than rolling. The uniform distribution of tooth pressures on these gears enables use of metals with inherently low coefficients of friction such as bronze wheel gears with hardened steel worm gears. These gears rely on full fluid film lubrication and require heavy oil compounded to enhance lubricity and film strength to prevent metal contact.

*g. Hypoid.* Hypoid gears are similar to spiral bevel gears except that the shaft center lines do not intersect. Hypoid gears combine the rolling action and high tooth pressure of spiral bevels with the sliding action of worm gears. This combination and the all-steel construction of the drive and driven gear result in a gear set with special lubrication requirements, including oiliness and antiweld additives to withstand the high tooth pressures and high rubbing speeds.

*h. Annular.* Annular gears have the same tooth design as spur and helical gears, but unlike these gears, the annular gear has an internal configuration. The tooth action and lubrication requirements for annular gears are similar to spur and helical gears.

## 9-3. Gear Wear and Failure

The most critical function provided by lubricants is to minimize friction and wear to extend equipment service life. Gear failures can be traced to mechanical problems or lubricant failure. Lubricant-related failures are usually traced to contamination, oil film collapse, additive depletion, and use of improper lubricant for the application. The most common failures are due to particle contamination of the lubricant Dust particles are highly abrasive and can penetrate through the oil film, causing “plowing” wear or ridging on metal surfaces. Water contamination can cause rust on working surfaces and eventually destroy metal integrity. To prevent premature failure, gear selection requires careful consideration of the following: gear tooth geometry, tooth action, tooth pressures, construction materials and surface characteristics, lubricant characteristics, and operating environment. The first four items are related to design and application, and further discussion is beyond the scope of this manual. These items may be mentioned where necessary, but discussions are limited to those aspects directly related to and affected by lubrication, including wear, scuffing, and contact fatigue. Refer to ANSI/AGMA Standard 1010-E95, and ASM Handbook Volume 18, for photographs illustrating the wear modes described in the following discussion.

*a. Normal wear.* Normal wear occurs in new gears during the initial running-in period. The rolling and sliding action of the mating teeth create mild wear that appears as a smooth and polished surface.

*b. Fatigue.*

(1) Pitting. Pitting occurs when fatigue cracks are initiated on the tooth surface or just below the surface. Usually pits are the result of surface cracks caused by metal-to-metal contact of asperities or

defects due to low lubricant film thickness. High-speed gears with smooth surfaces and good film thickness may experience pitting due to subsurface cracks. These cracks may start at inclusions in the gear materials, which act as stress concentrators, and propagate below and parallel to the tooth surface. Pits are formed when these cracks break through the tooth surface and cause material separation. When several pits join, a larger pit (or spall) is formed. Another suspected cause of pitting is hydrogen embrittlement of metal due to water contamination of the lubricant. Pitting can also be caused by foreign particle contamination of lubricant. These particles create surface stress concentration points that reduce lubricant film thickness and promote pitting. The following guidelines should be observed to minimize the onset of pitting in gear units:

- Reduce contact stresses through load reduction or by optimizing gear geometry.
- Steel should be properly heat-treated to high hardness. Carburizing is preferable.
- Gear teeth should have smooth surfaces produced by grinding or honing.
- Use proper quantities of cool, clean, and dry lubricant with the required viscosity.

(2) Micropitting. Micropitting occurs on surface-hardened gears and is characterized by extremely small pits approximately 10 µm (400 µ-inches) deep. Micropitted metal has a frosted or a gray appearance. This condition generally appears on rough surfaces and is exacerbated by use of low-viscosity lubricants. Slow-speed gears are also prone to micropitting due to thin lubricant films. Micropitting may be sporadic and may stop when good lubrication conditions are restored following run-in. Maintaining adequate lubricant film thickness is the most important factor influencing the formation of micropitting. Higher-speed operation and smooth gear tooth surfaces also hinder formation of micropitting. The following guidelines should be observed to reduce the onset of micropitting in gear units:

- Use gears with smooth tooth surfaces produced by careful grinding or honing.
- Use the correct amount of cool, clean, and dry lubricant with the highest viscosity permissible for the application
- Use high speeds, if possible.
- Use carburized steel with proper carbon content in the surface layers.

*c. Wear*.

(1) Adhesion.

(a) New gears contain surface imperfections or roughness that are inherent to the manufacturing process. During the initial run-in period, these imperfections are reduced through wear. Smoothing of the gear surfaces is to be expected . Mild wear will occur even when adequate lubrication is provided, but this wear is limited to the oxide layer of the gear teeth. Mild wear is beneficial because it increases the contact areas and equalizes the load pressures on gear tooth surfaces. Furthermore, the smooth gear surfaces increase the film thickness and improve lubrication.

(b) The amount of wear that is acceptable depends on the expected life, noise, and vibration of the gear units. Excessive wear is characterized by loss of tooth profile, which results in high loading, and loss of tooth thickness, which may cause bending fatigue.

(c) Wear cannot be completely eliminated. Speed, lubricant viscosity, and temperature impose practical limits on gear operating conditions. Gears that are highly loaded, operate at slow speeds, i.e., less than 30 m/min (100 ft/min), and rely on boundary lubrication are particularly subject to excessive wear. Slow-speed adhesive wear is highly dependent upon lubricant viscosity. Higher lubricant viscosities provide significant wear reduction, but viscosities must be carefully selected to prevent overheating.

(d) The following guidelines should be observed to minimize the onset of adhesive wear in gear units:

- Gear teeth should have smooth surfaces.
- If possible, the run-in period for new gear units should be restricted to one-half load for the first hours of operation.
- Use the highest speeds possible. High-load, slow-speed gears are boundary lubricated and are especially prone to excessive wear. For these applications, nitrided gears should be specified.
- Avoid using lubricants with sulfur-phosphorus additives for very slow-speed gears (less than 3 m/min, or 10 ft/min).
- Use the required quantity of cool, clean, and dry lubricant at the highest viscosity permissible.

(2) Abrasion. Abrasive wear is caused by particle contaminants in the lubricant. Particles may originate internally due to poor quality control during the manufacturing process. Particles also may be introduced from the outside during servicing or through inadequate filters, breathers, or seals. Internally generated particles are particularly destructive because they may become work-hardened during compression between the gear teeth. The following guidelines should be observed to prevent abrasive wear in gear units:

- Remove internal contamination from new gearboxes. Drain and flush the lubricant before initial start-up and again after 50 hours of operation. Refill with the manufacturer's recommended lubricant. Install new filters or breathers.
- Use surface-hardened gear teeth, smooth tooth surfaces, and high-viscosity lubricants.
- Maintain oil-tight seals and use filtered breather vents, preferably located in clean, nonpressurized areas.
- Use good housekeeping procedures.
- Use fine filtration for circulating-oil systems. Filtration to 3 μm (120 μ-in.) has proven effective in prolonging gear life.
- Unless otherwise recommended by the gear manufacturer, change the lubricant in oil-bath systems at least every 2500 hours or every 6 months.

! When warranted by the nature of the application, conduct laboratory analysis of lubricants. Analysis may include spectrographic, ferrographic, acid number, viscosity, and water content.

(3) Polishing. Polishing wear is characterized by a mirror-like finish of the gear teeth. Polishing is caused by antiscuff additives that are too chemically reactive. An excessive reaction rate, coupled with continuous removal of surface films by very fine abrasive particles in the lubricant, may result in excessive polishing wear. The following guidelines should be observed to prevent polishing wear in gearsets:

! Use less chemically active antiscuff additives such as borate.

! Remove abrasives from the lubricant by using fine filtration or by frequent oil changes.

*d. Scuffing.*

(1) General. The terms scuffing and scoring are frequently interchanged. The following definitions are provided to assist in correctly ascertaining the type of damage observed. The ASM Handbook Vol 18 defines scuffing as localized damage caused by the occurrence of solid-phase welding between sliding surfaces. It defines scoring as the formation of severe scratches in the direction of sliding. The handbook also stipulates that scoring may be caused by local solid-phase welding or abrasion, but suggests that minor scoring be considered as scratching. Gear scuffing is characterized by material transfer between sliding tooth surfaces. Generally this condition occurs when inadequate lubrication film thickness permits metal-to-metal contact between gear teeth. Without lubrication, direct metal contact removes the protective oxide layer on the gear metal, and the excessive heat generated by friction welds the surfaces at the contact points. As the gears separate, metal is torn and transferred between the teeth. Scuffing is most likely to occur in new gear sets during the running-in period because the gear teeth have not sufficient operating time to develop smooth surfaces.

(2) Critical scuffing temperature.

(a) Research has shown that for a given mineral oil without antiscuffing or extreme pressure additives, there is a critical scuffing temperature that is constant regardless of operating conditions. Evidence indicates that beyond the critical temperature, scuffing will occur. Therefore, the critical temperature concept provides a useful method for predicting the onset of scuffing. The critical scuffing temperature is a function of the gear bulk temperature and the flash temperature and is expressed as:

$$T_c = T_b + T_f \tag{9-1}$$

where the bulk temperature $T_b$ is the equilibrium temperature of the gears before meshing and the flash temperature $T_f$ is the instantaneous temperature rise caused by the local frictional heat at the gear teeth meshing point. The critical scuffing temperature for mineral oils without antiscuffing or extreme pressure additives increases directly with viscosity and varies from 150 to 300 °C (300 to 570 °F). However, this increased scuffing resistance appears to be directly attributed to differences in chemical composition and only indirectly to the beneficial effects of increased film thickness associated with higher viscosity. Examination of the critical temperature equation indicates that scuffing can be controlled by lowering either of the two contributing factors. The bulk temperature can be controlled by selecting gear geometry and design for the intended application. The flash temperature can be controlled indirectly by gear tooth smoothness and through lubricant viscosity. Smooth gear tooth surfaces produce less friction and heat while increased viscosity provides greater film thickness, which also reduces frictional heat and results in a lower flash temperature. Furthermore, judicious application of lubricant can cool the gears by removing heat.

(b) For synthetics and lubricants containing antiscuff additives, the critical temperature depends on the operating conditions and must be determined experimentally for each case. Antiscuff additives commonly used are iron sulfide and iron phosphate. These additives react chemically with the protected metal gear surface to form very strong solid films that prevent metal contact under extreme pressure and temperature conditions. As previously noted in the discussions of oil additives, the beneficial effects of extreme pressure additives are enhanced as the temperature increases.

(c) The following guidelines should be observed to prevent scuffing in gear units:

- Specify smooth tooth surfaces produced by careful grinding or honing.
- Protect gear teeth during the running-in period by coating them with iron-manganese phosphate or plating them with copper or silver. During the first ten hours of run-in, new gears should be operated at one-half load.
- Use high-viscosity lubricants with antiscuff additives such as sulfur, phosphorus, or borate.
- Make sure the gear teeth are cooled by supplying adequate amount of cool lubricant. For circulating-oil systems, use a heat exchanger to cool the lubricant.
- Optimize the gear tooth geometry. Use small teeth, addendum modification, and profile modification.
- Use accurate gear teeth, rigid gear mountings, and good helix alignment.
- Use nitrided steels for maximum scuffing resistance. Do not use stainless steel or aluminum for gears if there is a risk of scuffing.

## 9-4. Gear Lubrication

*a. Lubricant characteristics.* Gear lubricant must possess the following characteristics:

(1) General. The following characteristics are applicable to all gear lubricants. The lubrication requirements for specific gears follow this general discussion:

(a) Viscosity. Good viscosity is essential to ensure cushioning and quiet operation. An oil viscosity that is too high will result in excess friction and degradation of oil properties associated with high oil operating temperature. In cold climates gear lubricants should flow easily at low temperature. Gear oils should have a minimum pour point of 5 $^0$C (9 $^0$F) lower than the lowest expected temperature. The pour point for mineral gear oil is typically -7 $^0$C (20 $^0$F). When lower pour points are required, synthetic gear oils with pour points of -40 $^0$C (-40 $^0$F) may be necessary. The following equation from the ASM Handbook provides a method for verifying the required viscosity for a specific gear based on the operating velocity:

$$\nu_{40} = \frac{7000}{V^{0.5}} \tag{9-2}$$

where

$v_{40}$ = lubricant kinematic viscosity at 40°C (105°F) (cSt)

$V$ = pitch line velocity (ft/min) given by :

$$V = 0.262nd \tag{9-3}$$

where n is the pinion speed in rev/min and d is the pitch diameter (inches).

(b) Film strength. Good film strength helps prevent metal contact and scoring between the gear teeth.

(c) Lubricity (oiliness). Lubricity is necessary to reduce friction.

(d) Adhesion. Helps prevent loss of lubrication due to throw-off associated with gravity or centrifugal force especially at high speeds.

(e) Gear speed. The now superseded Industrial Gear Lubrication Standards, AGMA 250.04, used center distance as the primary criterion for gear lubricant selection. The new version of this standard, designated AGMA 9005-D94 Industrial Gear Lubrication, has adopted pitch line velocity as the primary selection criterion. As noted above, gear speed is a factor in the selection of proper oil viscosity. The pitch line velocity determines the contact time between gear teeth. High velocities are generally associated with light loads and very short contact times. For these applications, low-viscosity oils are usually adequate. In contrast, low speeds are associated with high loads and long contact times. These conditions require higher-viscosity oils. EP additives may be required if the loads are very high.

(f) Temperature. Ambient and operating temperatures also determine the selection of gear lubricants. Normal gear oil operating temperature ranges from 50 to 55 $^0$C (90 to 100 $^0$F) above ambient. Oils operating at high temperature require good viscosity and high resistance to oxidation and foaming. Caution should be exercised whenever abnormally high temperatures are experienced. High operating temperatures are indicative of oils that are too viscous for the application, excess oil in the housing, or an overloaded condition. All of these conditions should be investigated to determine the cause and correct the condition. Oil for gears operating at low ambient temperatures must be able to flow easily and provide adequate viscosity. Therefore these gear oils must possess high viscosity indices and low pour points.

(2) Open gears. In addition to the general requirements, lubrication for open gears must meet the following requirements:

(a) Drip resistance. Prevents loss of lubricant, especially at high temperatures which reduce viscosity.

(b) Brittle resistance. Lubricant must be capable of resisting embrittlement, especially at very low temperatures.

(3) Enclosed gears. In addition to the general requirements, lubrication for enclosed gears must meet the following requirements:

(a) Chemical stability and oxidation resistance. Prevents thickening and formation of varnish or sludge. This requirement is especially significant in high-speed gears because the oil is subjected to high operating oil and air temperatures.

(b) Extreme pressure protection. Provides additional galling and welding protection for heavily loaded gears when the lubricant film thickness fails. Extreme pressure lubricants are available for mild and severe (hypoid) lubricant applications.

*b. Types of gear lubricants*

(1) Oil. Refer to AGMA 9005-D94 for the specifications for the following lubricants.

(a) Rust and oxidation oils. These petroleum-based oils are frequently referred to as RO gear oils. RO oils are the most common gear lubricants and have been formulated to include chemical additives that enhance their performance qualities. RO lubricating oils have easy application properties for gear and bearings, good lubrication qualities, and adequate cooling qualities and they are economical to use. Disadvantages include restriction to enclosed gear applications to prevent contamination.

(b) Compounded gear lubricants. These oils are a blend of petroleum-based oils with 3 to 10 percent fatty or synthetic fatty oils. They are particularly useful in worm gear drives. Except as noted in the AGMA applicable specifications, compounded oils should comply with the same specifications as RO oils.

(c) Extreme pressure lubricants. These gear lubricants, commonly referred to as EP lubricants, are petroleum-based and specially formulated to include chemical additives such as sulfur-phosphorus or other similar materials capable of producing a film that provides extreme pressure and antiscuffing protection.

(d) Synthetic oils. Synthetic oils have the advantage of stable application over wide temperature range, good oxidation stability at high temperatures, high viscosity indices, and low volatility. Because gear oils must be changed periodically, the main disadvantage of synthetics is high cost, which can only be justified for applications at high temperature extremes where other lubricants fail. Another disadvantage of synthetics is possible incompatibility with seals and other lubricants. The equipment manufacturer should be consulted before using synthetic oils to ensure that exposed materials will not be damaged or warranties voided. Gear units should be flushed of all mineral oils before the filling with the final synthetic oil.

(e) Residual compounds. These are higher-viscosity straight mineral or EP lubricants that are mixed with a diluent to facilitate application. Viscosities range from 400 to 2000 $mm^2/s$ at 100 °C (mm sq/sec cST at 100 °C) without diluent. Once applied, the diluent evaporates and leaves a heavy residual lubricant coating on the treated surface.

(2) Special compounds and greases. These lubricants include special greases formulated for boundary lubricating conditions such as low-speed, low-load applications where high film strength is required. These lubricants usually contain a base oil, a thickener, and a solid lubricant such as molybdenum disulfide ($MoS_2$) or graphite. The gear manufacturer should be consulted before using grease. The primary disadvantage of using grease is that it accumulates foreign particles such as metal, dirt, and other loose materials that can cause significant damage if adequate maintenance is not provided.

Grease also has a tendency to be squeezed out of the gear tooth meshing zone, and it does not provide satisfactory cooling.

(3) Open-gear lubricants. Open-gear lubricants are generally reserved for slow-speed low-load boundary lubricating conditions. Due to the open configuration, the lubricants must be viscous and adhesive to resist being thrown off the gear teeth surfaces. The disadvantages of these lubricants are similar to those noted above for grease.

(4) Solid lubricants. The solid lubricants most commonly used in gear trains are molybdenum disulfide, graphite, polytetrafluoroethylene (PTFE), and tungsten disulfide ($WoS_2$). Because they are expensive to apply, use of these lubricants is reserved for special applications such as high and low temperature extremes where other lubricants fail to perform adequately.

*c. Applications.*

(1) Spur, helical, bevel, and hypoid gears. Spur, helical, and bevel gears have similar load and speed characteristics, and similar requirements for antiscuffing and viscosity.

(a) Spur and helical gears. Spur and helical gears usually require mineral oils with RO inhibitors. Low-viscosity RO oils, such as turbine oils, are commonly used in high-speed, low-load gear units. For high-speed, low-load gear applications, mineral oils without antiscuff/extreme pressure agents can be used successfully provided the oil viscosity is capable of maintaining the required film thickness. However, low-speed gears are usually heavily loaded so antiscuff/extreme pressure agents are necessary to ensure adequate protection.

(b) Hypoid gears. Hypoid gears combine the rolling action and high tooth pressure of spiral bevel gears with the sliding action of worm gears. These severe operating conditions result in high load, high sliding speeds, and high friction. Therefore, hypoid gears are very susceptible to scuffing. Mineral oils for this application must have high lubricity and high concentrations of antiscuffing/extreme pressure additives.

(2) Worm gears. Worm gears operate under high sliding velocity and moderate loads. The sliding action produces friction that produces higher operating temperatures than those that occur in other gear sets. Normal operating temperature for worm gears may rise to $93^{o}$ C ($200^{o}$ F) and is not a cause for concern. Lubricants for worm gears must resist the thinning due to high temperatures and the wiping effect of sliding action, and they must provide adequate cooling. Mineral oils compounded with lubricity additives are recommended. Extreme pressure additives are usually not required for worm gears. However, when EP protection is required, the additive should be selected with caution to prevent damaging the bronze worm wheel.

(3) Gear combinations. Many applications use different gears in the same gear housing. For these applications the lubricant must be suitable for the gears with the most demanding requirements. Generally, the other gears will operate satisfactorily with such high-performance lubricants.

(4) Gear shaft bearings. Gear shaft bearings are frequently lubricated by gear oil. In most instances this condition is acceptable. Bearings in high-speed, low-load applications may operate satisfactorily with the gear oil. However, low-speed, heavily loaded gears usually require a heavy oil. For these conditions a low-viscosity EP oil may provide adequate lubrication for the gears and bearings. The low-viscosity oil

will adequately lubricate the bearings while the EP additive will protect the gear teeth from the effects of using a low-viscosity oil.

# Chapter 10
# Bearings

## 10-1. General

Bearings can be divided into two subgroups: plain bearings and rolling-contact bearings. Both have their place in the world of machines. Each type has some obvious advantages and disadvantages, but there are subtle properties as well that are often ignored. Each type of bearing can be found in a multiplicity of places, and each can be lubricated with either oil or grease. Some bearings are lubricated by water, and some are lubricated by air (as in the case of a dentist's drill).

## 10-2. Plain Bearings

Plain bearings consist of two surfaces, one moving in relation to the other. Plain bearings can be the journal type, where both wear surfaces are cylindrical; thrust type, where there are two planar surfaces, one rotating upon the other; and various types of sliding bearings where one surface slides in relation to the other. All depend upon a lubricating film to reduce friction. Unless an oil pump is provided to generate the oil film, these bearings rely on shaft motion to generate a hydrodynamic oil wedge.

*a. Advantages of plain bearings.*

(1) They have a very low coefficient of friction if properly designed and lubricated.

(2) They have very high load-carrying capabilities.

(3) Their resistance to shock and vibration is greater than rolling-contact bearings.

(4) The hydrodynamic oil film produced by plain bearings damps vibration, so less noise is transmitted.

(5) They are less sensitive to lubricant contamination than rolling-contact bearings.

*b. Types of plain bearings*.

(1) Journal (sleeve bearings). These are cylindrical with oil-distributing grooves. The inner surface can be babbitt-lined, bronze-lined, or lined with other materials generally softer than the rotating journal. On horizontal shafts on motors and pumps, oil rings carry oil from the oil reservoir up to the bearing. In the case of very slow-moving shafts, the bearings may be called bushings.

(2) Segmented journal. These are similar to the journal except that the stationary bearing consists of segments or bearing shoes. Each shoe is individually adjustable. This type of bearing is commonly found in vertical hydrogenerators and large vertical pumping units. This bearing is usually partially immersed in an oil tub.

(3) Thrust bearings. These bearings support axial loading and consist of a shaft collar supported by the thrust bearing, many times in segments called thrust shoes. The thrust shoes are sometimes allowed to pivot to accommodate the formation of the supporting oil wedges. There are many different configurations

of the thrust bearing aimed at equalizing loading and oil wedges. The bearing is immersed in a tub of oil. On large hydrogenerators and pumps an oil pump is sometimes used to provide an oil film at start-up.

(4) Self-lubricated bearings. These are journal (sleeve) bearings in which the bearing surface contains a lubricant, usually solid, that is liberated or activated by friction in the bearing. This type of bearing is gaining popularity as a wicket gate bearing or wicket gate linkage bushing.

*c. Plain bearing lubrication selection.*

(1) The most common lubricants for plain bearings are mineral and synthetic oils, and greases. Mineral oils are generally used except in extreme hot and cold temperature applications where synthetics provide superior performance. Oil is used for faster rotational speeds where the hydrodynamic oil wedge can be formed and maintained. It also is used in high-temperature conditions where grease may melt or degrade. Grease is used for slower rotational speeds or oscillating movements where the hydrodynamic oil wedge cannot form. It is also used in cases of extreme loading where the bearing operates in boundary conditions. Table 10-1 shows some of the important considerations regarding lubricant selection.

**Table 10-1**
**Choice of Lubricant**

| Lubricant | Operating Range | Remarks |
|---|---|---|
| Mineral oils | All conditions of load and speed | Wide range of viscosities available. Potential corrosion problems with certain additive oils (e.g., extreme pressure) (see Table 7.1). |
| Synthetic oils | All conditions if suitable viscosity available | Good high- and low-temperature properties. Costly. |
| Greases | Use restricted to operating speeds below 1 to 2 m/s (3.28 to 6.56 fps) | Good where sealing against dirt and moisture is necessary and where motion is intermittent. |
| Process fluids | Depends on properties of fluid | May be necessary to avoid contamination of food products, chemicals, etc. Special attention to design and selection of bearing materials. |

Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

(2) The lubricating properties of greases are significantly affected by the base oil and type of thickeners used. Table 10-2 provides general guidelines for selecting the type of grease for bearing lubrications. In Table 10-2, speed factor (also referred to as speed index) is determined by multiplying the pitch diameter of the bearing by the bearing speed as follows;

$$d_n = n \frac{D + d}{2} \tag{10-1}$$

where $D$ is the bearing diameter (mm), $d$ is the bore diameter (mm), and $n$ is the rev/min. Speed factors above 200,000 are usually indicative of fluid film lubrication applications. The load column provides indications of the degree of loading on a bearing and is defined as the ratio of rated bearing load to the actual bearing load.

**Table 10-2**
**Bearing Lubrication Considering Speed Factor**

| Load, Rated Applied | Temperature, C° (°F) | Base Oil | Thickener | Additives |
|---|---|---|---|---|
| **Speed Factor Less than 100,000** | | | | |
| <10 | -56.6-17.7 (-70-0) | Mineral oil, synthetic, ester | Lithium | Graphite or $MoS_2$, rust oxidation |
| <10 | -17.7-176.6 (0-350) | Mineral oil | Lithium, calcium, barium, aluminum sodium | Graphite or $MoS_2$, rust oxidation |
| <10 | 176.6+ (350+) | Synthetic, ester | Sodium, clay, calcium, lithium, polyurea | Graphite or $MoS_2$, rust, oxidation |
| **Speed Factor 100,000 to 500,000** | | | | |
| <10 | -17.7-176.6 (0-350) | Mineral oil, synthetic, PAG, ester | Lithium, calcium, aluminum, barium, polyurea | Graphite or $Mos_2$, rust, oxidation |
| <10 (high)<br>>30 (low) | -17.7-176.6 (0-350) | Mineral oil, synthetic, PAG, ester | Lithium, calcium, aluminum, barium, polyurea | EP, rust, oxidation |
| >30 | 17-7-176.6 (0-350) | Mineral oil, synthetic, PAG, ester | Lithium, clay, polyurea, aluminum, barium, calcium | Antiwear, rust, oxidation |
| **Speed Factor Greater than 500,000** | | | | |
| >30 | -17.7-93.3 (0-200) | Mineral oil, synthetic, ester | Lithium, calcium, barium | Rust, oxidation |

(3) Viscosity is the most critical lubricant property for insuring adequate lubrication of plain bearings. If the viscosity is too high, the bearings will tend to overheat. If the viscosity is too low the load-carrying capacity will be reduced. Figure 10-1 is a guide to selection of viscosity for a given operating speed. For plain journal bearings the surface speed u is given by:

$$u = \pi dn, \quad \text{m/sec} \tag{10-1}$$

and the mean pressure $p_m$ is given by

$$P_m = \frac{W}{ld}, \ kN/m^2 \tag{10-2}$$

where

$n$ = shaft speed, rev/s

l = bearing width, m

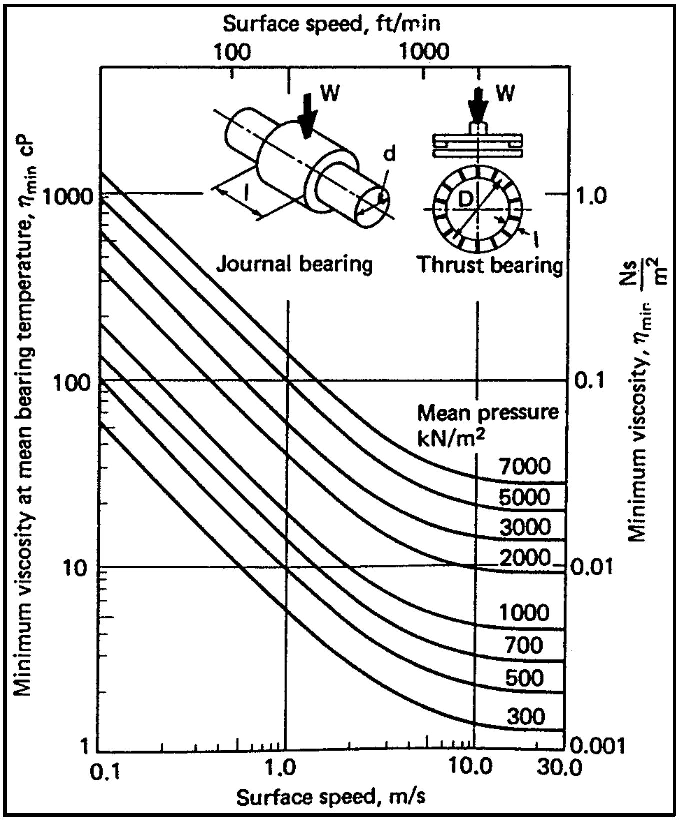


**Figure 10-1. Lubricant viscosity for plain bearings (Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford England)**

$d$ = shaft diameter, m

$W$ = thrust load, kN

For thrust bearings, the surface speed $u$ is given by Equation 10-1. The mean pressure is given by

$$p_m = \frac{0.4W}{lD}, \quad kN/m^2 \tag{10-3}$$

where $p_m$, and l are as previously defined, $W$ = thrust load, $kN$, and $D$ = mean pad diameter, m. Equations 10-1 through 10-3 are intended to provide a means for understanding Figures 10-1 and 10-2. Refer to Machinerys Handbook, 24th edition, for a detailed discussion and analysis of bearing loads and lubrication.) Figure 10-2 shows the relationship between temperature and viscosity for mineral oils.

(4) Table 10-3 identifies some of the methods used to supply lubricants to bearings. The lubricant should be supplied at a rate that will limit the temperature rise of the bearing to 20°C (68 °F).

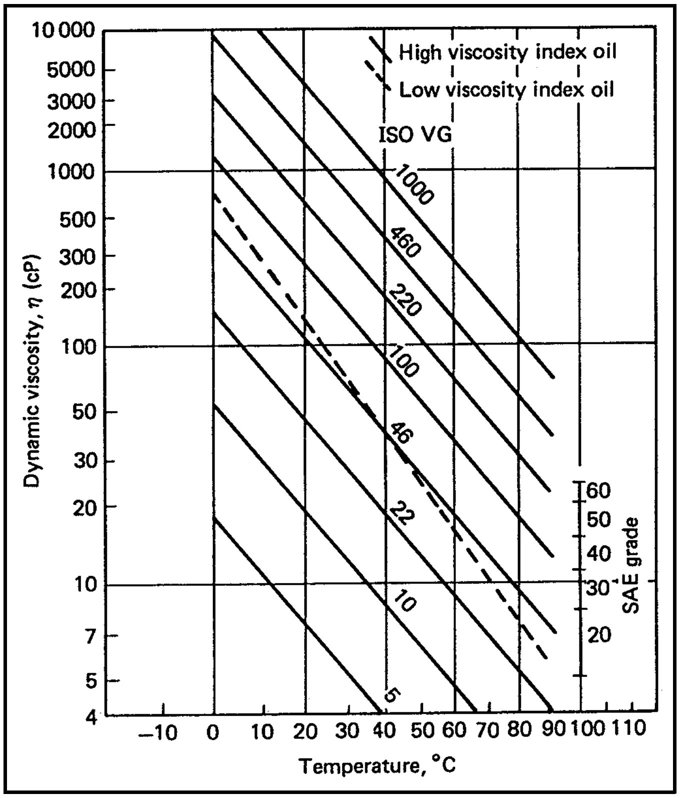


**Figure 10-2. Typical viscosity/temperature characteristics of mineral oils (Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England)**

**Table 10-3**
**Methods of Liquid Lubricant Supply**

| Method of Supply | Main Characteristics | Examples |
|---|---|---|
| Hand oiling | Nonautomatic, irregular. Low initial cost. High maintenance cost. | Low-speed, cheap journal bearings |
| Drip and wick feed | Nonautomatic, adjustable. Moderately efficient. Cheap | Journals in some machine tools, axles |
| Ring and collar feed | Automatic, reliable. Efficient, fairly cheap. Mainly horizontal bearings | Journals in pumps, blowers, large electric motors |
| Bath and splash lubrication | Automatic, reliable, efficient. Oiltight housing required. High initial cost. | Thrust bearings, bath only. Engines, process machinery, general |
| Pressure feed | Automatic. Positive and adjustable. Reliable and efficient. High initial cost. | High-speed and heavily loaded journal and thrust bearings in machine tools, engines, and compressors |

Notes:
Pressure oil feed: This is usually necessary when the heat dissipation of the bearing housing and its surroundings are not sufficient to restrict its temperature rise to 20 °C (68 °F) or less.
Journal bearings: Oil must be introduced by means of oil grooves in the bearing housing.
Thrust bearings: These must be lubricated by oil bath or by pressure feed from the center of the bearing.
Cleanliness: Cleanliness of the oil supply is essential for satisfactory performance and long life.
(Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England)

(5) Generally, oil additives such as those noted in Table 7-1 are not required in plain bearing applications. Some additives and contaminants may cause corrosion, so caution should be exercised when using bearing lubricants containing additives or when contaminants may be present. Table 10-4 identifies some of the most common bearing materials used, and their resistance to corrosion when subjected to the additives noted.

**Table 10-4**
**Resistance to Corrosion of Bearing Metals**

| | Maximum Operating Temperature, °C (F°) | Additive or Contaminant | | | | |
|---|---|---|---|---|---|---|
| | | Extreme-Pressure Additive | Antioxidant | Weak Organic Acids | Strong Mineral Acids | Synthetic Oil |
| Lead-base white metal | 130 (266) | Good | Good | Moderate/poor | Fair | Good |
| Tin-base white metal | 130 (266) | Good | Good | Excellent | Very good | Good |
| Copper-lead (without overlay) | 170 (338) | Good | Good | Poor | Fair | Good |
| Lead-bronze (without overlay) | 180 (356) | Good with good quality bronze | Good | Poor | Moderate | Good |
| Aluminum-tin alloy | 170 (338) | Good | Good | Good | Fair | Good |
| Silver | 180 (356) | Sulfur-containing additives must not be used | Good | Good - except for sulfur | Moderate | Good |
| Phosphor-bronze | 220 (428) | Depends on quality of bronze. Sulfurized additives can intensify corrosion. | Good | Fair | Fair | Good |
| Copper-lead or lead-bronze with suitable overlay | 170 (338) | Good | Good | Good | Moderate | Good |

Note:
Corrosion of bearing metals is a complex subject. The above offers a general guide. Special care is required with extreme-pressure lubricants; if in doubt refer to bearing or lubricants supplier.
(Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England)

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## 10-3. Rolling-Contact Bearings

In rolling-contact bearings, the lubricant film is replaced by several small rolling elements between an inner and outer ring. In most cases the rolling elements are separated from each other by cages. Basic varieties of rolling-contact bearings include ball, roller, and thrust.

*a. Advantages of rolling-contact bearings.*

(1) At low speeds, ball and roller bearings produce much less friction than plain bearings.

(2) Certain types of rolling-contact bearings can support both radial and thrust loading simultaneously.

(3) Rolling bearings can operate with small amounts of lubricant.

(4) Rolling-contact bearings are relatively insensitive to lubricant viscosity.

(5) Rolling-contact bearings have low wear rates and require little maintenance.

*b. Types of rolling-contact bearings.*

(1) Ball bearing. This bearing has spherical rolling elements in a variety of configurations. It is able to carry both radial and moderate axial loads. A special type, called maximum-type ball bearings, can take an extra 30 percent radial load but cannot support axial loads.

(2) Roller bearing. The roller bearing has cylindrical rolling elements and can take much higher radial loads than ball bearings but can carry no axial loads.

(3) Tapered roller bearing. This type has truncated-cone shaped rolling elements and is used for very high radial and thrust loads.

(4) Double-row spherical. The bearing has a double row of keg-shaped elements. The inner surface of the outer race describes part of a sphere. This bearing can handle thrust in both directions and very high radial loads.

(5) Ball thrust. This type has ball elements between grooved top and bottom races.

(6) Straight roller thrust. This bearing has short segments of cylindrical rollers between upper and lower races. The rollers are short to minimize skidding.

(7) Spherical thrust. This type is also called a tapered roller thrust bearing. The lower race describes part of a sphere. The rolling elements are barrel-shaped and the outside has a larger diameter than the inside.

(8) Needle bearing. These bearings have rollers whose lengths are at least four times their diameter. They are used where space is a factor and are available with or without an inner race.

*c. Rolling-contact conditions.* The loads carried by the rolling elements actually cause elastic deformation of the element and race as rotation occurs. The compressive contact between curved bodies results in maximum stresses (called Hertzian contact stresses) occurring inside the metal under the surfaces involved. The repeated stress cycling causes fatigue in the most highly stressed metal. As a result, normal wear of rolling contact bearings appears as flaking of the surfaces. Lubrication carries away the excessive heat generated by the repeated stress cycles. While lubrication is necessary, too much lubrication--especially with grease lubrication--results in churning action and heating due to fluid friction.

*d. Rolling bearing lubricant selection.* In most cases, the lubricant type--oil or grease--is dictated by the bearing or equipment manufacturer. In practice, there can be significant overlap in applying these two types of lubricant to the same bearing. Often the operating environment dictates the choice of lubricant. For example, a roller bearing on an output shaft of a gearbox will probably be oil-lubricated because it is contained in an oil environment. However, the same bearing with the same rotational speed and loading would be grease-lubricated in a pillow block arrangement.

(1) Selection of lubricant. Table 10-5 provides general guidance for choosing the proper lubricant.

**Table 10-5**
**General Guide for Choosing Between Grease and Oil Lubrication**

| Factor Affecting the Choice | Use Grease | Use Oil |
|---|---|---|
| Temperature | Up to 120 °C (248 °F) - with special greases or short relubrication intervals up to 200/220 °C (392/428 °F) | Up to bulk oil temperature of 90 °C or bearing temperature of 200 °C (428 °F) - These temperatures may be exceeded with special oils. |
| Speed factor* | Up to *dn* factors of 300,000/350,000 (depending on design) | Up to *dn* factors of 450,000/500,000 (depending on type of bearing) |
| Load | Low to moderate | All loads up to maximum |
| Bearing design | Not for asymmetrical spherical roller thrust bearings | All types |
| Housing design | Relatively simple | More complex seals and feeding devices necessary |
| Long periods without attention | Yes, depending on operating conditions, especially temperature | No |
| Central oil supply for other machine elements | No - cannot transfer heat efficiently or operate hydraulic systems | Yes |
| Lowest torque | When properly packed can be lower than oil on which the grease is based | For lowest torques use a circulating system with scavenge pumps or oil mist |
| Dirty conditions | Yes - proper design prevents entry of contaminants | Yes, if circulating system with filtration |

* *dn* factor (bearing bore (mm) x speed (rev/min)).
Note: For large bearings (0.65-mm bore) and $nd_m$ ($d_m$ is the arithmetic mean of outer diameter and bore (mm)).
(Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England)

(2) Grease.

(a) Grease is used for slower rotational speeds, lower temperatures, and low to medium loads. Grease is used in situations where maintenance is more difficult or irregularly scheduled. It can be used in dirty environments if seals are provided. Tables 10-6 and 10-7 provide guidance on method of application and environmental considerations when using grease.

**Table 10-6**
**Effect of Method of Application on Choice of a Suitable Grade of Grease**

| System | NLGI Grade No. |
|---|---|
| Air pressure | 0 to 2 depending on type |
| Pressure-guns or mechanical lubricators | Up to 3 |
| Compression cups | Up to 5 |
| Centralized lubrication | 2 or below |
| (a) Systems with separate metering values | Normally 1 or 2 |
| (b) Spring return systems | 1 |
| (c) Systems with multidelivery pumps | 3 |

Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England.

**Table 10-7**
**Effect of Environmental Conditions on Choice of a Suitable Type of Grease**

| Type of Grease | NLGI Grade No. | Speed Maximum (percentage recommended maximum for grease) | Environment | Typical Service Temperature: Maximum °C | Maximum °F | Minimum °C | Minimum °F | Base Oil Viscosity (approximate values) | Comments |
|---|---|---|---|---|---|---|---|---|---|
| Lithium | 2 | 100<br>75 | Wet or dry | 100<br>135 | 210<br>275 | -25 | -13 | Up to 140 cSt at 37.7 °C (100 °F) | Multipurpose, not advised at max. speed or max. temperatures for bearings above 65-mm (2.5-in.) bore or on vertical shafts |
| Lithium | 3 | 100<br>75 | Wet or dry | 100<br>135 | 210<br>275 | -25 | -13 | | |
| Lithium EP | 1 | 75 | Wet or dry | 90 | 195 | -15 | 5 | | Recommended for roll-neck bearings and heavily-loaded taper-roller bearings |
| Lithium EP | 2 | 100<br>75 | Wet or dry | 70<br>90 | 160<br>195 | <br>-15 | <br>5 | 14.5 cSt at 98.8 °C (210 °F) | |
| Calcium (conventional) | 1, 2, and 3 | 50 | Wet or dry | 60 | 140 | -10 | 14 | 140 cSt at 37.7 °C (100 °F) | |
| Calcium EP | 1 and 2 | 50 | Wet or dry | 60 | 140 | -5 | 25 | 14.5 cSt at 98.8 °C (210 °F) | |
| Sodium (conventional) | 3 | 75/100 | Dry | 80 | 175 | -30 | -22 | 30 cSt at 37.7 °C (100 °F) | Sometimes contains 20% calcium |
| Clay | | 50 | Wet or dry | 200 | 390 | 10 | 50 | 550 cSt at 37.7 °C (100 °F) | |
| Clay | | 100 | Wet or dry | 135 | 275 | -30 | -22 | Up to 140 cSt at 37.7 °C (100 °F) | |
| Clay | | 100 | Wet or dry | 120 | 248 | -55 | -67 | 12 cSt at 37.7 °C (100 °F) | Based on synthetic esters |
| Silicone/ lithium | | 75 | Wet or dry | 200 | 390 | -40 | -40 | 150 cSt at 25 °C (77 °F) | Not advised for conditions where sliding occurs at high speed or load |

Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England

(b) Figure 10-3 shows approximate maximum bearing speeds for grease-lubricated bearings based on the bore diameter and series of grease. Figure 10-4 provides guidance on grease life expectancy for various operating speeds (given in percent) as a function of temperature. Correction factors for use with Figure 10-3 are shown in Table 10-8.

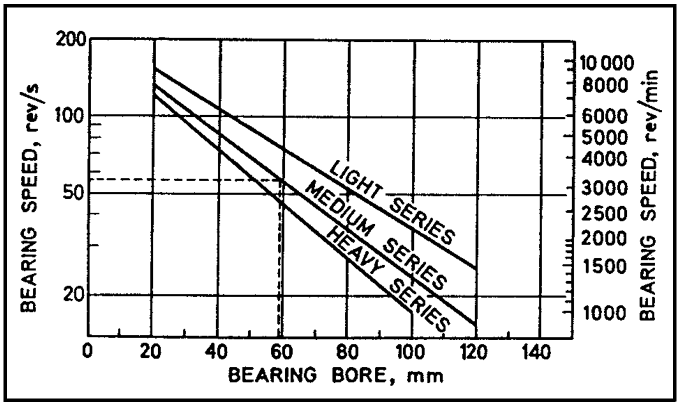


**Figure 10-3. Approximate maximum speeds for grease-lubricated bearings ((Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England)**

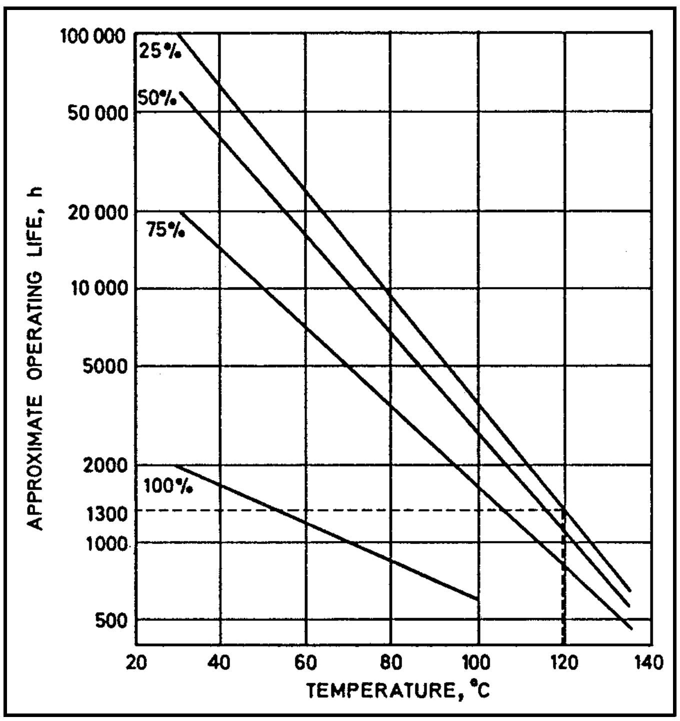


**Figure 10-4. Variation of operating life of Grade 3 lithium hydroxystearate grease with speed and temperature (Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England)**

**Table 10-8**
**Correction Factors for Figure 10-3**

| Bearing Type | | Multiply Bearing Speed from Figure 10-1 by This Factor to Get the Maximum Speed for Each Type of Bearing |
|---|---|---|
| Ball bearings and cylindrical roller bearings | Cage centered on inner race | As Figure 10-1 |
| | Pressed cages centered on rolling elements | 1.5-1.75 |
| | Machined cages centered on rolling elements | 1.75-2.0 |
| | Machined cages centered on outer race | 1.25-2.0 |
| Taper- and spherical-roller bearings | | 0.5 |
| Bearings mounted in adjacent pairs | | 0.75 |
| Bearings on vertical shafts | | 0.75 |
| Bearings with rotating outer races and fixed inner races | | 0.5 |

Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England

(3) Oil.

(a) Oil is used for higher rotational speeds and higher operating temperatures. It is used in maximum loading situations and for bearing configurations where a high amount of heat generated in the bearing can be carried away by the oil. It is used in dirty conditions when the oil is circulated and filtered. For moderate speeds, the following viscosities are recommended:

| | |
|---|---|
| Ball and cylindrical-roller bearings | 12 cSt |
| Spherical-roller bearings | 20 cSt |
| Spherical-roller thrust bearings | 32 cSt |

(b) In general, oils will be the medium to high viscosity index type with rust and oxidation inhibitors. Extreme pressure (EP) oils are required for taper-roller or spherical-roller bearings when operating under heavy loads or shock conditions. Occasionally EP oils may be required by other equipment or system components.

(c) Figure 10-5 provides a means for selecting bearing oil lubricant viscosity based on the bearing operating temperature, bore diameter, and speed. The following example shows how to use this figure. Assume a bearing bore diameter of 60 mm (2.3 in.), speed of 5000 rev/min and an operating temperature of 65 °C. To select the viscosity, locate the bore diameter then move vertically to the required speed. At this intersection move left to intersect the operating temperature. Since the required viscosity falls between an S8 and S14 oil, select the oil with the higher viscosity (S14). The correct oil selection has a viscosity of 14 cSt at 50 °C. Table 10-9 provides guidance on applying oil to roller bearings.

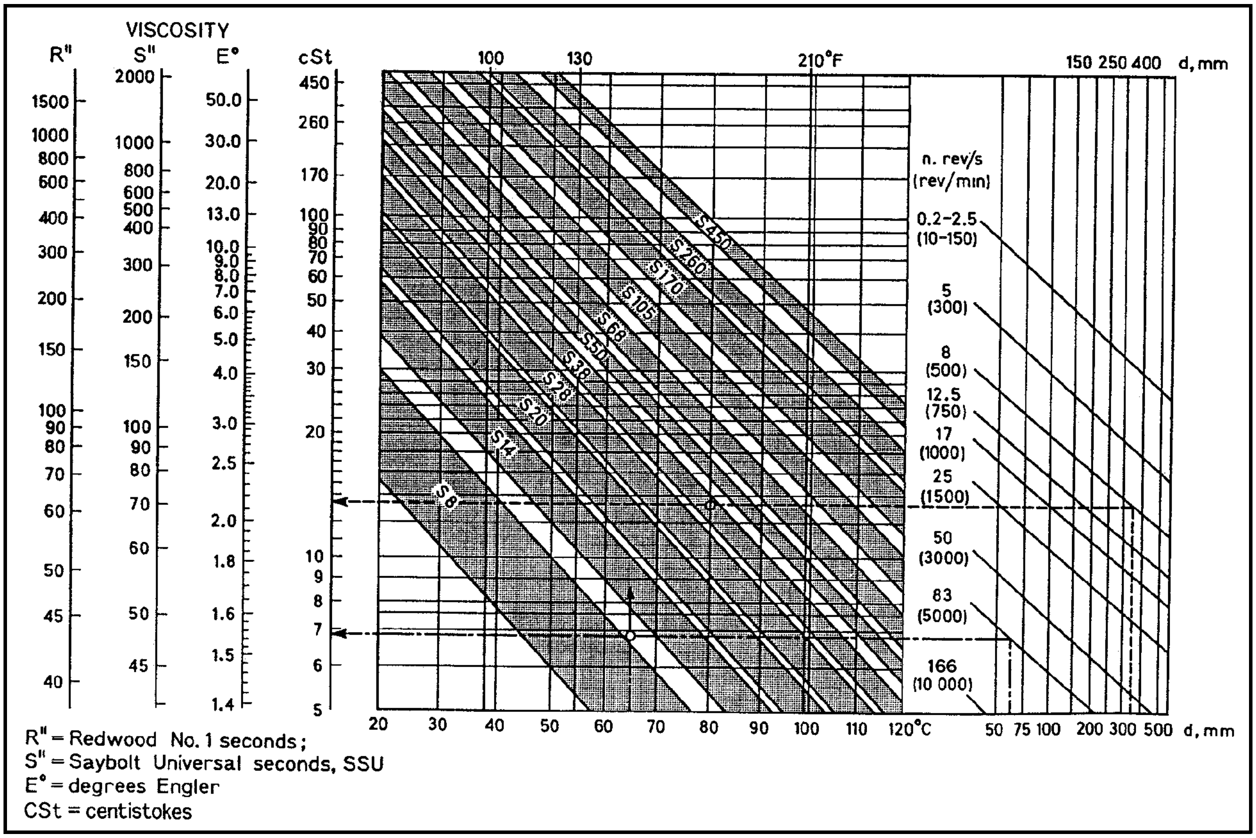


**Figure 10-5. Roller bearing oil selection (Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England)**

## 10-4 Calculation of Bearing Lubrication Interval

The following procedure for calculating lubrication intervals is extracted from Neale, "Lubrication: A Tribology Handbook" (see Appendix A for complete reference). The required interval is calculated using the data from Figures 10-3 and 10-4. The following example illustrates the procedure:

1. Given:

| | |
|---|---|
| Bearing type: | Medium series with 60-mm bore diameter |
| Cage: | Pressed cage centered on balls |
| Speed: | 950 rev/min |
| Temperature: | 120 °C (bearing temperature) |
| Position: | Vertical shaft |
| Grease: | Lithium grade 3 |
| Duty: | Continuous |

2. Determine the lubrication interval.

3. Procedure:

**Table 10-9**
**Application of Oil to Roller Bearings**

| System | Conditions | Oil Levels/Oil Flow Rates | Comments |
|---|---|---|---|
| Bath/splash | Generally used where speeds are low<br><br>A limit in *dn* value of 100,000 is sometimes quoted, but higher values can be accommodated if churning is not a problem. | Bearings on horizontal and vertical shafts, immerse half lowest rolling element<br><br>Multirow bearings on vertical shafts, fully immerse bottom row of elements | |
| Oil flingers, drip-feed lubricators, etc. | Normally as for bath/splash | Flow rate dictated by particular application; ensure flow is sufficient to allow operation of bearing below desired or recommended maximum temperature - generally between 70 °C and 90 °C (158 °F and 194 °F) | Allows use of lower oil level if temperature rise is too high with bath/splash |
| Pressure circulating | No real limit to *dn* value<br><br>Use oil mist where speeds are very high | As a guide, use: *0.6 $cm^3$/min $cm^2$ of projected area of bearing (o.d. x width) | The oil flow rate has generally to be decided by consideration of the operating temperature |
| Oil mist | No real limit to *dn* value<br><br>Almost invariably used for small-bore bearings above 50,000 rev/min, but also used at lower speeds | As a guide use: * 0.1 to 0.3 x bearing bore (cm/2.54) x no. of rows - $cm^3$/hour<br><br>Larger amounts are required for pre-loaded units, up to 0.6 x bearing bore (cm/2.54) x no. of rows - $cm^3$/hour | In some cases oil-mist lubrication may be combined with an oil bath, the latter acting as a reserve supply which is particularly valuable when high-speed bearings start to run |

* It must be emphasized that values obtained will be approximate and that the manufacturer's advice should be sought on the performance of equipment of a particular type.
Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England.

*a*. From Figure 10-3, determine the speed for a 60-mm bore medium series bearing (3100 rev/min).

*b*. Maximum speed correction factor for cage centered bearing from Table 10.8. (1.5).

*c*. Maximum speed = 1.5 x 3100 = 4650 rev/min.

*d*. Obtain correction factor for vertical shaft mounting from Table 10.8 (0.75).

*e*. Corrected speed = 0.75 x 4650 rev/min = 3,488 rev/min (this is the maximum speed rating, i.e., 100 %).

*f*. Percent of actual speed to maximum speed = 100 x [950/ 3488] = 27 %.

*g*. Refer to Figure 10-4. Using 120 °C and the 25 % line, obtain the estimated operating life = 1300 hours.

# Chapter 11
# Lubrication Applications

## 11-1. Introduction

This chapter discusses lubrication as it applies to specific equipment generally encountered at dams, hydroelectric power plants, pumping plants, and related water conveyance facilities. Lubrication of equipment related to navigation structures is also discussed. Complete coverage of all the auxiliary equipment to be encountered at these various facilities would be too extensive to include in this manual. Furthermore, a significant amount of information related to proper lubrication of this equipment is readily available. Therefore, auxiliary equipment, such as small pumps, air compressors, tools, etc., are not specifically discussed. The following discussions emphasize major equipment such as turbines, pumps, governors, gates, hoists, and gear drives. Much of this equipment is custom designed and constructed according to specifications, at significantly greater cost than off-the-shelf commercial equipment. Appendix B has results of a survey of locks and dams for lubricants and hydraulic fluids used to lubricate and operate lock gates, culvert valves, and navigation dams. Appendix C contains a procurement specification for turbine oil.

## 11-2. Turbines, Generators, Governors, and Transformers

*a. Thrust and journal bearings.*

(1) Hydro turbines, whether Francis, Pelton, or Kaplan designs, vertical or horizontal shaft, generally have a minimum of two journal bearings and one thrust bearing. These bearings consist of some form of babbitt surface bonded to a steel backing. The rotating element of the bearing is usually polished steel, either an integral part of the turbine shaft or else attached mechanically to the shaft. The thrust bearing is usually the most highly loaded bearing in the machine. The thrust bearing resists hydraulic thrust developed by the axial component of the force of the water on the turbine wheel. In the case of vertical shafts, the thrust bearing also supports the weight of the rotating parts of the hydro generator. The shaft bearings in the case of horizontal shaft machines support the weight of the rotating parts; in the case of Pelton wheels, they also support the component of the hydraulic thrust that is perpendicular to the shaft. In the case of both horizontal and vertical shaft hydro generators, the shaft bearings support and stabilize the shaft and resist the forces of imbalance.

(2) In general, the manufacturer of the hydro generator supplies, as part of the operation and maintenance data, a list of acceptable lubricating oils for the particular unit. Specifically this recommendation should include a chart of viscosities acceptable for various operating conditions. The oil recommendation will also include whether antiwear (AW) additives are necessary. The manufacturer has selected oils that will assure long life and successful operation of the equipment. The type of oil selected is usually of the general type called turbine oil. Even though this designation refers more to steam and gas turbines than hydro turbines, many of the operating requirements are similar. This makes turbine oil the most common type of commercially available lubricating oil used in hydro turbines.

(3) Most hydro turbines are connected to a plant oil system that has a centrally located oil filtration and moisture removal system. The governor system often uses oil from the same system, so in addition to lubricating the bearings, the oil must function satisfactorily in the governor. The following discussion identifies the requirements for selecting turbine lubricating oils. For additional information on lubrication and oil requirements for hydroelectric applications, refer to Corps of Engineers Engineer Manual

EM 1110-2-4205, “Hydroelectric Power Plants, Mechanical Design.” Also refer to Chapter 13 for sampling, testing, and analysis of turbine oils.

*b. Oil requirements.*

Specific oil requirements are as follows.

(1) Viscosity.

(a) The viscosity is perhaps oil’s most important quality as it is directly related to film strength. The manufacturer's operation and maintenance instructions usually contain suggested viscosities for specific operating conditions. These suggestions should be followed. In absence of such suggestions, or if the operating conditions have changed materially, or if there is compelling evidence of excessive wear that could be linked to breakdown of the oil film between stationary and moving parts, it may become necessary to revisit the viscosity selection process. Engineers at the oil company supplying the oil should be consulted about this decision. To recommend the proper oil, they will require information on dimensions of all the bearings, including area of the thrust bearing, rotational speed of the shaft, load supported by the bearings, and normal operating temperatures.

(b) Note: *when substituting or ordering lubricating oils, it is very important to use the correct units for the viscosity*. For example, many of the hydro generators in use today were built several years ago, when the most common unit of viscosity was the Saybolt Universal Seconds (SUS). Thus, a generic turbine oil called out in the O&M manual might be "Turbine Oil #44" (SUS). When the oil supplier is called for replacement oil, the closest oil number available would be "Turbine Oil #46" (cSt) if viscosity units are not mentioned. However, when the differing viscosity units are taken into account, the correct equivalent in terms of modern viscosity units would be "Turbine Oil #32" (cSt). This is probably the most common viscosity in use in hydro turbine bearings.

(2) Rust and corrosion inhibitors. The next requirement, which determines the corrosion protection provided by the oil additive package, is often denoted by the letter “R” in the lubricant’s trade name. One function of the oil must be rust protection for steel bearing surfaces because hydro turbine oils are naturally susceptible to water contamination. There is also a risk of the additive packages in the oil reacting with the metal in the bearings. Applicable standards that must be passed by the oil are:

- ASTM D 665 B, Rust Test using synthetic salt water (must be noted “Pass”).

- ASTM D 130, Copper Strip Corrosion Test, 3 hours at 100 °C (212 °F), Results 1B.

(3) Oxidation inhibitors. It is common for the lubricating oil in a hydraulic power unit to be kept in service for 20 years or more. One of the ways that the oil degrades is oxidation, which causes gums and varnishes to form. These contaminants may accumulate in narrow passages or oil system valves and damage the machine. Even though the operating temperatures are moderate, the oil is exposed to the air continuously and the extreme length of time the oil is kept in service makes it necessary to have a high-performance antioxidation package, often denoted by a letter “O” in the trade name. The oil must pass ASTM D 943, Turbine Oil Oxidation Test, and should be over 3500 hours to a 2.0 neutralization number.

(4) Antifoam additives. The oil in the bearing tubs splashes and entrains air. It is extremely difficult to lubricate with small bubbles of air in the oil, so it is important that the lubricating oil release entrained

air quickly. Additives that increase the air release rate are called antifoam additives. The oil must meet ASTM D 892 ," Foam Test," Sequence II.

(5) Water release or (demulsibility). The oil in hydro turbines often becomes contaminated with water. It is important that the oil and water not remain in emulsion as this affects the oil's film strength and causes increased oxidation and corrosion rates. The oil must pass ASTM D 1401, "Emulsion Test," at 54 °C (130 °F).

*c. Lubricant maintenance.* As there is usually a large amount of oil in the bearing oil system, it is more pertinent to discuss maintenance rather than change intervals. Usually, the facility has a testing laboratory run periodic tests on the oil. It is common for the oil company to offer this service, and this is worth consideration as the company is more familiar with factors affecting the oil's performance -- especially in the additive package. Regular sampling and testing can indicate the timing and effectiveness of filtration, can help pinpoint problem areas, and can indicate when the oil will need to be changed. The lubricant has four different areas of possible degradation: viscosity breakdown, particulate contamination, additive breakdown, and water contamination.

(1) Viscosity breakdown. The oil's ability to maintain separation between the surfaces in the bearing depends on its film strength, which is related closely to viscosity. A loss in viscosity is usually due to shearing stresses in the bearing that reduce the length of the oil molecules. An increase in viscosity usually indicates that the oil temperature is high enough that the lighter molecules are being boiled off. While this may not negatively affect the film strength, the increased viscosity can increase the bearing operating temperature.

(2) Particulate contamination. Unless the bearing surfaces are actually touching, the major cause of wear is through contamination by particles. The sources of particle contamination may be either internal or external. Internal sources may be loose particles created during run-in or oxide particles created by water in the oil. An increase in iron or other metallic oxide particles also may indicate additive breakdown. Particles may also be present in new equipment due to inadequate flushing after system run-in. External contamination may be due to dust and dirt introduced through vents, or poor filters. Contaminants may also be introduced through unclean oil-handling practices, used make-up oil, or contaminated new oil. For this reason, new oil should be tested before it is added to the system.

(3) Additive breakdown. As additives perform their intended functions they are used up. This depletion of additives may increase wear by allowing corrosion to create particles of different oxides that can damage bearings. Over-filtration may actually remove components of the additive system. As stated above, maintaining the additive package is the best reason to use a lubricant maintenance program offered by the manufacturer of the oil.

(4) Water contamination. This is the one form of degradation that can sometimes be observed visually, usually by the oil taking on a whitish, cloudy, or milky cast. This is in some ways a disadvantage. By the time enough water is mixed in the oil to be visible, the oil's film strength has been severely decreased. Thus testing for water should be performed with the other tests even if the oil does not appear to be contaminated with water.

*d. Wicket gates.*

(1) Wicket gates have two or three journal bearings and one thrust bearing or collar per gate. The journal bearings resist the hydrostatic and hydrodynamic loads involved in regulating the flow of water into

the turbine. They also resist bending in the shaft that results from the thrust of the actuating linkage. The thrust bearing or collar positions the wicket gate vertically between the upper and lower surfaces of the speed ring in the distributor. The thrust collar has to support the weight of the wicket gates but under some conditions must resist an upward thrust as well. Wicket gate bearings are subject to high loads and the shafts do not make complete revolutions, but instead move over an arc, with usually about 90 degrees of motion from completely closed to completely open. This quarter-turn usually takes 5 seconds or more. An improperly adjusted governor may hunt, moving the gates back and forth continually in an arc as small as 1 degree. Even when shaft seals are provided, the grease can come into contact with water. In the worst cases, water can wash the lubricant out of the bearings.

(2) Traditionally, wicket gate bearings have been lubricated with a lithium-based, EP NLGI-2 grease. Auto-lubrication can be used to provide fresh grease every day. Generally the bearings in the wicket gate linkages are lubricated with the same grease and by the same system. Environmental concerns have led to attempts to use environmentally acceptable greases. There are no standards for environmental acceptability, but two areas generally acknowledged to be important are biodegradability and toxicity. These areas are discussed in Chapter 8. It is important to note that greases meeting “food grade” standards do not necessarily meet any of the standards for biodegradability or toxicity.

(3) A way to reduce or eliminate the release of greases to the environment is to use self-lubricating bearings or bushings. There are many suppliers of such bushings, but there are no industry-wide standards to determine quality or longevity of these products. Use of these products should be considered on a case-by-case basis. Refer to Chapter 6, paragraph 6-3, for a description of Corps of Engineers and Bureau of Reclamation experience using greaseless bearings for this and similar applications.

*e. Governors.* A governor consists of a high-pressure pump, an accumulator tank, an unpressurized reservoir, control valves, hydraulic lines, filters, and actuators called servomotors. Servomotors develop the force that is used by the wicket gates to regulate the flow of water through the turbine, and thus the amount of power generation it generates. Governors generally utilize the same oil as is used in the hydro generator guide and thrust bearing system. Governors that operate at over 68.9 bar (1000 psi) may require an antiwear additive to the oil, but these are not common. Turbine oils operate successfully in the governor system because the requirements for the oils are very similar. For example, antifoam characteristics prevent compressible foam from being introduced into the high-pressure lines. Also RO characteristics are needed because the high-pressure pumps and the pilot valve assembly have very small clearances. Rust or other oxidation products could be transported into those clearances and cause the pump to wear or the pilot valve to stick or be sluggish, resulting in a degradation or loss of governor function. Auxiliary filters are sometimes used to keep the governor oil supply free of particulates.

*f. Transformers and oil circuit breakers.* Mineral-based insulating oil for electrical equipment functions as an insulating and cooling medium. This oil usually is produced from naphthenic base stocks and does not contain additives, except for an oxidation inhibitor. New electrical insulating oil, either provided in new equipment or purchased as replacement oil, must meet the following standards:

(1) ASTM D 3847, “Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus - Type II Mineral Oil.” This is the general specification for mineral insulating oil and contains references to more than 20 other ASTM standards that are used to determine the functional property requirements. The appendices to the standard explain the significance of the physical, electrical, and chemical properties for which the various tests are performed. One of the objectives of the standard is to specify insulating oils that are compatible and miscible with existing oils presently in service.

(2) ASTM D 4059, "Analysis of Polychlorinated Biphenyls in Insulating Liquid by Gas Chromatography Method." No detectable PCB content is permitted.

## 11-3. Main Pumps and Motors

Main pumps and motors come in various shapes and sizes, but can be divided into categories. The first dividing criterion is the orientation of the shaft. Pumps are available in vertical-shaft and horizontal-shaft configurations. The second criterion is the size of the unit. Large units are similar in layout and component size to hydro generators. Some parts are embedded, and the pump appears to be built into the pumping plant. Small units have a wide range of size, but generally have an identifiable pump and motor and often are mounted on skids or plates. For additional information on pumps and lubrication refer to Corps of Engineers Engineer Manual EM 1110-2-3105.

*a. Large units.*

(1) Large units with vertical shafts typically use journal bearings and a sliding contact thrust bearing. These units sometimes are dual-purpose, being used both as pumping units and turbine generators. There may be a plant oil system that has oil storage and filtering capabilities. RO turbine oil with viscosity 32 (cSt) is a common lubricant.

(2) Large units with horizontal shafts utilize journal bearings Each bearing has its own oil reservoir. Oil rings that rotate with the shaft pick up oil from the reservoir, and it runs or drips down into holes in the top of the bearing. Very large units may have an oil pump to provide an oil film before start-up. RO turbine oil with viscosity 32 (cSt) is a common lubricant.

*b. Small units.*

(1) Smaller vertical-shaft machines may have a variety of pumps attached to the motor, such as propeller, vertical turbine, or mixed flow. These pumps normally have a grease-lubricated suction bushing, and the rest of the bearings in the pump itself are sleeve-type -- either lubricated by the fluid being pumped (product-lubricated) or else by oil dripped into a tube enclosing the shaft bearings (oil-lubricated). There are also vertical-pumps with bronze bearings or bushings that are grease-lubricated by individual grease lines connected to grease points at floor level.

(2) Motors for the smaller vertical units generally utilize rolling-contact bearings. The upper bearing is a combination of radial and thrust bearing -- many times a single-row spherical bearing. Because of the large heat loads associated with these bearing types and conditions, they are usually oil-lubricated. The lower bearing is either a ball or roller bearing and is lubricated by grease. This bearing provides radial support and is configured in the motor to float vertically so it is not affected by axial thrust.

(3) Smaller horizontal units often have rolling-contact bearings in both pump and motor, and can be lubricated by either grease or oil. Oil-lubricated bearings will have an individual oil reservoir for each bearing that is fed by an oil-level cup that maintains the level of the oil. Grease-lubricated bearings can have grease cups that provide a reservoir with a threaded top that allows new grease to be injected into the bearing by turning the top a prescribed amount at set intervals of time. In some cases, grease nipples are provided. These receive a prescribed number of strokes from a manual grease gun at specified time intervals.

*c. Maintenance.* For all of the bearing types that use oil, the most common type of oil found is RO turbine oil. For the greased bearings, a lithium-based grease designated NLGI 2 is the most common. Maintenance problems with these machines center around oil changes and grease changes.

(1) Oil changes sometimes do little good if the oil is cold and particulate matter has been allowed to settle out. This problem is resolved by changing the oil after the pump has been running at normal operating temperature. Running the pump helps mix particles into the oil before it is drained. Another method that may work is to drain the oil, then flush the oil reservoir with warmed oil, discard the oil, then fill the bearing. This can help to dislodge foreign matter that has settled to the bottom.

(2) Another problem is condensation caused by thermal cycling of the motor as it starts and stops. A desiccant air breather on the bearing equalizing air intake will prevent extra moisture from being taken into the reservoir. Proper flushing of the oil reservoir can help carry out water that has collected in the low spots.

(3) Having adequate grease in rolling element bearings is important, but too much grease can cause overheating and bearing failure. Maintenance procedures must be followed to avoid over greasing.

(4) Bearing housings need to be disassembled and all the old grease cleaned out and replaced at intervals.

## 11-4. Gears, Gear Drives, and Speed Reducers

*a. General.* Lubrication requirements for gear sets are prescribed by the equipment manufacturers, based on the operating characteristics and ambient conditions under which the equipment will operate. Often the nameplate data on the equipment will indicate the type of lubricant required. If no lubricant is specified on the nameplate, recommendations should be obtained from the equipment manufacturer. If the manufacturer is unknown or no longer in business, a lubricant supplier should be consulted for recommendations.

*b. Gear drives.* In general, gear lubricants are formulated to comply with ANSI/AGA 9005-D94, “Industrial Gear Lubrication Standard.” Gear lubricants complying with AGA are also suitable for drive unit bearings in contact with the gear lubricant.

(1) The AGA standard is intended for use by gear designers and equipment manufacturers because it requires knowing the pitch line velocity of the gear set to select a lubricant. Because this information is rarely known, except by the gear manufacturer, the standard provides little assistance for equipment operators trying to select a gear lubricant. The superseded standards, AGA 250.01 and 250.02, require that the operators know the centerline distance for the gear sets. The centerline distance can be calculated or approximated by measuring the distance between the centerline of the driver and driven gear. Although updated standards have been in use for several years, many gear unit manufacturers and lubricant producers continue to publish selection criteria based on the old standard. Therefore, equipment operators may want to save the old standard for reference until manufacturers and producers update all their publications. When the pitch line velocity is unknown or cannot be obtained in a timely manner, an educated guess may be necessary. A lubricant can be selected by referring to the old standard and subsequently verified for compliance with the latest standard.

(2) Reference to manufacturer’s data indicates that an AGA 3 or 4 grade lubricant will cover most winter applications, and an AGA 5 or 6 will cover most summer applications. EP oil should be used for

heavily loaded low-speed equipment. Unlike the old standard, the new AGA standards no longer recommend EP oils for worm gear drives. Instead, a compounded oil such as AGA 7 Comp or 8 Comp should be used.

(3) Note that AGA provides recommended gear lubricants for continuous and intermittent operation. Inspection of some gear sets in radial gate applications at Bureau of Reclamation facilities found wear that may be attributable to use of improper oil due to runoff that left the tooth surfaces dry. The intermittent lubricant recommendations are especially important for these applications where water flow regulation requires that the gates remain in a fixed position for prolonged periods. Gear lubricants formulated for continuous operation are too thin and may run off during the standing periods, resulting in inadequate lubrication and possible gear tooth damage when the gate moves to a new position.

(4) Gear oils should be selected for the highest viscosity consistent with the operating conditions. When very low ambient temperatures are encountered, the oil viscosity should not be lowered. A reduced oil viscosity may be too low when the gears reach their normal operating temperature. If possible, oil heaters should be used to warm the oil in cold environments. The heater should be carefully sized to prevent hot spots that may scorch the oil. Another alternative is to switch to a synthetic oil that is compatible with the gear materials.

(5) Environmental concerns will have a growing impact on the development and use of lubricants. Although some lubricants are identified as food grade and have been FDA-approved and are subject to ASTM standard testing procedures, there is no worldwide standard definition or specification for environmental lubricants intended to replace standard lubricants. U.S. regulations are becoming more restrictive with regard to the contents, use, and disposal of lubricants. Four are of particular interest at the Federal level.

- Comprehensive Environmental Response Compensation and Liability Act (CERCLA), which imposes liability for cleaning up contamination caused by hazardous substances.

- Resource Conservation and Recovery Act (RCRA), which regulates hazardous waste and solid waste.

- Superfund Amendments and Reauthorization Act (SARA) - Extended and amended CERCLA to include toxicological profiles of hazardous substances.

- Toxic Substance Control Act (TSCA), which governs the manufacturing, importing, distribution, and processing of all toxic chemicals. All such chemicals must be inspected and approved by the Environmental Protection Agency (EPA) before entering the market.

(6) As environmental regulations become more restrictive, finding environmentally acceptable lubricants that comply with gear drive manufacturers' specifications is becoming increasingly difficult. Product users should exercise caution when evaluating and accepting alternative lubricants to ensure that the product selected complies with the gear manufacturer's requirements.

(7) Lubrication of gear drives, such as "limitorques" used to operate gates and valves, are grease-lubricated and are covered under the lubricating requirements for gates and valves.

(8) Corps of Engineers facilities should ensure that gear lubricants conforming to the Corps Guide Specification CEGS 15005 are purchased and used for storm water pump gear reducer applications.

## 11-5. Couplings

Couplings requiring lubrication are usually spring, chain, gear, or fluid drive type. Table 11-1 provides lubricant recommendations for couplings. Additional recommendations are provided below.

**Table 11-1**
**Recommendations for the Lubrication of Gear, Spring-Type, Chain Couplings**

| | Limiting Criteria | | | | |
|---|---|---|---|---|---|
| | Centrifugal Effects | | | | |
| **Lubricant Type** | ***Pitch-line Acceleration*** $d\omega^2/2$ ***(m/sec²)*** | ***Range in Practical Units*** $Dn^2$ ***(ft/sec²)*** | **Heat Dissipation Pn** | ***Lubricant Change Period*** | ***Remarks*** |
| No. 1 Grease (mineral oil base) | $0.15 \times 10^3$<br>$0.5 \times 10^3$ | 25 max<br>25-80 | -<br>- | 2 years<br>12 months | Soft grease preferred to ensure penetration of lubricant to gear teeth |
| No. 3 Grease (mineral oil base) | $1.5 \times 10^3$<br>$5.0 \times 10^e$<br>$12.5 \times 10^3$ | 80-250<br>250-850<br>850-2000 | -<br>-<br>- | 9 months<br>6 months<br>3 months | Limitation is loss of oil causing hardening of grease; No. 3 grease is more mechanically stable than No. 1 |
| Semifluid polyglycol grease or mineral oil | $45.0 \times 10^3$ | 3000-5000 | $230 \times 10^3$ max | 2 years | Sealing of lubricant in coupling is main problem |

d = pcd, m; D = pcd, ft; ω = rads/sec; n = rev/sec; P = hp transmitted
Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England

*a. General lubrication.* Lubrication should follow the manufacturer's recommendations. When no suitable recommendations are available, NLGI No 1 to 3 grease may be used for grid couplings. Gear and chain couplings may be lubricated with NLGI No. 0 to 3 grease.

*b. Grease-lubricated couplings.*

(1) Normal applications. This condition is descriptive of applications where the centrifugal force does not exceed 200 g (0.44 lb), motor speed does not exceed 3600 rpm, hub misalignment does not exceed three-fourths of 1 degree, and peak torque is less than 2.5 times the continuous torque. For these conditions, an NLGI No. 2 grease with a high-viscosity base oil (higher than 198 cSt at 40 °C (104 °F) should be used.

(2) Low-speed applications. This application includes operating conditions where the centrifugal force does not exceed 10 g (0.2 lb). If the pitch diameter "*d*" is known, the coupling speed "*n*" can be estimated from the following equation (Mancuso and South 1994):

$$n = \frac{200}{\sqrt{d}}$$

Misalignment and torque are as described for normal conditions in (1) above. For these conditions an NGLI No. 0 or No. 1 grease with a high-viscosity base oil (higher than 198 cSt at 40 °C (104 °F)) should be used.

(3) High-speed applications. This condition is characterized by centrifugal forces exceeding 200 g (0.44 lb), misalignment less than 0.5 degrees, with uniform torque. The lubricant must have good resistance to centrifugal separation. Consult a manufacturer for recommendations.

(4) High-torque, high-misalignment applications. This condition is characterized by centrifugal forces less than 200 g (0.44 lb), misalignment greater than 0.75 degrees, and shock loads exceeding 2.5 times the continuous torque. Many of these applications also include high temperatures (100 °C (212 °F), which limits the number of effective greases with adequate performance capability. In addition to the requirements for normal operation, the grease must have antifriction and antiwear additives (polydisulfide), extreme pressure additives, a Timken load greater than 20.4 kg (40 lb), and a minimum dropping point of 150 °C (302 °F).

*c. Oil-lubricated couplings.* Most oil-filled couplings are the gear type. Use a high-viscosity grade oil not less than 150 SUS at 36.1 °C (100 °F). For high-speed applications, a viscosity of 2100 to 3600 SUS at 36.1 °C (100 °F) should be used.

## 11-6. Hoist and Cranes

*a. General.* Various types of hoisting equipment are used in hydroelectric power plants and pumping plants, including gantry cranes, overhead traveling cranes, jib cranes, monorail hoists, and radial gate hoists. The primary components requiring lubrication are gear sets, bearings, wire ropes, and chains. The lubrication requirements for gear sets should comply with the same AGA requirements for gears discussed above. Lubrication of wire ropes and chains used in hoists and cranes is discussed later in this chapter.

*b. Hydraulic brakes.* Hydraulic brakes are commonly found on cranes and hoists. Both drum and disk brakes are used in these applications. Components closely resemble automotive parts and similar brake fluids are used. Brake fluid is glycol-based and is not a petroleum product. Hydraulic brake fluid has several general requirements:

- It must have a high boiling temperature.
- It must have a very low freezing temperature.
- It must not be compressible in service.
- It must not cause deterioration of components of the brake system.
- It must provide lubrication to the sliding parts of the brake system.

(1) Hydraulic brake fluids are acceptable for use if they meet or exceed the following requirements:

(a) Federal Motor Vehicle Safety Standard (FMVSS) No. 116 (DOT 3). This includes a dry boiling temperature of 205 °C (401 °F). This is commonly known as DOT 3 brake fluid. Some industrial braking systems require Wagner 21B fluid, which is a DOT 3 fluid with a 232 °C (450 °F) dry boiling temperature and containing additional lubrication and antioxidation additives.

(b) Society of Automotive Engineers (SAE) Specification J1703 - Motor Vehicle Brake Fluid. This standard assures all the necessary qualities of the brake fluid and also assures that fluids from different manufacturers are compatible.

(2) SAE Recommended Practice J1707, "Service Maintenance of SAE J1703, Brake Fluids in Motor Vehicle Brake Systems." This guidance provides basic recommendations for general maintenance procedures that will result in a properly functioning brake system. The largest problem with glycol brake fluids is that they absorb moisture from the atmosphere. If left in service long enough, the brake fluid will become contaminated with water, and this can cause brake failure. Water can collect in the lowest part of the system and cause corrosion, which damages seals or causes leak paths around them. DOT 3 brake fluid that is saturated with water will have its boiling temperature reduced to 140 °C (284 °F). If water has separated out, the brake fluid will have a boiling temperature of 100 °C (212 °F). Under heavy braking, the temperature of the brake fluid can become so high that the brake fluid will boil or the separated water will flash into steam and make the brake fluid very compressible. This will result in loss of braking capacity, from spongy brakes to a complete loss of braking function. Brake fluid should be completely replaced every 3 years unless the manufacturer's recommended interval is shorter. Also if brake fluid deterioration is noticeable due to a high-humidity working environment it should also be replaced more frequently. Because brake fluid so readily absorbs moisture from the air, only new dry fluid from unopened containers should be used as a replacement. This means that brake fluid left over from filling or refilling operations should be discarded. For this reason it is recommended that the user purchase brake fluid in containers small enough that the fluid can be poured directly from the original container into the brake system fill point. Under no circumstances should brake fluid be purchased in containers larger than 3.7 liters (1 gallon).

## 11-7. Wire Rope Lubrication

*a. Lubricant-related wear and failure.* Wear in wire ropes may be internal or external. The primary wear mode is internal and is attributed to friction between individual strands during flexing and bending around drums and sheaves. This condition is aggravated by failure of the lubricant to penetrate the rope. Additional information on wire rope selection, design, and lubrication can be found in Corps of Engineer Engineer Manual EM 1110-2-3200, "Wire Rope Selection."

(1) Corrosion. Corrosion damage is more serious than abrasive damage and is usually caused by lack of lubrication. Corrosion often occurs internally where it is also more difficult to detect. Corrosion of wire ropes occurs when the unprotected rope is exposed to weather, to corrosive environments such as submergence in water (especially salt water), or to chemicals. Corrosion results in decreased tensile strength, decreased shock or impact-load resistance, and loss of flexibility. Unprotected wire ropes that are used infrequently have a greater potential for rust damage due to moisture penetration. Rust may prevent relative sliding between wires, creating increased stresses when the rope is subsequently placed in service.

(2) Abrasion. A common misconception among facility operators is that stainless steel ropes do not require lubrication. This misconception is probably due to corrosive operating conditions. This misconception is easily corrected by considering a wire rope as a machine with many moving parts. The typical wire rope consists of many wires and strands wrapped around a core. A typical 6 x 47 independent wire rope core (IWRC ) rope, is composed of 343 individual wires that move relative to each other as the rope is placed under load or wrapped around a drum. During service these wires are subject to torsion, bending, tension, and compression stresses. Like all machine parts, ropes also wear as a result of abrasion and friction at points of moving contact. Therefore proper lubrication is essential to reduce friction and wear between the individual wires and to ensure maximum performance.

*b. Lubrication.* During operation, tension in the rope and pressure resulting from wrapping around drums forces the internal lubricant to the rope surface where it can be wiped or washed off. Tests conducted on dry and lubricated rope operating under similar conditions provide ample evidence of the beneficial effects of lubrication. The fatigue life of a wire rope can be extended significantly (200 to 300 percent) through the application of the correct lubricant for the operating conditions. However, under certain operating conditions lubrication may be detrimental. Unless recommended by the rope manufacturer, wire rope operating in extremely dirty or dusty environment should not be lubricated. Abrasives may combine with the lubricant to form a grinding compound that will cause accelerated wear. In applications where ropes undergo frequent and significant flexing and winding around a drum, the rope should be lubricated regardless of whether the wire rope is constructed from stainless steel. However, Corps of Engineers experience has shown that wire ropes used in fairly static applications, where flexing and winding are minimal, should not be lubricated. Tests have shown that lubricated ropes may actually experience more severe corrosion than unlubricated ropes because the lubricant tends to tap and seal moisture in the voids between the wires.

*c. Lubricant qualities.*

(1) To be effective, a wire rope lubricant should:

(a) Have a viscosity suitable to penetrate to the rope core for thorough lubrication of individual wires and strands.

(b) Lubricate the external surfaces to reduce friction between the rope and sheaves or drum.

(c) Form a seal to prevent loss of internal lubricant and moisture penetration.

(d) Protect the rope against external corrosion.

(e) Be free from acids and alkalis.

(f) Have enough adhesive strength to resist washout.

(g) Have high film strength.

(h) Not be soluble in the medium surrounding it under actual operating conditions.

(i) Not interfere with the visual inspection of the rope for broken wires or other damage.

(2) New wire rope is usually lubricated by the manufacturer. Periodic lubrication is required to protect against corrosion and abrasion and to ensure long service life. Wire rope lubricants may require special formulations for the intended operating conditions (for example, submerged, wet, dusty, or gritty environments). The rope manufacturer's recommendations should always be obtained to ensure proper protection and penetration. When the manufacturer's preferred lubricant cannot be obtained, an adhesive-type lubricant similar to that used for open gearing may be acceptable.

(3) Two types of lubricants are generally used: oils and adhesives. Often mineral oil, such as an SAE 10 or 30 motor oil, is used to lubricate wire rope. The advantage of a light oil is that it can be applied cold with good penetration. However, the light oil may not contain adequate corrosion inhibitors for rope applications. Also, it tends to work out of the rope just as easily as it works in, necessitating frequent applications.

(4) Heavy, adhesive lubricants or dressings provide longer lasting protection. To ensure good penetration, these lubricants usually require thinning before applying. Thinning can be accomplished by heating the lubricant to a temperature of 71.1 to 93.3 °C (160 to 200 °F), or by diluting with a solvent. A properly applied heavy lubricant will provide both internal lubrication and a durable external coating to prevent corrosion and penetration of dust and abrasives.

(5) In addition to the qualities noted above, good adhesive lubricants or rope dressings:

(a) Must not cake, gum, or ball up when contaminated with dust and dirt.

(b) Must not thin and drip at the highest operating temperature.

(c) Must not become brittle or chip at the lowest operating temperature.

(d) Should have inherently high viscosity without adding thickeners or fillers.

(6) When damp conditions prevail, or when severe flexing under heavy loads is encountered, a two-stage lubricant application may be the most effective. Application of a lighter adhesive followed by a very heavy adhesive lubricant to seal in the oil provides the best protection. In certain ropes subjected to highly corrosive environments such as acids, alkalis, or salt water, providing a heavy impervious exterior lubricant coating to guard against corrosion may be more important than ensuring adequate penetration.

(7) Wire rope lubricants can be applied by brush, spray, drip, or -- preferably -- by passing the rope through a heated reservoir filled with the lubricant. Before application the rope must be cleaned of any accumulated dirt, dust, or rust to ensure good penetration. The lubricant should be applied to the entire circumference of the rope and the rope slowly wound on and off the drum several times to work the lubricant into the rope. If the lubricant is being applied by hand it may be helpful to apply the lubricant as it passes over a sheave where the rope's strands are spread by bending and the lubricant can penetrate more easily.

*d. Rope applications and lubricant requirements.* There are five general rope application categories based on operating conditions: industrial or outdoor, friction, low abrasive wear and corrosion, heavy wear, and standing. These conditions are summarized in Table 11-2. Each of these conditions has its own lubrication requirements.

(1) Industrial or outdoor applications. This category includes mobile, tower, and container cranes. Internal and external corrosion are possible, but external corrosion is the more serious and deserves primary consideration. Desirable lubricant qualities include good penetration into the wires and core, moisture displacement, corrosion protection, resistance to washout and emulsification, and freedom from buildup due to repeated applications. The best lubricants for these applications are solvent-based that leave a thick, semidry film after evaporation of the solvent. A tenacious semidry film will minimize adhesion of abrasive particles that cause wear. Thin-film lubricants such as $MoS_2$ and graphite are not recommended because they tend to dry, causing surface film breakdown and subsequent exposure of the wires.

(2) Friction applications. This category includes elevators, friction hoists, and capstan winches. Fatigue and corrosion are the primary considerations. Desirable lubricant qualities include corrosion protection, internal lubrication, moisture displacement, lubricant buildup prevention, and minimizing loss of friction grip. Note that unlike other lubrication applications, where efforts are made to reduce friction,

**Table 11-2**
**Lubrication of Wire Ropes in Service**

| | Operating Conditions | | | | |
|---|---|---|---|---|---|
| | (1) Ropes working in industrial or marine environments | (2) Ropes subject to heavy wear | (3) Ropes working over sheaves where (1) and (2) are not critical | (4) As (3) but for friction drive applications | (5) Standing ropes not subject to bending |
| Predominant cause of rope deterioration | Corrosion | Abrasion | Fatigue | Fatigue - corrosion | Corrosion |
| Typical applications | Cranes and derricks working on ships, on docksides, or in polluted atmospheres | Mine haulage, excavator draglines, scrapers, and slushers | Cranes and grabs, jib suspension ropes, piling, percussion, and drilling | Lift suspension, compensating and governor ropes, mine hoist ropes on friction winders | Pendant ropes for cranes and excavators. Guys for masts and chimneys |
| Dressing requirements | Good penetration to rope interior. Ability to displace moisture. Internal and external corrosion protection. Resistance to "wash off." Resistance to emulsification | Good antiwear properties. Good adhesion to rope. Resistance to removal by mechanical forces | Good penetration to rope interior. Good lubrication properties. Resistance to "fling off." | Non-slip property. Good penetration to rope interior. Ability to displace moisture. Internal and external corrosion protection | Good corrosion protection. Resistance to "wash off." Resistance to surface cracking. |
| Type of lubricant | Usually a formulation containing solvent leaving a thick (0.1 mm) soft grease film | Usually a very viscous oil or soft grease containing $MoS_2$ or graphite. Tackiness additives can be of advantage | Usually a good general purpose lubricating oil of about SAE 30 viscosity | Usually a solvent-dispersed temporary corrosion preventative leaving a thin, semihard film | Usually a relatively thick, bituminous compound with solvent added to assist application |
| Application technique | Manual or mechanical | Manual or mechanical | Mechanical | Normally by hand | Normally by hand |
| Frequency of application* | Monthly | Weekly | 10/20 cycles per day | Monthly | Six monthly/2 years |

* The periods indicated are for the general case. The frequency of operation, the environmental conditions, and the economics of service dressing will more correctly dictate the period required.
Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd, Oxford, England

in this instance a desirable quality includes increasing the coefficient of friction. A solvent-based dressing that deposits a thin slip-resistant semidry film offers the best protection.

(3) Low abrasive wear and corrosion applications. This category includes electric overhead cranes, wire rope hoists, indoor cranes, and small excavators. Internal wear leading to fatigue is the primary

consideration. Maximum internal and external lubrication are essential. Mineral-oil-base lubricants such as SAE 30 are commonly accepted as the best alternative, but these oils provide minimal corrosion protection and tend to run off. The best alternative is to use a lubricant specifically designed for wire rope applications. These lubricants contain corrosion inhibitors and tackiness agents. Thin-film dry lubricants such as $MoS_2$ and graphite are also commonly used, but claims of increased fatigue life attributed to these lubricants have been questioned by at least one wire rope manufacturer.

(4) Heavy wear applications. This category includes ropes used in excavators, winches, haulage applications, and offshore mooring systems and dredgers. Protection against abrasion is the primary consideration. Desirable lubricant qualities include good adhesion, crack and flake resistance, antiwear properties, resistance to moisture, emulsification, and ultraviolet degradation, and corrosion-resistance -- especially in offshore applications. The best lubricants are those with thixotropic (resistance to softening or flow under shear) characteristics to ensure good lubricity under shearing action. These lubricants offer good penetration, and they resist cracking and ultraviolet degradation. Viscous oils or soft grease containing $MoS_2$ or graphite are commonly used. Tackiness additives are also beneficial.

(5) Standing rope applications. This category includes guy and pendant ropes for onshore use, and towing cables, cranes, derricks, and trawl warps for offshore applications. Corrosion due to prolonged contact in a corrosive environment is the primary consideration. Desirable lubricant qualities include high corrosion protection, long-term stability over time and temperature, good adhesion, and resistance to wash-off, emulsification, and mechanical removal. The best lubricants are thixotropic oils similar to those required for heavy-wear applications, except that a higher degree corrosion-resistance additive should be provided.

## 11-8. Chain Lubrication

Drive chains combine the flexibility of a belt drive with the positive action of a gear drive. Various designs are available. The simplest consist of links that are rough cast, forged, or stamped. These chains are seldom enclosed and therefore exposed to various environmental conditions. They are generally limited to low-speed applications and are seldom lubricated. Roller chains have several moving parts and, except for the self-lubricating type, require periodic lubrication. Lubricants should be applied between the roller and links to ensure good penetration into the pins and inner bushing surfaces.

*a. Lubricant-related wear and failure.*

(1) Like wire ropes, chains experience both internal and external wear. Internal wear generally occurs on the pins and adjacent bearing surface of the roller bushing, and at the link surfaces. Wear is attributed to friction between metal contacting surfaces. Use of improper lubricant, inadequate lubricant penetration into the pin and bushing clearances, poor lubricant retention, and inadequate or infrequent lubrication are the primary causes of premature wear. Poor chain designs, such as those that provide no grease fittings or other lubricating schemes, also contribute to premature wear.

(2) Corrosion damage is a serious problem and often occurs internally where it is difficult to detect after the chain is assembled and placed in service. Corrosion occurs when the unprotected chain is exposed to weather or corrosive environments such as prolonged submergence in water. Corrosion results in decreased tensile strength, decreased shock or impact-load resistance, and loss of flexibility.

*b. Lubricant characteristics.* The most important considerations in chain lubrication are boundary lubrication and corrosion. Chain life can be extended through the proper selection and application of lubricant for the operating conditions. An effective chain lubricant should possess the following characteristics:

(1) Have a viscosity that will enable it to penetrate into the link pins and bearings.

(2) Lubricate the external surfaces to reduce friction between the sliding link surfaces and chain sprockets.

(3) Form a seal to prevent moisture penetration.

(4) Protect the chain against corrosion.

(5) Be free of acids and alkalis.

(6) Resist washout.

(7) Have high film strength.

(8) Not be soluble in the medium surrounding it under actual operating conditions.

(9) Displace water.

(10) Not cake, gum, or ball up when contaminated with dust and dirt.

(11) Not thin and drip at the highest operating temperature.

(12) Not become brittle, peel, or chip at the lowest operating temperature.

*c. Lubrication problems.*

(1) Most chains, such as those used on conveyors, transporters, and hoists, are accessible and easily lubricated while in service. Lubrication of these chains is generally accomplished through oil baths, brushing, or spray applications.

(2) Lubrication of tainter (radial) gate chains poses an especially difficult challenge. Chain design, construction, application, and installation often render them inaccessible. The operating constraints imposed on these gates include water flow regulation, changing water surface elevations, poor accessibility, and infrequent and minimal movement. These gates may remain in fixed positions for prolonged periods. The submerged portions of chains have a significantly greater potential for rust damage due to exposure to corrosive water, lubricant washout, and moisture penetration into the link pins and bearings. Infrequent movement and inaccessibility adversely affect the frequency of lubrication.

*d. Lubricants.*

(1) Typical chain lubricants include light general purpose mineral oils, turbine oils, gear oils, penetrating fluids, and adhesives. Light oils may be adequate for continuous chains exposed to oil baths. Synthetic sprays employing solid lubricants such as graphite, $MoS_2$, and PTFE are also common. When the potential for environmental contamination or pollution is a major concern, food-grade lubricant may be required to prevent contamination of water supplies. When manufacturer's data are not available,

recommended lubricants are shown below. For heavily loaded chains, the extreme pressure (EP) grades should be used.

- Low speed--0 to 3 m/s (0 to 10 ft/s) :
  below 38 °C (100°F) ISO 100 (AGMA 3).
  above 38 °C (100 °F) ISO 150 (AGMA 4)

- Medium speed--3 to 9 m/s (10 to 30 ft/s):
  below 38 °C (100 °F) ISO 150 (AGMA 4)
  above 38 °C (100 °F) ISO 220 (AGMA 5)

(2) Chain lubricants may require special formulation or incorporation of multiple lubricants to cope with severe operating conditions including submerged, wet, dusty, and gritty environments. When possible, the chain manufacturer should be consulted for lubricant recommendations. If the recommended lubricant is not available, a lubricant manufacturer can recommend a substitute lubricant for the application provided the operating conditions are accurately described. When necessary, an adhesive-type lubricant similar to that used for open gearing may be acceptable.

(3) Heavy roller chains such as those used in radial gate applications require heavier lubricants to ensure adequate protection over prolonged periods of submergence without benefit of periodic lubrication. Chain lubricants used in this application must be especially resistant against washout.

(4) New or rebuilt gate chains are usually lubricated during assembly, but periodic lubrication is required to protect against corrosion and abrasion and to ensure long service life. A properly applied lubricant will provide both internal lubrication and a durable external coating to prevent corrosion and penetration of dust and abrasives.

(5) The following example is provided to stress the complex nature of certain lubricant applications, such as heavily loaded roller chains. In a 1996 radial gate rehabilitation at Folsom Dam, a three-stage lubricant application was used during assembly of the new lift chains. The procedure was recommended by Lubrication Engineers, Inc., based on their experience with similar applications. The Folsom chains were not fitted with grease fittings , so once reassembled, the pins and bushings could not be lubricated. An initial coat of open gear lubricant was applied to the pins and bushings. This coating provided primary protection for the internal parts of the chain which would be inaccessible after the chain was placed in service. After assembly, the entire chain received a coat of wire rope lubricant. This is a penetrating fluid that will lubricate assembled areas of the chain that the final coat will not penetrate. The final coat consisted of open gear lubricant similar to initial coating except that the product contained a solvent for easier application -- especially at low temperatures. After evaporation of the solvent, the remaining lubricant has characteristics similar to the initial coating. The top coat must be reapplied as necessary to ensure lubrication and corrosion-protection between the sliding links.

(6) Although the multistage lubricant application described above was conducted on new chain, it may also be possible to extend the service life of existing chains by using this procedure. However, since this work is labor-intensive and requires placing the affected gate out of service, the economics and logistics must be considered.

*e. Lubricant application.* The need for lubrication will be evident by discoloration appearing as reddish-brown deposits. Often bluish metal discoloration can be detected. Chains can be lubricated by various methods including brush, oil can, spray, slinger, dip, pump, or oil mist. The method of application depends on operating conditions such as load, speed, and size and whether the components are exposed or enclosed. Lubricant should be applied to the lower strand of the chain immediately before engaging the gear or sprocket. Centrifugal action will force the lubricant to the outer areas.

## 11-9. Trashrake Systems and Traveling Water Screens

*a. Gear drives.* The most common drive units are standard speed-reducers using helical gears, although worm gears are also used. Lubrication requirements for these gear drives are similar to those discussed in the gear lubrication section above.

*b. Couplings*. All types may be used. The lubrication requirements are similar to those discussed above.

*c. Chains.* Roller chains are the most common type used. The lubrication should be selected according to the requirements outlined in the section on chain lubrication above.

*d. Hydraulic operated trashrakes.* These trashrakes use a hydraulically operated boom. Bureau of Reclamation projects specify a food-grade polymer oil complying with Code of Federal Regulations 21 CFR 178.3570 and USDA H1 authorization for food-grade quality. The oil must also comply with ASTM D 2882 for hydraulic pump wear analysis.

*e. Bearings.* Trashrake conveyor belts or systems are commonly provided with rolling contact bearings, either in the ends of the rollers or in pillow block bearings. These bearings are normally manually lubricated with NLGI 2 lithium-based grease.

## 11-10. Gates and Valves

Various gates and valves and essential lubricated components for each are listed and discussed below. The lubricated components discussed below also apply to unlisted gates and valves that incorporate these same components. Hydraulic fluids for operating systems are also discussed. The discussion of gate trunnions provides more detail as it encompasses “lessons learned” from the investigation of a 1995 tainter gate failure at Folsom Dam. Recommended frequencies of lubrication are noted, but frequency should be based on historical data. Each component has its own effect on lubricants, and each facility should pattern its frequency of lubrication around its own particular needs. For example, lock culvert valves such as tainter gates are lubricated more frequently than tainter gates on spillways of water storage dams because culvert valves are operated much more often. The manufacturer’s schedule should be followed until operating experience indicates otherwise. Gates and valves, and their lubricated components (shown in italics), are:

- Tainter (radial) gates and reverse tainter gates. *Trunnions.*

- Other lubricated hinged gates. *Same lubricant as trunnions*.

- Bonneted gates, including outlet, ring-follower, and jet-flow gates. *Seats, threaded gate stems, gears for electrically and manually operated lifts.*

- Unbonneted slide gates. *Threaded gate stems, gears for electrically and manually operated lifts.*

- Roller-mounted gates, including stoney. *Roller trains and roller assemblies.*

! Ring-seal and paradox gates. *Roller trains and roller assemblies.*

! Wheel-mounted, vertical-lift gates. *Wheel bearings.*

! Roller gates. *See chains.*

! Butterfly, sphere, plug valves. *Trunnions. Gears for electrically and manually operated lifts.*

! Fixed cone valves. *Threaded drive screws, gears for electrically and manually operated lifts.*

*a. Trunnions.* Grease for trunnions should be selected for high-load, low-speed applications (boundary lubrication). Other considerations include frequency of operation, trunnion friction, temperature range, condition of bearing surfaces (rust, scuffing, etc.), whether the trunnions are exposed to sunlight or submerged, and contaminants such as moisture and debris. During the warranty period, specific greases are recommended by equipment manufacturers and should be used. If another grease is desired, the testing of a number of greases by a qualified lubricant expert to the exacting conditions of the application will determine the optimal grease. However, testing can be expensive and is not necessary unless highly unusual conditions exist. Suitable greases can be identified by finding out what works at other facilities that use the same equipment under similar conditions. . Commonly used greases and lubrication frequencies for trunnions on gates and culvert valves at navigational dams and locks are noted in the survey in Appendix B. Also, lubricant suppliers are readily available to recommend a grease, but they should be advised of all conditions for the particular application.

(1) Recommended greases and desirable properties from field experience.

A spillway tainter gate failure at Folsom Dam in 1995 led to an investigation and testing of greases for trunnions. Table 11-3 lists desirable grease properties for the Folsom Dam trunnion bearings. Details of the investigation may be found in the report "*Folsom Dam Spillway Gate 3 Failure Investigation Trunnion Fixture Test,*" prepared by the U.S. Bureau of Reclamation Mid-Pacific Regional Office, July 1997. The properties compiled for the trunnions at Folsom Dam are applicable to trunnions in general. Table 11-3 shows the purpose of the grease property, base oils for grease, grease gelling (thickening) agents, additives, and ASTM grease test and properties. Further explanation of desirable trunnion grease properties are as follows:

(a) Lubricity. Low breakaway (static) and running (kinetic) friction and no stick-slip are necessary for smooth gate and valve operation. The grease should possess good lubricity for low start-up and running torque.

(b) Rust prevention. Rust on a trunnion pin thickens with time. This thickening takes up bearing clearance, soaks up the oil from grease, prevents film formation, causes high friction, and abrades bronze bushing material. Since rust takes up about 8 times the volume of the iron from which it is formed, it is very important for trunnion pin grease to inhibit rust.

(c) Low corrosion of leaded bronze. Grease degradation products such as organic acids and chemically active sulfur and chlorine compounds used in gear oils can corrode leaded bronze bushings. Some light tarnishing is acceptable, but excessive corrosion is indicated by stains, black streaks, pits, and formation of green copper sulfate from sulfuric acid.

**Table 11-3**
**Desirable Grease Properties for the Folsom Dam Trunnion Bearings. (Reference: "Lubricating Grease Guide," NLGI 4th Ed., 1996)**

| Purpose of Grease Property (a) | Examples of Composition | | | | | | ASTM Test | |
|---|---|---|---|---|---|---|---|---|
| | | | Additives | | | | | |
| | Base Oil | Gelling Agent | Type | % | Chemical | Number | Desired Result | Maximum |
| Lubricity, that is, low static and kinetic friction for bronze on steel | Mineral or synthetic including polyol ester, jojoba oil, vegetable oils | Lithium or calcium soaps, or polyurea | Lubricity (reduction of friction) | 2.5 | Fatty materials, oleic acid, oleyl amine, jojoba oil | D 99-95 Pin-on-disk apparatus applicable | Coefficient of static friction, fs, (breakaway), 0.08, (b) Coefficient of kinetic friction at 5.1 mm/min (0.2-inch/ min, fk, 0.10) | fs,0.10, (b) fk, 0.12 |
| Prevent rusting of steel | Mineral, or synthetic | Calcium, lithium or aluminum complex soaps, or calcium sulfonates, or polyurea | Rust inhibitors, calcium sulfonate | 0.2 to 3 | Metal sulfonates, amines | D 1743-94 | Pass- no rusting of steel after 48 hours in aerated water | Pass |
| Low corrosion of leaded bronze (Cu 83, Sn 8, Pb 8%) | Mineral, or synthetic | Lithium or calcium sulfonate and soaps, or polyurea | Corrosion inhibitors, metal deactivators | 0.2 to 3 | Metal sulfonates phosphites | D 4048 (copper strip) | 1 to 1B | 4C |
| Prevent scuffing of steel vs bronze | Mineral or synthetic | Lithium or calcium soaps, or polyurea | Antiscuff (EP) | 1 to 2 | Sulfur and phosphorous compounds, sulfurized fats, ZDDP | D 99-95, bronze pin vs steel disk | No scuffing, that is, transfer of bronze to steel. "EP" film formation | No scuffing |
| Resists wash-out by water | Mineral or synthetic | Polyurea or calcium hydroxystearate | - | - | - | D 1264-93 | 0 wash-out | 1.9% |
| Does not "harden" in pipes | Mineral or synthetic | Lithium or calcium soaps or polyurea | - | - | - | | No change in consistency with aging | No change |
| Easy to pump and distribute through tubing and grooves in bronze bushing | Mineral or synthetic, ISO 100 to 150 | Polyurea, lithium or calcium soaps | - | - | - | a. D 217 | a. NLGI 1 or 1.5, cone penetration 340 to 275, b. Pumps through 7.62 m to 0.0762 m (25' to 1/4") copper tubing | NLGI 2 |
| Adherence to metal, and retention in areas of real contact of trunnion | Mineral or synthetic | Lithium or calcium soaps or polyurea | Tackiness agent | | Polymers, isobutylene or polyethelene | none | Slightly tacky between metals | Slightly tacky |
| Long life, oxidation stable | Mineral or synthetic | Polyurea | Oxidation inhibitors | | Amines, phenols, sulfur compounds | D 942-90 | Pass, also no acid formation, odor, or discoloration. | Pass |
| Low bleeding, oil does not separate from grease excessively | Mineral or synthetic | Lithium or calcium soaps or polyurea | High-viscosity base oil | - | - | D 1742-94 and Federal Test | Limited "bleeding" of oil, less than 0.1% | 1.6% in 24 hr, 3% in 48 hr. |

(a) Applied to low carbon (SAE1045) steel pin 812.7 mm (32") diam., rotating in trunnion bronze bushing, at 5.1 mm/min (0.2 in/min) and 816,461 kg (1.8 million pounds) load.
dam site environment - temperature range -1.1°C to 51.6 °C (30 to 125 °F), wet, long periods of no sliding under load.
(b) Only known bench test with Pin (bronze pad)-on-Disk (1045 steel) tribometer, at Herguth Laboratories, P.O. Box B, Vallejo, CA 94590 run at 50 N (11-2 lb of force) load, 5.1 mm (0.2 inch) per minute sliding velocity, and room temperature.

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(d) Scuff prevention. Scuffing causes serious damage to surfaces in the form of metal transfer, melting, and tearing. Antiscuffing additives are activated by the heat of friction and form a surface film. If used in a trunnion grease, sulfur concentrations must be low to prevent chemical corrosion of sliding surfaces.

(e) Wash-out resistance. Especially when trunnions are submerged, the grease should be resistant to water wash-out.

(f) Pumpability. Grease should be nonhardening and flow into the load-bearing clearances of the trunnion. A grease should easily pump and flow through piping and tubing. The grease should retain its NLGI grade over long periods during any temperature fluctuations.

(g) Adherence to metal. Tackiness agents provide this characteristic

(h) Oxidation resistance. Grease oxidation will occur over long periods at dam environment temperatures. Symptoms of oxidation are discoloration, hardening, and bronze corrosion. An effective oxidation inhibitor will increase grease longevity.

(I) Low oil separation. Oil separation or “bleeding” from the gelling agent should be minimized during inactivity and storage. Excessive bleeding hardens the remaining grease because of the decreased oil-to-thickener ratio. However, some separation -- especially under pressure -- is desired so the oil and its additives can flow into the molecular-scale clearances between pin and bushing for boundary lubrication.

(j) Solid lubricants. The Folsom Dam tainter gate failure investigation recommended that molybdenum disulfide ($MoSO_2$) and polytetrafluoroethylene (PFTE) not be used in greases for tainter trunnions at Folsom. The lowest friction coefficients were achieved with greases that did not have these solid additives. Furthermore, addition of $MoSO_2$ to greases is shown to reduce their ability to prevent corrosion. Although not a factor in the Folsom Dam tainter gate failure, graphite is not recommended as an additive for lubricating trunnions because it has been found to promote corrosion.

(2) Load. Tainter gate trunnions operate under high loads and extremely low speeds. The load on the trunnion is the water-level pressure plus a portion of the gate weight. Typical design loading on tainter trunnions is 137.9 to 206.8 bar (2000 to 3000 psi) for leaded tin bronze bearing surfaces and 275.8 to 344.7 bar (4000 to 5000 psi) for aluminum bronze.

(3) Speed. Relatively speaking, a trunnion pin rotates at extremely low speeds. The tainter trunnion pins at Folsom Dam rotate at 0.002 rpm. Trunnions in reverse tainter gates at locks have faster rotational speeds than those in dam gates.

(4) Friction. Trunnion friction increases during operation as the bearing rotates. Friction increase is caused by lubricant thinning at the loaded bearing surfaces. Trunnion friction is especially critical at high water levels and low gate openings, but lessens as the gate is opened and the reservoir level drops. Typical design coefficient of friction for grease-lubricated trunnion bearings is 0.3. There was no trunnion coefficient of friction calculated into the design of the failed Folsom gate, but the friction coefficient rose to 0.3 over a long period of time, perhaps the entire life of the gate, due to rust on the trunnion pin. When new equipment is purchased or existing bushings are replaced, self-lubricated bushings are recommended. The trunnion bushings for the failed gate at Folsom Dam were replaced with self-lubricated bushings. Modern gates such as the clamshell gate are specified exclusively with self-lubricated trunnion bushings.

Typical design coefficient for self-lubricated trunnion bushings is 0.15, which translates into less structural support (to keep gate arms from buckling under friction) than for grease-lubricated bearings.

(5) Lubrication regime. Two grease lubrication regimes are applicable to trunnions operating under high-load, low-speed conditions. They are hydrostatic lubrication and boundary lubrication.

(a) Hydrostatic lubrication. Hydrostatic lubrication may be used when bearing surface velocities are extremely slow or zero. Under hydrostatic lubrication, a pressurized grease physically separates the bearing surfaces to produce a thick film. Trunnion friction can be reduced by about 40 percent if a grease film can be maintained during operation by an automatic greasing system.

(b) Boundary lubrication. Boundary lubrication occurs when bearing surfaces are separated by a lubricant film of molecular thickness and there is momentary dry contact between asperities (microscopic peaks). Friction is caused by contact of bushing and pin surface asperities. Since viscosity depends on film thickness, when boundary lubrication occurs, friction is not affected by of the grease viscosity and can only be reduced through additives.

(6) Grease selection based on boundary lubrication. Grease should be selected based on its performance specifically for boundary lubrication, whether for manual lubrication or automatic greasing system. Manual hydrostatic lubrication on stationary equipment under load reduces trunnion friction for the next operation, but as the pin rotates, the lubricant film thins until pure boundary lubrication results. With rust on the trunnion pins, the preferred method of trunnion lubrication is hydrostatic lubrication during gate operation using an automatic greasing system. However, automatic systems are subject to occasional breakdown which could produce catastrophic results.

(7) Frequency of lubrication.

(a) Frequency of lubrication depends on many factors, such as frequency of operation, trunnion friction, temperature, condition of bearing surfaces (rust, pitting, etc.), whether the equipment is submerged, replacement of grease lost to leakage or oxidation, and the need to flush out moisture or other contaminants. An example of two different lubrication frequencies based on factors and gate conditions are as follows:

- The Folsom Dam spillway tainter gate investigation suggests that, in general, if the allowable gate trunnion friction in the design is at least 0.5 and the bearing is well protected from its given environment, the Bureau of Reclamation standard of lubricating tainter gates twice a year is adequate.

- The same Folsom investigation found there was no allowable trunnion friction in its gate design. The trunnion pins were rusted, scuffed, and had inadequate protection from rain and spray. Based on these factors, it was concluded that a reasonable lubrication schedule would be to grease once a month when the lake level is below the gates; grease once a week when the lake level is above the gate sill; and employ automatic greasing while the gate is in motion. Frequent applications can remove moisture from trunnion surfaces and decelerate rust progress.

(b) Frequencies for lubricating gate and culvert valve trunnions at locks and dams are shown in the survey in Appendix B. These vary from weekly to twice a year, indicating that there is no set frequency of lubrication. Aside from recommendations for new equipment, lubrication frequencies become individualized based on the factors and conditions noted above and operating experience.

(8) General suggestions for tainter gates. Some of the recommendations made for Folsom Dam, such as the automatic greasing system and the lubricant type, are made partly due to existing rust of the trunnion pins and bushings. Other tainter gates may have different conditions such as local climate, frequency of gate operation, the designed allowable trunnion friction, and the lubrication system. The following procedures are suggested to determine the requirements for tainter gate trunnions at other locations:

(a) If exposed to water, air, and abrasive dust and debris, install weather protection seals on the edges of the trunnions to protect the bearing. Seals will protect against rusting of the pin while protecting the grease from oxidation and contamination.

(b) Determine the allowable trunnion friction. An allowable friction coefficient below 0.3 would be considered low.

(c) Carefully review the design of the trunnion assembly and lubrication system.

(d) Review the frequency of gate operations.

(e) Inspect the trunnions using some of the techniques listed below to determine the presence of rust and to estimate the existing trunnion friction. (These techniques have been established as a result of the investigation. Their effectiveness or feasibility has not been extensively determined and may depend on local conditions.) If corrosion is suspected, determine trunnion friction. Friction coefficients above design value may require a change of lubricants and/or lubrication frequency. Techniques are:

- Send used grease that is pumped out of the trunnions to a laboratory to test for contaminants such as rust.

- Measure the gate's hoist motor current as an indication of possible increased trunnion friction.

- Attach strain gages to the gate arms to measure induced stresses caused by trunnion friction.

- Attach a laser and target to the gate structure to measure deflections caused by trunnion friction.

- Fabricate probes that can access the trunnion pin through the lubrication ports to determine the presence of rust.

(f) Review the type of lubricant in use. Consider the lubricant specification recommended for the Folsom Dam trunnions (reference Table 11-3).

(g) Rotate trunnion pins 180 degrees. Loading is typically on one side of the pin, and the pin will corrode first on the side with the thinnest lubricant film.

(h) If pins are rusted, use new steel pin, because previously rusted steel is susceptible to rapid rusting.

*b. Seats for bonneted gates.* With design loading on the bronze sliding surfaces of these gates at 206.8 to 275.8 bar (3000 to 4000 psi), seats are typically lubricated with a multipurpose lithium, lithium complex, or lithium 12 hydroxystearate-thickened grease with EP additives. The grease must be suitable for the temperature range intended. Desired grease properties are good water wash-out resistance, copper alloy corrosion protection, and low start-up/running torque. Recommended greasing frequency is every 6 months, however, but chattering or jerking during operation is a sign of inadequate lubrication and indicates the need for more frequent lubrication. Greases recommended by gate manufacturers are usually NLGI grade 2. However, it has been noted that cold seasonal temperatures may dictate a lower NLGI grade for better flow through piping to the seats.

*c. Threaded gate stems.* The same multipurpose EP greases recommended by gate manufacturers for seats are recommended for stems. The grease must be suitable for the temperature range intended. Good water resistance and low start-up/running torque are also desired grease properties for stems. Cold seasonal temperatures may necessitate a lower NLGI grade if the grease accumulates excessively at the lift nut during operation due to low temperature. Keeping threaded stems clean and greased is critical. When excess dried grease or other foreign material is carried into the threads of the lift nut, extremely hard operation will result. If the foreign material is not cleaned from interior threads, seizure can result. Moreover, if the foreign material is abrasive and the stem is coated with this grit, frequent use of the gate will wear the threads in the thrust nut creating a potentially dangerous situation. An excessively worn thrust nut may not support the weight of the gate and may cause it to fall. Use of pipe covers will protect stems above the deck. Plastic stem covers will allow visual inspection. Recommended cleaning and greasing frequency is at least every 6 months or 100 cycles, whichever occurs first, and more often if the grease becomes dirty.

*d. Threaded drive screws.* The lubricant should have good water-separating characteristics and must be suitable for the temperature range intended. It should have extreme pressure characteristics and low start-up/running torque for quick start-up and smooth operation. The same multipurpose EP greases used for threaded gate stems can be used on drive screws.

*e. Roller trains and roller assemblies for roller-mounted gates.* When chains are part of roller assemblies, they should be lubricated according to the requirements discussed below for chains. Grease for roller trains should contain an EP additive and generally be NLGI grade 2. It should be formulated for rust and corrosion protection and be resistant to water wash-out. It should be suitable for the temperature range intended and for the shock loading of wave action. Frequency of lubrication depends on factors such as frequency of operation and accessibility, but roller trains should be lubricated a minimum of twice a year. When possible, the equipment manufacturer should be consulted for lubricant and frequency recommendations.

*f. Wheel bearings.* Grease should be suitable for boundary lubrication of a high-load, low-speed journal bearing and contain EP additives. It should be noncorrosive to steel and resistant to water wash-out conditions. It must be suitable for the temperature range intended. The grease should conform to the recommendations of the bearing manufacturer. Bearings should be lubricated at least once a year. When this is not possible they should be lubricated whenever accessible.

*g. Grease-lubricated gears for electrically and manually operated lifts.*

(1) Grease for the main gearboxes of operating lifts should contain an EP additive and be suitable for the temperature range intended. It should be water- and heat-resistant, and be slightly fluid (approximating NLGI grade 1 or 0). It should not be corrosive to steel gears, ball, or roller bearings, and should not create more than 8 percent swell in gaskets. Its dropping point should be above 158 °C (316 °F) for temperature ranges of -29 °C (-20 °F) to 66 °C (150 °F). It should not contain any grit, abrasive, or fillers.

(2) Frequency of lubrication varies among manufacturers. One lift manufacturer recommends pressure greasing through fittings after 100 cycles or every 6 months, whichever comes first. The frequency of inspections and/or lubrication should be based on historical data. The manufacturer's schedule should be followed unless operating experience indicates otherwise. Grease should be inspected at least every 18 months. It should contain no dirt, water, or other foreign matter. Should dirt, water, or foreign matter be found, the units should be flushed with a noncorrosive commercial degreaser/cleaner that does not affect seal materials such as Buna N or Viton. All bearings, bearing balls, gears, and other close-tolerance parts that rotate with respect to each other should be recoated by hand with fresh grease. The operator should then be repacked with fresh grease. Different lubricants should not be added unless they are based on the same soap (calcium, lithium, etc.) as the existing lubricant and approval has been given by the lubricant manufacturer. (Oil-lubricated gears are discussed in paragraph 9.4 ).

*h. Hydraulic fluids for operating systems.* Commonly used hydraulic fluids for gates at locks and dams and culvert valves at locks are tabulated in Appendix B. An oil with a high viscosity index should be selected to minimize the change in pipe friction between winter and summer months. The oil selected must have a viscosity range suitable for the system components and their expected operating temperature and pressure ranges. Generally, the maximum viscosity range is between 4000 Saybolt Universal Seconds (SUS) at start-up and 70 SUS at maximum operating temperature. However, this range will vary between manufacturers and types of equipment. Hydraulic systems containing large quantities of fluid should include rust and oxidation inhibitors. Consideration should also be given to biodegradable fluids composed of vegetable-base oils with synthetic additives. These fluids should be used with caution to ensure that they are compatible with the components used in the hydraulic system. A more detailed discussion of hydraulic fluids properties can be found in Chapter 4 of this manual.

## 11-11. Navigation Lock Gates, Culvert Valves, and Dam Gates

*a. General requirements.*

(1) Corps of Engineers navigation facilities use many types of lock gates, including miter, sector, vertical lift, and submergible tainter. The machinery required to operate these gates consists of speed reducers, gear couplings, bearings, open gearing, wire ropes, and chains. Most of this equipment is heavily loaded and operates at low speeds. Consequently, hydrodynamic lubrication cannot be established and boundary lubricating conditions predominate.

(2) The general lubricating requirements for this equipment have already been discussed. The following discussion is limited to the lubricating requirements specific to the lock gate noted. Refer to paragraph 11-10 (gates and valves) for lubrication requirements for culvert valves and dam gate components. Refer to the survey (Appendix B) discussed in the next paragraph for commonly used lubricants and hydraulic fluids.

*b. Survey of locks and dams for lubricants.* About 45 Corps of Engineers locks and dams around the country were surveyed for lubricants and hydraulic fluids used for lock gates, culvert valves, and navigation dams. Twenty-three survey responses showed lubricant products from more than 25 different lubricant companies. Each product appears suitable for the particular application. Information on frequency of lubrication and method of application was also included in the responses. Respondents expressed interests in environmentally acceptable lubricants, but use has been limited. Responses also covered lubricants for equipment not specifically queried for on the survey. These responses and comments on environmentally acceptable lubricants are included with the survey results in Appendix B.

*c. Speed reducers.* Speed reducers are usually worm, helical. or herringbone-type gear trains in accordance with the applicable American Gear Manufacturers Association (AGMA) standards. Integral bearings are usually antifriction type. Gear oil must be suitable for the expected ambient temperatures. Where ambient temperature ranges will exceed the oil producer's recommendations, a thermostatically controlled heater should be provided in the reducer case. The surface area of the heater should be as large as possible to prevent charring of the oil. The density of heating elements should not exceed 21.44 hp/$m^2$ (10 watts per square inch). If possible, insulate the reducer case to minimize heat loss. If heaters are impractical, synthetic gear oils should be considered. A number of locks are using synthetic oils in gearboxes. One reason given is that in cold weather, heaters have scorched petroleum oils, requiring additional maintenance. Synthetic oils eliminate the need for heaters. A synthetic gear lubricant with a -40 °C (-40 °F) pour point is recommended if acceptable to the reducer manufacturer. Lubricant selection should be based on published manufacturer's data for the required application and operating conditions. Gear oils used at locks and dams are listed in the survey in Appendix B.

*d. Couplings.* Flexible couplings are usually the gear type. The lubrication requirements for these couplings were discussed above.

*e. Bearings.*

(1) Antifriction bearings should be selected in accordance with manufacturer's published catalog ratings. Life expectancy should be based on 10,000 hours B-10 life with loads assumed equal to 75 percent of maximum.

(2) Bronze sleeve bearings should have allowable unit bearing pressures not exceeding the following:

- Sheave bushings, slow speed, 3500 psi.

- Main pinion shaft bearings and other slow-moving shafts, hardened steel on bronze, 1000 psi.

- Bearings moving at ordinary speeds, steel or bronze, 750 psi.

*f. Open gearing.* Open gears are usually the spur teeth involute form, complying with AGMA 201.02 ANSI Standard System, "Tooth Proportions For Coarse-Pitch Involute Spur Gears" (Information Sheet A). Lubricants used at Corps of Engineers locks and dams are noted in the survey in Appendix B.

*g. Hydraulic fluid.* A petroleum oil with a high viscosity index should be selected to minimize the change in pipe friction between winter and summer months. The oil selected must have a viscosity range suitable for the system components and their expected operating temperature range. Generally, the maximum viscosity range is between 4000 SUS at start-up and 70 SUS at maximum operating temperature. However, this range will vary among manufacturers and types of equipment. Hydraulic systems containing large quantities of fluid should include rust and oxidation inhibitors. Consideration should also be given to biodegradable fluids composed of vegetable-base oils with synthetic additives. These fluids should be used with caution to ensure that they are compatible with the components used in the hydraulic system. Refer to Chapter 8 for a more detailed discussion of desirable properties and the survey in Appendix B for hydraulic fluids commonly used at locks and dams.

*h. Miter gates.* There are various types of operating linkages for miter gates. Generally these gates are operated through electric motors, enclosed speed reducers, a bull gear, sector arm, and spring strut. Alternatively, the gates may be hydraulically operated. Miter gate gudgeon pins and pintles are grease-lubricated with automatic and manual greasing systems. Spring struts are lubricated with graphite-based grease or lubricated with the same grease used on the pintles, depending on type of strut. Refer to the survey in Appendix B for commonly used lubricants and frequency of application.

*i. Sector gates.* The operating machinery for sector gates is similar to that used in miter gate and may consist of a hydraulic motor, or an electric motor, a herringbone gear speed reducer, and a specially designed angle drive gear unit. In some applications a system consisting of a steel wire rope and drum arrangement replaces the rack and pinion assembly, and is used to pull the gates in and out of their recesses. Sector gates gudgeon pins and pintles are lubricated with the same grease used on miter gate gudgeon pins and pintles.

*j. Vertical-lift gates.* The hoisting equipment for vertical-lift gates consists of a gear-driven rope drum. The actual gear drive depends on the gate use. Emergency gates use two-stage open-spur gearing, a herringbone or helical gear speed reducer, and an electric motor. The downstream gate is wheel-mounted. These wheels may be provided with self-lubricating spherical bushings. Tide gate drums are operated by a pinion gear driven by a triple-reduction enclosed gear unit. Vertical gates are also equipped with a hydraulically operated emergency lowering mechanism. The hydraulic fluid is used to absorb heat so a heat exchanger is required to ensure that the oil temperature does not exceed 49 °C (120 °F). Wire ropes are usually 6 x 37, preformed, lang lay, independent wire rope core, 18-8 chrome-nickel corrosion-resistant steel.

*k. Submergible tainter gates.* Submergible tainter gates are operated by two synchronized hoist units consisting of rope drum, open gear set, speed reducer, and hoist motor. Due to continuous submergence, stainless steel wire ropes are commonly used. Refer to paragraph 11-10 (gates and valves) for trunnion lubrication requirements.

## 11-12. Information Sources for Lubricants

There are many valuable information resources on the subject of lubrication.

*a. Operations and maintenance manuals.* The primary information sources are the manufacturer's installation, operation, and maintenance manuals. The information contained in these manuals applies specifically to the equipment requiring servicing.

*b. Industry standards.* Industry standards organizations such as ANSI, ASTM, AGMA, and IEEE publish standard specifications for lubricants and lubricating standards for various types of equipment.

*c. Journals.* Engineering and trade publications and journals such as Lubrication, Lubrication Engineering, and Wear specialize in the area of lubrication or tribology. Articles featured in these publications are generally technical in nature and describe the results of current research. Occasionally research results are translated into practical information that can be readily applied.

*d. General trade publications.* Magazines such as Power, Power Engineering, Hydraulics and Pneumatics, Machine Design, Pump and Systems, and Plant Engineering Magazine frequently contain practical articles pertaining to lubrication of bearings, gears, and other plant equipment. Of particular interest is Plant Engineering's "Chart of Interchangeable Industrial Lubricants" and "Chart of Synthetic Lubricants." Each of these charts is updated every 3 years. These charts cross-reference lubricants by application and company producing the product. Chart users should note that Plant Engineering Magazine product names are provided by the manufacturers, and that publishing of the data does not reflect the quality of the lubricant, imply the performance expected under particular operating conditions, or serve as an endorsement. As an example of the information contained in the interchangeable lubricant chart, the 1995 chart identifies available products from 105 lubricant companies in nine categories. Fluid products in each category are listed within viscosity ranges. Greases are NLGI 2 only. Included is a chart entitled "Viscosity/Grade Comparison Chart" that tabulates viscosity equivalents for ISO viscosity grade, kinematic viscosity (CSt), Saybolt viscosity (SUS), gear lubricant (AGMA) specification, EP gear lubricant, and worm gear lubricant (Comp). Lubricant categories include:

- General-purpose lubricants
- Antiwear hydraulic oil
- Spindle oil
- Way oil
- Extreme pressure gear oil
- Worm gear oil
- Cling-type gear shield (open gears)
- General-purpose extreme pressure lithium-based grease
- Molybdenum disulfide extreme pressure grease.

The 1997 chart for synthetic lubricants identifies available products from 69 lubricant companies in eight categories. Fluid products in each category are listed within viscosity ranges. Greases are NLGI 2 only. Included is a table entitled "Performance Characteristic of Various Synthetic Lubricants" that shows the relative performance characteristics of seven types of synthetic lubricants and a paraffinic mineral oil. Lubricant categories are:

- Gear and bearing circulation oil
- Extreme pressure gear oil
- High pressure (antiwear) hydraulic oil
- Fire-resistant hydraulic fluid
- Compressor lubricant
- Multipurpose extreme pressure grease (without molybdenum)
- Multipurpose molybdenum disulfide extreme pressure grease
- Multipurpose high temperature grease (without molybdenum).

Plant Engineering Magazine notes that the synthetic lubricant products presented in each category are not necessarily interchangeable or compatible. Interchangeability and compatibility depend on a variety of interrelated factors, and each application requires an individual analysis.

*e. Hydropower industry publications.* Hydro Review and Water Power and Dam Construction are widely known publications throughout the hydropower industry. Hydro Review tends to be more research-oriented and, therefore, more technical. Water Power and Dam Construction includes technical and practical information. Occasionally, lubrication-related articles are published.

*f. Lubricant producers.* Lubricant producers are probably the most valuable source for information and should be consulted for specific application situations, surveys, or questions.

*g. Internet.* The Internet offers access to a large amount of information, including lubrication theory, product data, and application information. The Internet also provides a means for communicating and sharing information with personnel at other facilities. Problems, causes , and solutions are frequently described in great detail. Since the credentials of individuals publishing information through the Internet are more difficult to ascertain, caution should be used when evaluating information obtained through the Internet. The amount of information located depends on the user's ability to apply the most pertinent keywords on any of the search engines. Hyperlinks are usually available and lead to other information sources. Users should note that broad search categories, such as "lubrication," will provide the greatest returns but will undoubtedly include much extraneous data. Alternatively, searching on a phrase such as "lubrication of hydroturbine guide bearings" may be too restrictive. Generally, inserting too many words in the search field narrows the scope of the search and may produce little or no useful information. The search field must be adjusted until the desired information is obtained or the search is abandoned for another reference source.

*h. Libraries.* In a manner similar to Internet searches, librarians can also help locate information within their collections or outside their collections by conducting book and literature searches. Unlike the Internet, literature searches rely on large databases that require password entry not available to the general public. Therefore, these searches are usually conducted by a reference librarian. The search process is a very simple method used for locating books an a specific subject, or specific articles that have been included in technical publications. Usually, searches begin with the current year to find the most recent articles published. The search is expanded to previous years as necessary until useful articles or information are located. All that is required is the subject keyword and the time period to be searched. For example: locate all articles on "guide bearing lubrication" written over the past 2 years. If this does not return the desired information, two options are available: extend the time period further into the past or change the search title to "journal bearing lubrication" and try new search. Again, the amount of information located depends on using the proper search keywords. Searches can be expanded or contracted until the desired information is obtained.

# Chapter 12
# Operation and Maintenance Considerations

## 12-1. Introduction

This chapter discusses the maintenance aspects of lubrication. Detailed discussions cover maintenance scheduling; relative cost of lubricants; essential oil properties that must be retained to ensure adequate lubrication of equipment; degradation of lubricating oils, hydraulic fluids, and insulating transformer oils; particulate, water, and biological contamination; monitoring programs, including trend monitoring and oil testing; storage and handling; and environmental impacts.

## 12-2. Maintenance Schedules

*a.* Modern maintenance schedules are computer-generated, and are frequently referred to as computer maintenance management systems (CMMS). These systems are essential in organizing, planning, and executing required maintenance activities for complex hydropower, pumping, and navigation facilities. A complete discussion of CMMS is beyond the scope of this manual. Some Corps of Engineers and Bureau of Reclamation facilities recognize the value of CMMS and are currently using these systems to document operation and maintenance activities. The following discussion summarizes some key concepts of CMMS.

*b.* The primary goals of a CMMS include scheduling resources optimizing resource availability and reducing the cost of production, labor, materials, and tools. These goals are accomplished by tracking equipment, parts, repairs, and maintenance schedules.

*c.* The most effective CMMS are integrated with a predictive maintenance program (PdM). This type of program should not be confused with preventive maintenance (PM), which schedules maintenance and/or replacement of parts and equipment based on manufacturer's suggestions. A PM program relies on established service intervals without regard to the actual operating conditions of the equipment. This type of program is very expensive and often results in excess downtime and premature replacement of equipment.

*d.* While a PM program relies on elapsed time, a PdM program relies on condition monitoring of machines to help determine when maintenance or replacement is necessary. Condition monitoring involves the continuous monitoring and recording of vital characteristics that are known to be indicative of the machine's condition. The most commonly measured characteristic is vibration, but other useful tests include lubricant analysis, thermography, and ultrasonic measurements. The desired tests are conducted on a periodic basis. Each new measurement is compared with previous data to determine if a trend is developing. This type of analysis is commonly referred to as trend analysis or trending, and is used to help predict failure of a particular machine component and to schedule maintenance and order parts. Trending data can be collected for a wide range of equipment, including pumps, turbines, motors, generators, gearboxes, fans, compressors, etc. The obvious advantage of condition monitoring is that failure can often be predicted, repairs planned, and downtime and costs reduced.

## 12-3. Relative Cost of Lubricants

Cost is one of the factors to be considered when selecting lubricants. This is especially true when making substitutions such as using synthetics in place of mineral oils. Tables 12-1 and 12-2 provide basic

**Table 12-1**
**Relative Cost of Vegetable and Synthetic Oils**

| Lubricant | Relative Cost to Mineral Oil[1,2] |
| --- | --- |
| *Vegetable Oils*[1] | 2 - 3 |
| *Synthetic Fluids*[2] | |
| Polybutenes | 2 |
| Polyalphaolefins | 3 |
| Dialkylbenzene | 5 |
| Polyalkyline glycols | 3 - 5 |
| Polyol esters | 3 - 5 |
| Diesters | 2 - 6 |
| Phosphate esters | 4 - 7 |
| Cycloaliphatics | 9 - 15 |
| Silicone fluids | 12 - 24 |
| Silicate esters | 33 - 45 |
| Halogenated hydrocarbons | 100 - 450 |
| Polyphenyl ethers | 625 - 700 |

[1] Rhee, 1996 (Vegetable oils).
[2] Straiton, 1998 (Synthetic fluids).

**Table 12-2**
**Relative Cost of Greases**

| Grease Type | Base Oil | Relative Cost to Lithium Grease [1] |
| --- | --- | --- |
| Aluminum | Mineral | 2.5 - 3 |
| Calcium | Mineral | 0.8 |
| Lithium | Mineral | 1 |
| Sodium | Mineral | 0.9 |
| Aluminum complex | Mineral | 2.5 - 4 |
| Calcium complex | Mineral | 0.9 - 1.2 |
| Lithium complex | Mineral | 2 |
| Sodium complex | Mineral | 3.5 |
| Lithium | Ester | 5 - 6 |
| Lithium complex | Ester | 10 |
| Lithium complex | Silicone | 20 |
| Bentonites (organo clay) | Mineral | 2 - 6 |
| Polyurea | Mineral | 3 |
| Polyurea | Silicone | 35 - 40 |
| Polyurea | Fluorosilicone | 100 |

[1] Mancuso and South 1994.

information on the relative cost of various lubricants. Reference to these tables and charts reveals that synthetic lubricants are considerably more expensive than mineral lubricants. Therefore, justification for their use must be based on operating requirements for which suitable mineral lubricants are not available.

## 12.4. Lubricating Oil Degradation

A lubricating oil may become unsuitable for its intended purpose as a result of one or several processes. Most of these processes have been discussed in previous chapters, so the following discussions are brief summaries.

*a. Oxidation.* Oxidation occurs by chemical reaction of the oil with oxygen. The first step in the oxidation reaction is the formation of hydroperoxides. Subsequently, a chain reaction is started and other compounds such as acid, resins, varnishes, sludge, and carbonaceous deposits are formed.

*b. Water and air contamination.* Water may be dissolved or emulsified in oil. Water affects viscosity, promotes oil degradation and equipment corrosion, and interferes with lubrication. Air in oil systems may cause foaming, slow and erratic system response, and pump cavitation.

(1) Results of water contamination in fluid systems

! Fluid breakdown, such as additive precipitation and oil oxidation

! Reduced lubricating film thickness

! Accelerated metal surface fatigue

! Corrosion

! Jamming of components due to ice crystals formed at low temperatures

! Loss of dielectric strength in insulating oils.

(a) Effects of water on bearing life. Studies have shown that the fatigue life of a bearing can be extended dramatically by reducing the amount of water contained in a petroleum based lubricant. See Table 12-3.

(b) Effect of water and metal particles. Oil oxidation is increased in a hydraulic or lubricating oil in the presence of water and particulate contamination. Small metal particles act as catalysts to rapidly increase the neutralization number of acid level. See Table 12-4.

**Table 12-3**
**Effect of Water on Bearing Fatigue Life**

| Lubricant | Water Concentration | Relative Life Factor |
|---|---|---|
| SAE 20 | 25 ppm | 4.98 |
| SAE 20 | 100 ppm | 1.92 |
| SAE 20 | 400 ppm | 1.00 |

Reference: Effect of Water in Lubricating Oil on Bearing Life, 31st annual ASLE meeting, 1975.

**Table 12-4**
**Effect of Water and Metal Particles on Oil Oxidation**

| Run | Catalyst | Water | Hours | Total Acid* Number Change |
|---|---|---|---|---|
| 1 | None | No | 3500+ | 0 |
| 2 | None | Yes | 3500+ | +0.73 |
| 3 | Iron | No | 3500+ | +0.48 |
| 4 | Iron | Yes | 400 | +7.93 |
| 5 | Copper | No | 3000 | +0.72 |
| 6 | Copper | Yes | 100 | +11.03 |

*Total acid number increases that exceed 0.5 indicate significant fluid deterioration.
Reference: Weinshelbaum, M., Proceedings, National Conference on Fluid Power, VXXXIII:269.

(2) Sources of Water Contamination

! Heat exchanger leaks

! Seal leaks

! Condensation of humid air

! Inadequate reservoir covers

! Temperature drops changing dissolved water to free water.

(3) Forms of water in oil

! Free water (emulsified or droplets)

! Dissolved water (below saturation level).

(4) Typical oil saturation levels

! Hydraulic--200 to 400 ppm (0.02 to 0.04%)

! Lubricating--200 to 750 ppm (0.02 to 0.075%)

! Transformer--30 to 50 ppm (0.003 to 0.005%).

(5) Results of Dissolved Air and Other Gases in Oils

! Foaming

! Slow system response with erratic operation

! A reduction in system stiffness

- Higher fluid temperatures
- Pump damage due to cavitation
- Inability to develop full system pressure
- Acceleration of oil oxidation

*c. Loss of additives.* Two of the most important additives in turbine lubricating oil are the rust- and oxidation-inhibiting agents. Without these additives, oxidation of oil and the rate of rusting will increase.

*d. Accumulation of contaminants.* Lubricating oil can become unsuitable for further service by accumulation of foreign materials in the oil. The source of contaminants may be from within the system or from outside. Internal sources of contamination are rust, wear, and sealing products. Outside contaminants are dirt, weld spatter, metal fragments, etc., which can enter the system through ineffective seals, dirty oil fill pipes, or dirty make-up oil.

*e. Biological deterioration.* Lubricating oils are susceptible to biological deterioration if the proper growing conditions are present. Table 12-5 identifies the type of “infections” and associated characteristics. Hydraulic oils are also susceptible to this type of deterioration. These are discussed in paragraph 12-5. Procedures for preventing and coping with biological contamination include cleaning and sterilizing, addition of biocides, frequent draining of moisture from the system, avoidance of dead-legs in pipes.

**Table 12-5**
**Characteristics of Principal Infecting Organisms (Generalized Scheme)**

| Organism | pH Relationship | Products of Growth | Type of Growth |
|---|---|---|---|
| Aerobic bacteria (use oxygen) | Prefer neutral to alkaline pH. | Completely oxidized products ($CO_2$ and $H_2O$) and some acids. Occasionally generate ammonia. | Separate rods, forming slime when agglomerated. Size usually below 5 $\mu$m in length (1.64 × $10^{-5}$ ft) |
| Anaerobic bacteria (grow in absence of oxygen) | Prefer neutral to alkaline pH | Incompletely oxidized and reduced products including $CH_4$, $H_2$, and $H_2S$. | As above. Often adhere to steel surfaces, particularly swarf |
| Yeasts | Prefer acid pH. | Oxidized and incompletely oxidized products. pH falls. | Usually separate cells, 5-10 $\mu$m (1.64 × $10^{-5}$ ft to 3.28 × $10^{-5}$ ft), often follow bacterial infections or occur when bacteria have been inhibited. Sometimes filamentous. |
| Fungi (molds) | Prefer acid pH, but some flourish at alkaline pH in synthetic metal working fluids. | Incompletely oxidized product organic acids accumulate. | Filaments of cells forming visible mats of growth. Spores may resemble yeasts. Both yeasts and molds grow more slowly than bacteria. |

## 12.5 Hydraulic Oil Degradation

*a. Water contamination.*

(1) Due to the hygroscopic nature of hydraulic fluid, water contamination is a common occurrence. Water may be introduced by exposure to humid environments, condensation in the reservoir, and when

adding fluid from drums that may have been improperly sealed and exposed to rain. Leaking heat exchangers, seals, and fittings are other potential sources of water contamination.

(2) The water saturation level is different for each type of hydraulic fluid. Below the saturation level water will completely dissolve in the oil. Oil-based hydraulic fluids have a saturation level between 100 and 1000 ppm (0.01% to 0.1%). This saturation level will be higher at the higher operating temperatures normally experienced in hydraulic systems.

*b. Effects of water contamination.* Hydraulic system operation may be affected when water contamination reaches 1 to 2%.

(1) Reduced viscosity. If the water is emulsified, the fluid viscosity may be reduced and result in poor system response, increased wear of rubbing surfaces, and pump cavitation.

(2) Ice formation. If free water is present and exposed to freezing temperatures, ice crystals may form. Ice may plug orifices and clearance spaces, causing slow or erratic operation.

(3) Chemical reactions.

(a) Galvanic corrosion. Water may act as an electrolyte between dissimilar metals to promote galvanic corrosion. This condition first occurs and is most visible as rust formations on the inside top surface of the fluid reservoir.

(b) Additive depletion. Water may react with oxidation additives to produce acids and precipitates that increase wear and cause system fouling. Antiwear additives such as zinc dithiophosphate (ZDTP) are commonly used for boundary lubrication applications in high-pressure pumps, gears, and bearings. However, chemical reaction with water can destroy this additive when the system operating temperature rises above 60 °C (140 °F). The end result is premature component failure due to metal fatigue.

(c) Agglomeration. Water can act as an adhesive to bind small contaminant particles into clumps that plug the system and cause slow or erratic operation. If the condition is serious, the system may fail completely.

(d) Microbiological contamination. Growth of microbes such as bacteria, algae, yeast, and fungi can occur in hydraulic systems contaminated with water. The severity of microbial contamination is increased by the presence of air. Microbes vary in size from 0.2 to 2.0 µm for single cells and up to 200 µmM for multicell organisms. Under favorable conditions, bacteria reproduce exponentially. Their numbers may double in as little as 20 minutes. Unless they are detected early, bacteria may grow into an interwoven mass that will clog the system. A large quantity of bacteria also can produce significant waste products and acids capable of attacking most metals and causing component failure.

## 12-6. Transformer and Circuit Breaker Insulating Oil Degradation

*a.* The consequences of oil degradation in a transformer can be even more serious than with other equipment. Combustible gases may form as the transformer develops faults. Some gases are present in a dissolved state while others are found in the free space of the transformer. The type and concentration of gases and the ratio in which they are present are commonly used to assess the serviceable condition of transformers. Under the right conditions these gases may explode, causing significant damage and injury to personnel. The testing of transformer oils and assessment of transformer serviceable conditions has become a specialty. The Bureau of Reclamation has published a manual that provides detailed procedures and criteria for testing insulating oils. The reader should refer to Reclamation Facilities Instructions, Standards, and Techniques (FIST) publication Volume 3-5, "Maintenance of Liquid Insulation Mineral Oils and Askarels" for detailed information on transformer and circuit breaker oil maintenance and testing. For information on monitoring, testing, and assessment of transformer serviceability, refer to IEEE Standard C57.104-1991, "IEEE Guide for the Interpretation of Gases."

*b.* Transformer and circuit-breaker insulating oils suffer degradation similar to that of lubricating oil and hydraulic fluid including as oxidation, sludge formation, additive depletion, and moisture contamination. Sludge can significantly affect the flow of heat from the oil to the coolant and from the core and coils to the cooling coil. If these conditions are prolonged, the excessive temperature and heat can damage the transformer insulation and eventually cause short circuits and breakdown of the transformer. Moisture can be present in three forms: dissolved, emulsified, or free state. Emulsified water is especially harmful since it has significant influence in reducing the dielectric strength of the oil. Another form of contamination is the presence of dissolved nitrogen, which can cause problems due to corona discharge. Circuit breakers may have all the above problems plus the formation of carbon particles, which can cause short circuits.

## 12.7. Essential Properties of Oil

Several important properties of used oil must be retained to ensure continued service, as discussed below.

*a. Viscosity.* New turbine oils are sold under the International Standards Organization (ISO) Viscosity Grade System. Oil manufacturers normally produce lubricating oil with viscosity of ISO-VG-22, VG-32, VG-46, VG-68, VG-100, VG-150, VG-220, VG-320, and VG-460. The numbers 22 through 460 indicate the average oil viscosity in centistoke units at 40°C (104 °F) with a range of ±10 percent. Most hydroelectric power plants use ISO-VG -68 or ISO-VG-100 oils.

*b. Oxidation stability.* One of the most important properties of new turbine oil is its oxidation stability. New turbine oils are highly stable in the presence of air or oxygen. In service, oxidation is gradually accelerated by the presence of a metal catalyst in the system (such as iron and copper) and by the depletion of antioxidant additives. Additives control oxidation by attacking the hydroperoxides (the first product of the oxidation step) and breaking the chain reaction that follows. When oxidation stability decreases, the oil will undergo a complex reaction that will eventually produce insoluble sludge. This sludge may settle in critical areas of the equipment and interfere with lubrication and cooling functions of oil. Most rust inhibitors used in turbine oils are acidic and contribute to the acid number of the new oil. An increase in acid number above the value for new oil indicates the presence of acidic oxidation products or, less likely, contamination with acidic substances. An accurate determination of the total acid number (TAN) is very important. However, this test does not strictly measure oxidation stability reserve, which is better determined by the Rotating Bomb Oxidation Test (RBOT), ASTM Test Method D 2272.

*c. Freedom from sludge.* Sludge is the byproduct of oil oxidation. Due to the nature of the highly refined lubricant base stocks used in the manufacture of turbine oils, these oils are very poor solvents for sludge. This is the main reason why the oxidation stability reserve of the oil must be carefully monitored. Only a relatively small degree of oxidation can be permitted; otherwise, there is considerable risk of sludge deposition in bearing housings, seals, and pistons. Filtration and centrifugation can remove sludge from oil as it is formed, but if oil deterioration is allowed to proceed too far, sludge will deposit in parts of the equipment, and system flushing and an oil change may be required.

*d. Freedom from abrasive contaminants.* The most deleterious solid contaminants found in turbine oil systems are those left behind when the system is constructed and installed or when it is opened for maintenance and repair. Solid contaminants may also enter the system when units are outdoors, through improperly installed vents, and when units are opened for maintenance. Other means of contamination are from the wearing of metals originating within the system, rust and corrosion products, and dirty make-up oil. The presence of abrasive solids in the oil cannot be tolerated since they will cause serious damage to the system. These particles must be prevented from entering the system by flushing the system properly and using clean oil and tight seals. Once abrasive solids have been detected, they must be removed by filtration or centrifugation, or both.

*e. Corrosion protection.* The corrosion protection provided by the lubricant is of significant importance for turbine systems. New turbine oil contains a rust-inhibitor additive and must meet ASTM Test Method D 665. The additive may be depleted by normal usage, removal with water in the oil, absorption on wear particles and debris, or chemical reaction with contaminants.

*f. Water separability.* Water can enter the turbine lubricating oil system through cooler leaks, by condensation, and, to a lesser degree, through seal leaks. Water in the oil can be in either the dissolved or insoluble form. The insoluble water may be in the form of small droplets dispersed in the oil (emulsion) or in a separate phase (free state) settled at the bottom of the container. Water can react with metals to catalyze and promote oil oxidation. It may deplete rust inhibitors and may also cause rusting and corrosion. In addition to these chemical effects on the oil, additives, and equipment, water also affects the lubrication properties of the oil. Oil containing large amounts of water does not have the same viscosity and lubricating effect of clean oil. Therefore, turbine lubricating oil should not contain a significant amount of free or dispersed water. Normally, if the oil is in good condition, water will settle to the bottom of the storage tank, where it should be drained off as a routine operating procedure. Water may also be removed by purification systems. If turbine oil develops poor water separability properties (poor demulsibility), significant amounts of water will stay in the system and create problems. The water separability characteristics of an oil are adequately measured using the ASTM Test Method D 1401 procedure. Insoluble water can be removed by filtration and centrifugation.

## 12-8. Other Properties of Used Oils

Other properties of lubricating oil that are important, but for which direct measurement of their quantitative values is less significant, are described below.

*a. Color.* New turbine oils are normally light in color. Oil will gradually darken in service. This is accepted. However, a significant color change occurring in a short time indicates that something has changed. For example, if oil suddenly becomes hazy, it is probably being contaminated with water. A rapid darkening or clouding may indicate that oil is contaminated or excessively degraded.

*b. Foaming characteristics.* Foaming characteristics are measured by ASTM Test Method D 892. This test will show the tendency of oil to foam and the stability of the foam after it is generated. Foaming can result in poor system performance and can cause serious mechanical damage. Most lubricants contain antifoam additive to break up the foam.

*c. Water content.* Turbine oil should be clear and bright. Most turbine oil will remain clear up to 75 ppm water at room temperature. A quick and easy qualitative analysis of insoluble water in oil is the hot plate test. A small amount of oil is placed on a hot plate. If oil smokes, there is no insoluble water. If it spatters, the oil contains free or suspended water.

*d. Inhibitor content.* The stability of turbine lubricating oil is based on the combination of high-quality base stock with highly effective additives. Therefore, it is very important to monitor the oxidation of the turbine oil. ASTM Test Method D 2272 (RBOT) is very useful for approximating the oxidation inhibitor content of the turbine oil. The remaining useful life of the oil can be estimated from this test.

*e. Wear and contaminant metals.* Quantitative spectrographic analysis of used oil samples may be used to detect trace metals (and silica) and identify metal-containing contaminants. System metals such as iron and copper can be accurately identified if the sample is representative and the metals are solubilized or are very finely divided. A high-silica level generally indicates dirt contamination.

## 12-9. Oil Monitoring Program

Periodic oil testing can measure the effects of oxidation, and detect the types and amount of various contaminants in the oil. Periodic testing can provide early detection of problems within a lubricating system; determine whether the oil is still serviceable; and provide information to prepare a filtering or purification schedule. By monitoring the condition of the oil, premature equipment failure due to oil deterioration can be prevented. Various standard tests are available depending on the type of oil and service. Table 12-6 briefly identifies and compares the various analysis methods available, and their benefits and limitations. Table 12-7 shows that each category of oil analysis is well suited to provide important information, but no single test can provide complete information about the causes of lubricant deterioration. The appropriate tests must be conducted to obtain the information desired. Field tests can

**Table 12-6**
**Fluid Analysis Methods**

| Method | Units | Benefits | Limitations |
|---|---|---|---|
| Optical particle count | Number/ml | Accurate size and quantity distribution | Sample preparation time |
| Automatic particle count | Number/ml | Fast, repeatable | Sensitive to particle concentration and nonparticulate contaminants, e.g., water, air, gels |
| Patch test and fluid contamination comparator | Visual comparison/ cleanliness code | Rapid analysis of fluid cleanliness levels in field; helps to identify type of contaminant | Provides approximate contamination levels |
| Ferrography | Scaled number of large/small particles | Basic information which will indicate the need for more sophisticated testing upon abnormal results | Cannot detect nonferrous particles, e.g., brass, copper, silica etc. |
| Spectrometry | ppm | Identifies and quantifies contaminant material | Cannot size contaminants; limited sensitivity above 5 µm ($1.64 \times 10^{-5}$ ft). |
| Gravimetric | mg/l | Indicates total amount of contaminant | Cannot distinguish particle size; when comparing samples, sensitivity is limited to extremely large differences in particulate level |

Reference: Contamination Control and Filtration Fundamentals, Pall Corporation, Glen Cove, NY.

**Table 12-7**
**Categories of Oil Analysis**

| What is being analyzed / Possible tests | Fluid Properties (Physical and chemical properties of used oil) (aging process) | Contamination (Fluid and machine destructive contaminants) | Wear Debris (Presence and identification of particles) |
|---|---|---|---|
| Particle counting | NB | PB | MB |
| Moisture analysis | NB | PB | NB |
| Viscosity analysis | PB | MB | NB |
| Wear debris density | NB | NB | PB |
| Analytical ferrography | NB | MB | PB |
| TAN/TBN | PB | MB | MB |
| FTIR | PB | MB | NB |
| Patch test | NB | PB | MB |
| Flash point test | MB | PB | NB |
| Elemental Analysis | PB | MB | PB |

Note: PB - Primary Benefit, MB - Minor Benefit, NB - No Benefit
Reference: Reprinted by permission of Noria Corporation, Tulsa, OK

be performed to expedite assessment of an oil's condition. However, field testing is not as complete or as accurate as laboratory analysis. Generally, laboratory tests should be performed to confirm field test results. Project personnel should establish a monitoring program for their lubricating oils. This program should include sampling and testing of significant oil properties at appropriate intervals, logging, interpretation of test data, and action steps. In this section and in the discussion of sampling technique, recommendations on properties to be tested, testing intervals, ASTM test methods, and action steps to correct the problems are discussed.

*a. Sampling and testing schedule.*

(1) Sample collection. The sample should be drawn into clean oil bottles or oil-compatible containers while the equipment is operating at normal temperature or immediately after shutdown. To minimize sample contamination, bottle suppliers can provide bottles in three levels of cleanliness: clean (fewer than 100 particles greater than 10 µm/ml (fewer than 100 particles in 1 ml (0.00026 gal) greater than 10 µm ($3.28 \times 10^{-6}$ ft)), superclean (fewer than 10), and ultraclean (fewer than 1). The sample should be labeled immediately with the date it was taken, the source, and the type and brand name of the lubricant.

(a) Lubricating oil. The oil sample must be representative of oil in the system. The preferred sampling location is in the return lines upstream of filters. If a static oil sample must be drawn, a drop-tube static sampling setup should be used to prevent contamination with sludge from the bottom of the sump. If oil must be drawn from a tap on the oil sump, wipe the tap and let sufficient oil flow to clear stagnant oil from the tap before taking the actual test sample.

(b) Hydraulic oil. The preferred sampling location is in the return line immediately upstream from the return-line filter. This location will sample particles circulating in the system. An alternative location is the supply line directly downstream from the pump. Extracting samples from the reservoir is not recommended except when no other choice is available. When necessary, reservoir samples should be taken midway between the surface and bottom of the reservoir. To ensure the most accurate results and to develop meaningful trends, all samples should be taken from the same location, in the same manner, and under the same conditions. Do not compare samples drawn from an operating machine with samples from a stationary machine.

(c) Transformer and circuit breaker insulating oil. Sampling procedures for transformer and circuit breaker insulating oils are covered in Reclamation FIST manual entitled “Maintenance of Liquid Insulation Mineral Oils and Askarels”.

(2) Field testing. Many oil properties can be field-tested economically and with relatively simple procedures and equipment. Suspicious test results should be verified by more comprehensive laboratory analysis. The following procedures are intended for oils other than those used in transformers and circuit breakers.

(a) Visual test. A visual inspection of an oil sample is the simplest type of field test. Table 12-8 outlines the procedures for conducting a visual test of oil samples. The sample to be inspected should be stored at room temperature away from direct sunlight for at least 24 hours before the inspection. The sample should be checked for sediment, and separated water. Oils also may have unusual color cloudiness or unusual odors. For comparison, it is a good idea to keep a sample of new unused oil of the same type and manufacturer stored in a sealed container in a cool dark place. The used sample can then be compared with the new sample with respect to color, odor, and general appearance.

(b) Water contamination. Hazy or cloudy oil may indicate water contamination. The “crackle” test is a simplified procedure that can be used to verify the presence of water in oil, but the test does not provide quantitative results. The crackle test can be conducted by making a small cup from aluminum foil, adding a few drops of the oil, and heating rapidly over a small flame. The test can also be conducted by using a hot plate, as previously noted, or by immersing a hot soldering iron in a sample of the oil. An audible crackling sound will be heard if water is present. Eye protection should be worn during the test to prevent injury if oil splatters during the heating. If water contamination is evident, the oil should be purified and a sample of the purified oil should be sent to a laboratory for analysis. If sediment is present, the oil should be purified, and samples of both the unpurified oil and the purified oil should be submitted for analysis. The sediment of the unpurified oil can be analyzed to determine its source.

(c) Microbial contamination. Initial microbial contamination of hydraulic fluids may also be detected by a foul odor due to waste and decomposition products of the microbes. Fluid viscosity may appear thicker due to the microbes. Fluid color may range from a light brown to a slimy green appearance.

(d) Neutralization number. An oil's neutralization number can also be determined in the field. With the exception of some motor oils, which may be alkaline, most lubricating oils are essentially neutral. An acidic oil is probably the result of oxidation due to extended service or abnormal operating conditions. The neutralization number of new oil is usually less that 0.08. The maximum allowable number depends on the type of oil and service, and this number should be obtained from the oil manufacturer. The maximum value is usually less than 0.5. Of greatest concern in this test is the rate of increase, not necessarily the neutralization number itself. A sudden increase in the neutralization number may indicate that an operational problem exists or that the oil has reached the end of its useful life. In either case, action is required to prevent further deterioration and equipment damage. If tests show a large increase in the neutralization number, or if the neutralization number exceeds the maximum value allowable, the oil manufacturer should be consulted to determine if the oil can be economically reclaimed.

**Table 12-8**
**Visual Examination of Used Lubricating Oil**

| Appearance of Sample | | | Action To Be Taken | |
|---|---|---|---|---|
| **When Taken** | **After 1 hour** | **Reason** | **System without filter(1) or centrifuge** | **System with filter (1) or centrifuge** |
| Clear | --- | --- | None | None |
| Opaque(2) | Clear | Foaming | Cause of foaming to be sought (3) | Cause of foaming to be sought (3) |
| | Clear oil with separated water layer | Unstable emulsion(4) | Runoff water (and sludge) from drain(5) | Check centrifuge(6) |
| | No change | Stable emulsion | Submit sample for analysis(7) | Check centrifuge:(6) if centrifuge fails to clear change oil |
| Dirty | Solids separated(8) | Contamination | Submit sample for analysis(7) | Check filter or centrifuge |
| Black (acrid smell) | No change | Oil oxidized | Submit sample for analysis(7) | Submit sample for analysis(7) |

1. Take sample of circulating oil in clean glass bottle (50-100 ml).
2. If dirty or opaque, stand for 1 hour, preferably at 60° C (an office radiator provides a convenient source of heat).

Notes:

(1) The term filter is restricted to units able to remove particles less than 50 µm; coarse strainers, which are frequently fitted in oil pump suctions to protect the pump, do not remove all particles liable to damage bearings, etc.

(2) Both foams (mixtures of air and oil) and emulsions (mixtures of water and oil) render the oil opaque.

(3) Foaming is usually mechanical in origin, being caused by excessive churning, impingement of high-pressure return oil on the reservoir surface, etc. Foam can be stabilized by the presence of minor amounts of certain contaminants, e.g., solvents, corrosion preventives, grease. If no mechanical reason can be found for excessive foam generation, it is necessary to change oil.

(4) Steps should be taken to remove the water as soon as possible. Not only is water liable to cause lubrication failure, but it will also cause rusting; the presence of finely divided rust tends to stabilize emulsions.

(5) Failure of water to separate from oil in service may be the result of inadequate lubricant capacity or the oil pump suction being too close to the lowest part of the reservoir. More commonly, it results from re-entrainment of separated water from the bottom of the sump when, by neglect, it has been allowed to build up in the system.

(6) The usual reason for a centrifuge failing to remove water is that the temperature is too low. The oil should be heated to 80 °C (176 °F) before centrifuging.

(7) It is not always possible to decide visually whether the oil is satisfactory or not. In doubtful cases, it is necessary to have laboratory analysis.

(8) In a dark oil, solids can be seen by inverting the bottle and examining the bottom.

Reference: Neale, M. J., Lubrication - A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

(e) Particle counting. Portable particle counters are available for in-house testing. The advantage is that measurement results can be obtained quickly, as opposed to the 1- to 2-week waiting period typical for laboratory testing. The quick results also allow timely preventive measures to reduce the potential for severe damage. Two types of portable particle counters are generally available: laser and differential pressure. Laser counters transmit a light beam through the fluid to a photodetector on the opposite side. The light intensity measured varies with the number of particles in the fluid. As the number of particles increases, the light scattering increases and the light intensity measured at the detector is reduced. The intensity of the measured light is an indication of the number of particles in the fluid sample. Laser counters are accurate and can measure a particle to 2 µm ($6.56 \times 10^{-6}$ ft). Laser counters have several disadvantages, including sensitivity to other conditions that may restrict light passage through the fluid: aeration, haziness (typically caused by water), fluid opacity, and emulsions. The differential particle counter measures differential pressure across standard 5- and 15-µm ($1.64 \times 10^{-5}$ and $4.96 \times 10^{-5}$ ft) screens, which correlate with ISO particle counting standards. As fluid passes through the screens, large particles are filtered, causing the differential pressure across the screens to increase. This type of counter is not affected by the disadvantages that affect laser counters.

(3) Laboratory testing and analysis. When field testing is inadequate or indicates that additional testing is required, oil samples should be submitted for laboratory analysis. Laboratory analysis should include viscosity, neutralization number, water contamination, and the identification of wear metal and other contaminants. Properties to be tested, along with the ASTM test method to be used, are listed in Table 12-9. If possible, the oil's manufacturer should perform tests periodically. Since the composition and additive content of oils is usually considered proprietary information, only the manufacturer can accurately determine the extent of additive depletion. When analysis is conducted by independent laboratories, the oil manufacturer should be contacted anytime the test results suggest questionable serviceability of an oil. When problems arise or abnormal situations develop, other properties may be tested or the testing frequency of the recommended properties should be increased. For example, if oil color suddenly becomes hazy or dark, the oil should be tested immediately for water or other contamination. The tests included in Table 12-9 are used to determine contamination and degradation of the oil. Viscosity, appearance, water content, and cleanliness are related to contamination. Total acid number (TAN), color, and Rotating Bomb Oxidation Test (RBOT) are related to degradation. The RBOT and TAN tests are excellent for following the degradation of turbine oil. If RBOT results for the new oil are known, these can be compared with the values for the used oil to determine the oxidation stability reserve of the used oil. Changes in the RBOT and TAN of the oils are the best indication of the remaining useful life of the lubricating oil.

**Table 12-9**
**Key Tests for Oil Quality Control Monitoring**

| Property Test | ASTM Test Method |
|---|---|
| Total acid number (TAN) | D 664, D 974 |
| Color | D 1500 |
| Appearance | Visual |
| Viscosity | D 445 |
| Rotating Bomb Oxidation Test (RBOT) | D 2272 |
| Water content | D 95, D 1744 |
| Rust test | D 665A |
| Cleanliness | Particle Counter, F 311 and F 312 |

(4) Test frequencies

(a) New oil. Oil should be tested prior to filling the unit and retested 3 months later. Sampling should continue at this interval until a trend is established. The sampling interval can then be extended as dictated by the test results.

(b) Installation of new components. When new components are installed the above oil testing frequency should be followed.

(c) Normal operation. Equipment maintenance records should suggest oil sampling frequencies. Additional testing should be conducted on a periodic basis, and at increased frequencies as dictated by the oil analysis results. In the absence of recommended sampling frequencies, 500 hours is commonly suggested for journal and roller bearing lubricant applications. Oil samples should be drawn from governors and all guide and thrust bearings annually and submitted for laboratory analysis. In addition to the annual tests, samples should be visually inspected at frequent intervals. Test oil annually or more often if conditions warrant. If oil appears clean and no operational problems have been noted, testing may be postponed to the next unit overhaul. When a unit is overhauled, test the oil before draining into a storage tank. If oil is degraded, discard it to prevent storage tank contamination.

(d) Logging and interpretation of test data. It is important to keep accurate records of test results. Properties that change as the oil degrades, such as viscosity, oxidation, TAN, and RBOT, should be graphed to provide a visual indication of relative changes or trends. This procedure highlights any unusual trends and allows for a more accurate estimate of the remaining service life of lubricating oil. Oil properties can be affected by routine addition of make-up oil and by the type of oil added. Whenever a reservoir is topped, the data baseline must be reset to prevent erroneous interpretation of trend results.

(e) Recommended corrective action. The primary purpose of an oil monitoring program is to ensure long, trouble-free operation of the turbine and generators, main pumps and motors, or other equipment. To achieve this purpose, the monitoring program must include prompt and appropriate action steps. The corrective action must be based on correct interpretation of the test data, as outlined in Tables 12-10 and 12-11. It is very important to follow the monitoring schedule that has been established. Interpretation is more meaningful if the data have been collected over an extended period of time.

## 12-10. Oil Purification and Filtration

*a. Cleanliness.*

(1) Oil must be free of contaminants to perform properly. Most hydraulic systems use an in-line filter to continually filter the oil while the system is operating to maintain the required cleanliness rating in accordance with ISO standards (Table 12-12). ISO 4406 is an internationally recognized standard that expresses the level of particulate contamination of a hydraulic fluid. The standard is also used to specify the required cleanliness level for hydraulic components and systems. ISO 4406 is a hydraulic cleanliness rating system that is based on a number of contamination particles larger than 2 microns, 5 microns, and 15 microns in a 1-milliliter fluid sample. Once the number and size of the particles are determined, the points are plotted on a standardized chart of ISO range numbers to convert the particle counts into an ISO 4406 rating. The ISO 4406 rating provides three range numbers that are separated by a slash, such as 16/14/12. In this rating example, the first number 16 corresponds to the number of particles greater than 2 microns in size; the second number 14 corresponds to the number of particles greater than 5 microns in size; and the third number 12 corresponds to the number of particles greater than 15 microns in size. All three values for applicable range numbers can be determined through the use of the ISO 4406 standardized chart based on the actual number of particles counted within the 1-milliliter (ml) sample for each size category (>2, >5, >15 microns). For example, if a 1-ml sample contained 6000 2-mm particles, 140 5-mm particles, and 28 15-mm particles, the fluid would have a cleanliness rating of 20/14/12. The number of 2-mm particles (6000) falls in the range greater than 5000 but less than 10,000, which results in an ISO 4406 range number of 20. The number of 5-m particles (140) falls in the range greater than 80 but less than 160, which results in an ISO 4406 range number of 14. The number of 15-mm particles (28) falls in the range greater than 20 but less than 40, which results in an ISO 4406 range number of 12.

**Table 12-10**
**Interpretation of Test Data and Recommended Action**

| Test | Warning Limit | Interpretation | Action Steps |
|---|---|---|---|
| Total acid No. (TAN) increase, over new oil | 0.1-0.5 mg KCH/g | This represents above-normal deterioration. Possible causes are anti-oxidant depletion or oil contamination. | Investigate cause. Increase frequency of testing; compare with RBOT data. Consult with oil supplier for possible reinhibition. |
| | Exceeds 0.5 mg KOH/g | Oil at or approaching end of service life: oil may be contaminated. | Look for signs of increased sediment on filters and centrifuge. Check RBOT. If RBOT less than 25 percent of original, review status with oil supplier and consider oil change. Increase test frequency if left in system. |
| RBOT2 | Less than half value of original oil | Above-normal degradation. | Investigate cause. Increase frequency of testing. |
| | Less than 25 percent of original | Together with high TAN, indicates oil at or approaching end of service life. | Resample and retest. If same, change oil and consider discarding the oil. |
| Water content | Exceeds 0.2 percent | Oil contaminated: potential water leak | Investigate and remedy cause. Clean system by centrifugation. If still unsatisfactory, consider oil change or consult oil supplier |
| Cleanliness | Exceeds 0.01 percent volume, particulates | Source of particulates may be make-up oil, dust, or ash entering system. or wear condition in system. | Locate and eliminate source of particulates. Clean system oil by filtration or centrifugation, or both. |
| Rust test, Procedure A | Failure, light rusting | Possibilities: (a) the system is wet or dirty, or both, (b) the system is not maintained properly (for example, water drainage neglected, centrifuge not operating, or (c) additive depleted. | Investigate cause and make necessary maintenance and operating changes. Check rust test. Consult oil supplier regarding reinhibition if test result unchanged. |
| Appearance | Hazy | Oil contains water or solids, or both. | Investigate cause and remedy. Filter or centrifuge oil, or both. |
| Color | Unusual and rapid darkening | This is indicative of contamination or excessive degradation. | Determine cause and rectify. |
| Viscosity | ±20 percent from original oil viscosity | Possibilities: oil is contaminated, or oil is severely degraded. | Determine cause. If viscosity is low, determine flash point. Consult oil supplier. Change oil, if necessary. |
| Flash point | Drop 30° F (-1° C) or more compared to new oil | Probably contamination. | Determine cause. Check other quality parameters. Consider oil change. |
| Foam test ASTM D 892, Sequence 1 | Exceeds following limits: tendency - 450, stability - 10 | Possibly contamination or antifoam depletion. In new turbines, residual rust preventatives absorbed by oil may cause problem. | Rectify cause. Check with oil supplier regarding reinhibition. (Note: plant problems are often mechanical in origin.) |

[1] Typical TAN value for new oil is 0.1 to 0.3 mg KOH/g.
[2] Typical RBOT value for new oil is 250 min.
Reference: Reprinted by permission of Noria Corporation, Tulsa, OK.

(2) Table 12-13 shows the desirable cleanliness levels for different types of systems and typical applications rated by the system sensitivity, from noncritical systems through super-critical systems. Table 12-14 shows the desired ISO cleanliness code for specific components in hydraulic and lubricating systems.

**Table 12-11**
**Oil Analysis Data Interpretation and Problem Indication**

| Problem Area | Analytical Indications[(a)] | Inspection/Sensory Indications[(b)] |
|---|---|---|
| Air entrainment | Increased viscosity, TAN[(c)], water, and/or FTIR[(b)] for oxidation<br>Silicon defoamant levels too high/low<br>Blotter test: cokelike carbon on patch | Oil clouding/foaming, increase in oil gage temperature.<br>Spongy/slow hydraulics, cavitation of pump/bearing, noisy operation. |
| Abrasive wear conditions | Increased silicon, aluminum, particle count, and/or ferrous particles<br>Water contamination<br>Ferrogram has cutting wear, silica particles | Scratch marking or/polishing of frictional surfaces<br>Cutting wear on blotter/patch/filter media<br>Filter/breather/seal failure |
| Corrosive wear conditions | Increased TAN[(c)], particle count, spectrographic iron & bearing metals, water<br>Decrease in TBN[(d)]<br>Ferrogram shows submicron debris at ferrogram tail, rust particles, metal oxides | Fretting, pitting, and etching on contact surfaces<br>Transient electric currents, high-engine blowby<br>Rust on patch or filter media |
| Failed filter | Increasing silicon/aluminum, particle count, ferrous particles, and/or elemental iron<br>Ferrograms show green-looking particles, cutting wear, filter fibers | Valve silt lock, noisy bearings<br>Unchanging or high delta P of filter<br>Frequent bearing failures, high levels of bottom sediment |
| Overheating | Increasing ferrous particles, particle count, flash point, viscosity, or oil specific gravity<br>Ferrograms show friction polymers, oxides, bluing/tempering of particles, sliding wear particles, bearing particles, e.g., babbitt metal | Bearing distress/failure<br>Hot spots and high bearing metal temperature<br>Evidence of coking/sludge<br>Burn/rancid odor, high oil gage temperature |
| Misalignment, imbalance, overloading | Ferrograms densely loaded with black-iron oxides, dark metal oxides, severe cutting and sliding wear, tempered particles, large, chunky particles, or bearing metals<br>Increase in viscosity, TAN[(c)], particle count, and/or ferrous particles<br>Depletion of Zn and P | Engine lugging/stalling, black exhaust<br>Raised oil, bearing metal, or jacket-water temperature<br>Dark, foul-smelling oil, bearing distress/failure, hard turning of shaft<br>Abnormal vibration, noise<br>Blotter test: coke, metal chips<br>Metal chips on filter, highly loaded chip detectors |
| Impending failure of bearing, gear, pump, etc. | Exponential increase in particle count and number of wear particle concentration<br>Increase in iron or bearing metals<br>Ferrogram shows rate increase in spheres, dark metal oxides, particle bluing, spalling/chunks, severe sliding/galling particles, cutting wear | Shaft wobble, vibration, acoustic changes, blue exhaust smoke, hot spots, hard turning shaft, and/or high-bearing metal temperatures<br>Patch/blotter shows coking |
| Wrong lubricant | Change in viscosity, VI, flash point, additive elements, FTIR[(b)] specta, TAN[(c)]/TBN[(d)]<br>Change in wear patterns | Change in oil gage or bearing temperature<br>Bearing distress or noise<br>Hard turning of shaft |
| Antioxidant depletion | Decreasing TAN[(c)], RBOT oxidation life, and Zn/P content<br>Increasing viscosity, TAN[(c)], particle count<br>FTIR: decreasing antioxidant, increasing oxidation, sulphation, and/or nitration | Oil darkening<br>Pungent odor<br>Hot running |

(a) Not all of the identified indications would be expected for each problem area; (b) Fourier Transform Infrared Spectroscopy; (c) Total Acid Number; (d) Total Base Number; (e) Vapor-Induced Scintillation Analysis; (f) Karl Fischer.
Reference: Reprinted by permission of Noria Corporation, Tulsa, OK.

(Continued)

**Table 12-11 (Concluded)**

| Problem Area | Analytical Indications[a] | Inspection/Sensory Indications[b] |
|---|---|---|
| Dispersancy failure | FTIR[b], low TBN[d]<br>Increasing particle count, pentane insolubles<br>Defined inner spot on blotter test | Filter inspection: sludge on media, filter in bypass<br>Black exhaust smoke<br>Deposits on rings and valves |
| Base oil deterioration | Increasing viscosity, TAN[c], particle count, and/or ferrous particles<br>Decreasing TBN[d]<br>Change in VI and lower dielectric strength | Poor oil/water separability<br>Air entrainment/foaming<br>Pungent odor, sludge/varnish formation<br>Blotter spot yellow/brown, oil darkening |
| Water contamination | Increasing viscosity, TAN[c], Ca, Ma, and/or Na<br>Rapid additive depletion/failure<br>Crackle test, VISA[e], KF[f], FTIR[b]<br>Reduced dielectric strength<br>Blotter test: sharp or star burst periphery on inner spot | Oil clouding/opacity, water puddling/separating, sludging, foaming<br>Evidence of fretting wear/corrosion<br>Filter: paper is wavy, high-pressure drop, short life; ferrogram shows rust<br>Valve sticking, orifice silting, bearing distress/failure, noisy pump/bearings |
| Coolant contamination | Increasing viscosity, copper, particle count, wear metal, Na, B, and/or K<br>FTIR[b], glycol<br>Crackle test, VISA[e], KF[f] | Bearings dark charcoal color, distressed<br>Dispersancy failure, sludging, varnishing<br>Blotter test: sticky, black center<br>Filter plugs prematurely, oil has mayonnaise consistency, white exhaust smoke |
| Fuel dilution | Low oil viscosity, flash point<br>Additive and wear metal dilution (elemental analysis)<br>FTIR[b]/gas chromatography for fuel<br>Rising particle count and wear metals | Rising oil levels and oil gage temperatures<br>Blotter test: halo around center spot<br>Blue exhaust smoke (collapsed rings), plugged air filter, defective injectors<br>Oil has diesel odor, overfueling conditions |

(3) However, for most lubricating systems filter or purify oil periodically as dictated by the results of the oil testing program. Water is the most common contaminant found in hydroelectric plants, and its presence in oil may promote oxidation, corrosion, sludge formation, foaming, additive depletion, and generally reduce a lubricant's effectiveness. Solid contaminants such as dirt, dust, or wear particles also may be present. These solid particles may increase wear, and promote sludge formation, foaming, and restrict oil flow within the system. The following are some of the most common methods used to remove contaminants from oil.

*b. Gravity purification.* Gravity purification is the separation or settling of contaminants that are heavier than the oil. Gravity separation occurs while oil is in storage but is usually not considered an adequate means of purification for most applications. Other purification methods should also be used in addition to gravity separation.

*c. Centrifugal purification.* Centrifugal purification is gravity separation accelerated by the centrifugal forces developed by rotating the oil at high speed. Centrifugal purification is an effective means of removing water and most solid contaminants from the oil. The rate of purification depends on the viscosity of the oil in a container and the size of the contaminants.

*d. Mechanical filtration.* Mechanical filtration removes contaminants by forcing the oil through a filter medium with holes smaller than the contaminants. Mechanical filters with fine filtration media can remove particles as small as 1 micron, but filtration under 5 microns is not recommended because

**Table 12-12**
**ISO 4406 Range Numbers**

| Number of Particles per Milliliter | | |
|---|---|---|
| **Greater Than** | **Less Than** | **ISO 4406 Range Number** |
| 80,000 | 160,000 | 24 |
| 40,000 | 80,000 | 23 |
| 20,000 | 40,000 | 22 |
| 10,000 | 20,000 | 21 |
| 5,000 | 10,000 | 20 |
| 2,500 | 5,000 | 19 |
| 1,300 | 2,500 | 18 |
| 640 | 1,300 | 17 |
| 320 | 640 | 16 |
| 160 | 320 | 15 |
| 80 | 160 | 14 |
| 40 | 80 | 13 |
| 20 | 40 | 12 |
| 10 | 20 | 11 |
| 5 | 10 | 10 |
| 2.5 | 5 | 9 |
| 1.3 | 2.5 | 8 |
| 0.64 | 1.3 | 7 |
| 0.32 | 0.64 | 6 |
| 0.16 | 0.32 | 5 |
| 0.08 | 0.16 | 4 |
| 0.04 | 0.08 | 3 |
| 0.02 | 0.04 | 2 |
| 0.01 | 0.02 | 1 |

Reference: Contamination Control and Filtration Fundamentals, Pall Corporation, Glen Cove, NY.

many of the oil additives will be removed. A typical mechanical filter for turbine oil would use a 6- to 10-micron filter. The filter media will require periodic replacement as the contaminants collect on the medium's surface. Filters have absolute, beta, and nominal ratings as follows:

(1) Absolute rating. Absolute rating means that no particles greater than a certain size will pass through the filter and is based on the maximum pore size of the filtering medium.

**Table 12-13**
**Desirable Fluid System Cleanliness Levels**

| ISO Contaminations Code | System Sensitivity | Types of Systems and Typical Applications |
|---|---|---|
| 15/13/9 | Supercritical | Silt-sensitive control system with very high reliability. Laboratory apparatus, aerospace systems. |
| 17/15/11 | Critical | High-performance servo and high-pressure long-life systems, e.g., aircraft, machine tools, industrial robots. |
| 19/16/13 | Very important | High-quality reliable systems, e.g., turbo machinery (steam, gas, hydro), lube and electro-hydraulic controls, general machine requirements. |
| 20/18/14 | Important | General machinery and mobile hydraulic systems. Medium pressure, medium capacity. Acceptable in-service oil quality for steam turbines without lift pumps. |
| 21/19/15 | Average | Low oil pressure heavy-duty industrial system and construction equipment or applications where long life is not critical, e.g., winches, mobile heavy equipment transmissions. |
| 23/21/17 | Noncritical | Low-pressure systems with large clearances, e.g., ships' elevators. |

Reference: Contamination Control and Filtration Fundamentals, Pall Corporation, Glen Cove, NY.

(2) Beta rating. The beta rating or beta ratio is a filter-rating expressed as the ratio of the number of upstream particles to the number of downstream particles of a particular size or larger. It expresses the separating effectiveness of a filter. The beta ratio counts the results from the multipass "beta" test for filters, ANSI/(NFPA) T3.10.8.8, and ISO 4572, "Hydraulic Fluid Power - Filters - Multi-Pass Method for Evaluating Filtration Performance."

(3) Nominal rating. Nominal rating is not an industry standard but an arbitrary value assigned by the filter manufacturer and means that a filter stops most particles of a certain micron size. Due to its imprecision, filter selection by nominal rating could lead to system contamination and component failure.

*e. Coalescence purification.* A coalescing filter system uses special cartridges to combine small, dispersed water droplets into larger drops. The larger water drops are retained within a separator screen and fall to the bottom of the filter while the dry oil passes through the screen. A coalescing filter will also remove solid contaminants by mechanical filtration.

*f. Vacuum dehydration.* A vacuum dehydration system removes water from oil through the application of heat and vacuum. The contaminated oil is exposed to a vacuum and is heated to temperatures of approximately 38 °C to 60 °C (100 °F to 140 °F). The water is removed as a vapor. Care must be exercised to ensure that desirable low-vapor-pressure components and additives are not removed by the heat or vacuum.

*g. Adsorption purification.* Adsorption or surface-attraction purification uses an active-type medium such as fuller's earth to remove oil oxidation products by their attraction or adherence to the large internal surfaces of the media. Because adsorption purification will also remove most of an oil's additives, this method should not be used for turbine oil purification.

*h. Filter system.* A system consisting of a vacuum purifier to remove the water, a centrifuge to remove large solid particles, and a 10-micron filter to remove the finer solid particles is the most desirable

**Table 12-14**
**System Cleanliness Level Guidelines**

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Hydraulic System** | | | | | | | | | |
| Servo Valve | A | B | C | D | E | | | | |
| Proportional Valve | | A | B | C | D | E | | | |
| VariableVolume Pump | | | A | B | C | D | E | | |
| Cartridge Valve | | | | A | B | C | D | E | |
| Fixed Piston Pump | | | | A | B | C | D | E | |
| Vane Pump | | | | | A | B | C | D | E |
| Pressure/Flow Control Valve | | | | | A | B | C | D | E |
| Solenoid Valve | | | | | A | B | C | D | E |
| Gear Pump | | | | | A | B | C | D | E |
| **Lubrication System** | | | | | | | | | |
| Ball Bearings | | A | B | C | D | E | | | |
| Roller Bearings | | | A | B | C | D | E | | |
| Journal Bearings | | | | A | B | C | D | E | |
| Gear Box (Industrial) | | | | A | B | C | D | E | |
| Gear Box (Mobile) | | | | | A | B | C | D | E |
| Diesel Engine | | | | | | A | B | C | D |
| Cleanliness Level (PCC) | 12/10/7 | 13/11/9 | 14/12/10 | 15/13/11 | 16/14/12 | 17/15/12 | 17/16/13 | 18/16/14 | 19/17/14 |

Hydraulic system pressure (kPa) range- C > 172,500, D 10,350 to 17,250, E < 10,350
Lubrication system: Pressure ranges do not apply. Start at midrange C and adjust per following guidelines:
To determine system cleanliness level:

1. Starting at the top of the system component list. Find the first item used in hydraulic or lubrication system.
2. Locate box to the right of selected component, which corresponds to the operating pressure range.
3. Recommended cleanliness level is given at the bottom of each column that the box falls into.
4. Shift one column to the left if any of the following factors apply:
   a. System is critical to maintaining production schedules.
   b. High cycle/severe duty application.
   c. Water-containing hydraulic fluid is used.
   d. System is expected to be in service more than seven years.
   e. System failure can create a safety concern
5. Shift two columns to the left if two or more factors apply.
6. For lubrication systems, shift one column to the right if operating viscosity is greater than 500 SUS.
7. For flushing, shift one to two columns to the left.

Reference: Contamination Control and Filtration Fundamentals, Pall Corporation, Glen Cove, NY

system. The vacuum purifier should be specified as being suitable for the lubricating oil. The ability of a filter system to remove water is especially important to prevent microbial contamination in lubricants and hydraulic fluids. However, this type of system alone may not be sufficient. Introduction of biocides may be necessary to minimize the chemical reaction byproducts and contamination due to microbes.

*i. Location and purpose of filters.* Table 12-15 provides information on the location and purpose of filters. Table 12-16 lists various types of filters and the range of particle sizes filtered by each.

**Table 12-15**
**Location and Purpose of Filter in Circuit**

| Location | Degree of Filtration | Type | Purpose |
|---|---|---|---|
| Oil reservoir vent | Coarse | Wire wool<br>Paper<br>Oil bath | Removal of airborne contaminant |
| Oil reservoir filler | Coarse | Gauze | Prevention of ingress of coarse solids |
| Suction side of pump | Medium | Paper<br>Gauze | Protection of pump |
| Delivery side of pump | Fine | Sintered metal<br>Felt<br>Paper | Protection of bearings/system |
| Return line to reservoir | Medium | Gauze<br>Paper | Prevention of ingress of wear products to reservoir |
| Separate from system | Very fine | Centrifuge | Bulk cleaning of whole volume of lubricant |

Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

**Table 12-16**
**Range of Particle Sizes That Can be Removed by Various Filtration Methods**

| Filtration Method | Examples | Range of Minimum Particle Size Trapped Micrometers (μm) |
|---|---|---|
| Solid fabrications | Scalloped washers, wire-wound tubes | 5-200 |
| Rigid porous media | Ceramics and stoneware<br>Sintered metal | 1-100<br>3-100 |
| Metal sheets | Perforated<br>Woven wire | 100-1000<br>5-200 |
| Porous plastics | Plastic pads, sheets, etc.<br>Membranes | 3-100<br>0.005-5 |
| Woven fabrics | Cloths of natural and synthetic fibers | 10-200 |
| Cartridges | Yarn-wound spools, graded fibers | 2-100 |
| Nonwoven sheets | Felts, lap, etc.<br>Paper - cellulose<br>- glass<br>Sheets and mats | 10-200<br>5-200<br>2-100<br>0.5-5 |
| Forces | Gravity settling, cyclones, centrifuges | Sub-micrometer |

Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

## 12-11. Oil Operating Temperature

The recommended oil operating temperature range for a particular application is usually specified by the equipment manufacturer. Exceeding the recommended range may reduce the oil's viscosity, resulting in inadequate lubrication. Subjecting oil to high temperatures also increases the oxidation rate. As previously noted, for every 18 °F (10 °C) above 150 °F (66 °C), an oil's oxidation rate doubles and the oil's life is essentially cut in half. Longevity is especially critical for turbines in hydroelectric generating units where the oil life expectancy is several years. Ideally the oil should operate between 50 °C and 60 °C (120 °F and 140 °F). Consistent operation above this range may indicate a problem such as misalignment or tight bearings. Adverse conditions of this nature should be verified and corrected. Furthermore, when operating at higher temperatures, the oil's neutralization (acid) number should be checked more frequently than dictated by normal operating temperatures. An increase in the neutralization number indicates that the oxidation inhibitors have been consumed and the oil is beginning to oxidize. The lubricant manufacturer should be contacted for recommendations on the continued use of the oil when the operating temperatures for a specific lubricant are unknown. Figures 12-1 through 12-3 show relationships between hours of operation and temperature for mineral and synthetic oils and greases. Figure 12-4 shows base oil temperatures for mineral and synthetic lubricants. Figure 12-5 shows usable temperature range for greases. Table 12-17 shows pour point temperatures for mineral and synthetic lubricants. Table 12-18 shows practical high-temperature limits for solid lubricants.

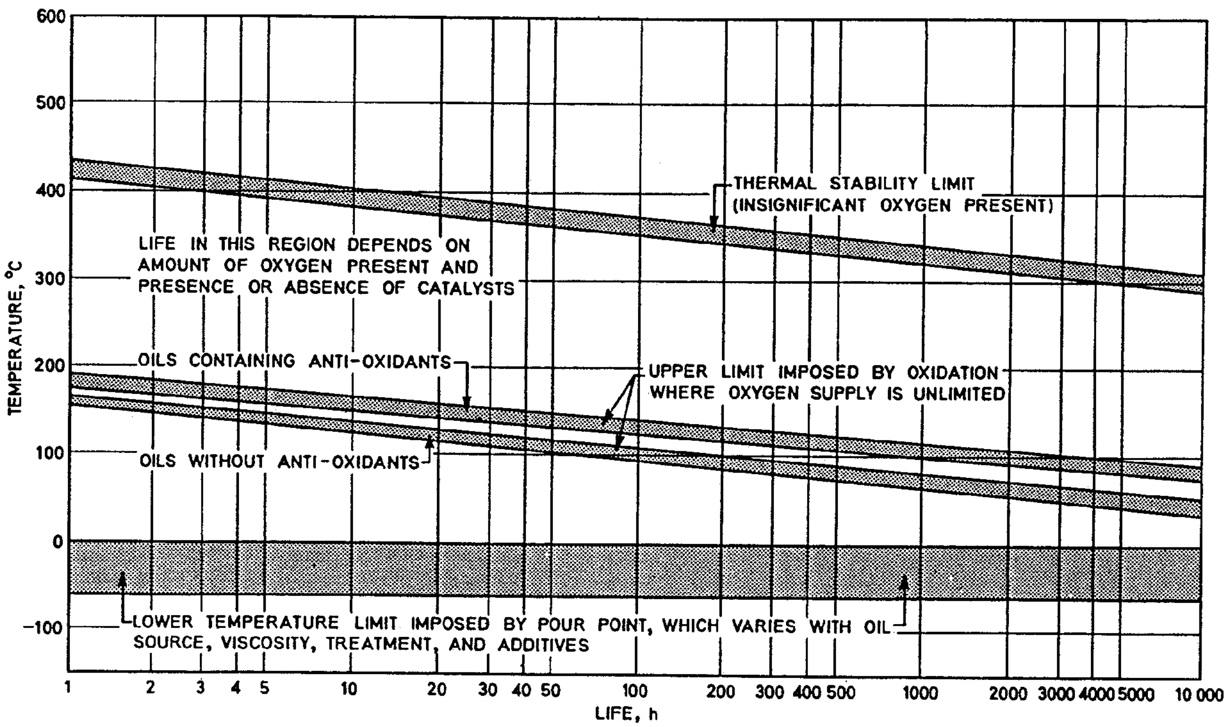



**Figure 12-1. Temperature limits for mineral oils (Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England)**

## 12-12. Lubricant Storage and Handling

Lubricants are frequently purchased in large quantities and must be safely stored. The amount of material stored should be minimized to reduce the potential for contamination, deterioration, and health and explosion hazards associated with lubricant storage. Table 12-19 identifies the causes of lubricant deterioration and prevention during storage. Although lubricant storage receives due attention, equipment that has received a lubricant coating and stored is frequently forgotten. Stored equipment should be inspected on a periodic basis to ensure that damage is not occurring. Table 12-20 lists recommended frequency of inspection for stored equipment. Table 12-21 provides inspection and relubrication recommendations for equipment in storage.

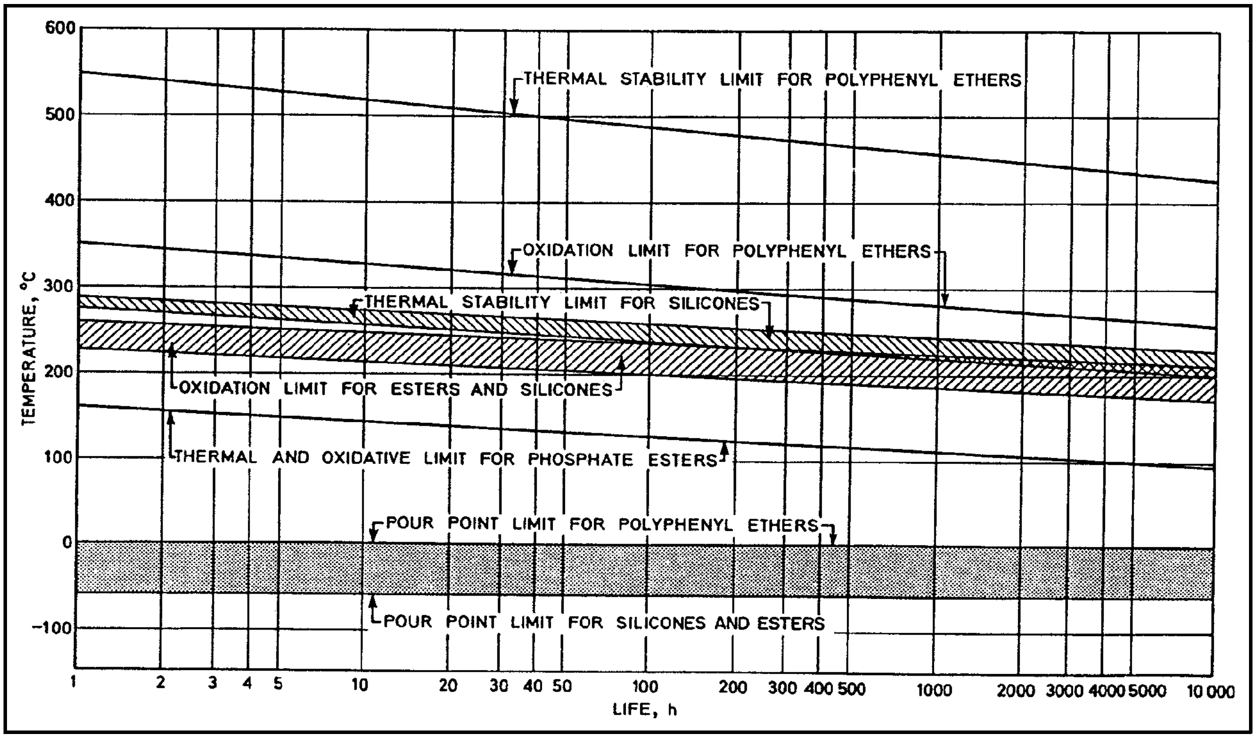



**Figure 12-2. Temperature limits for some synthetic oils (Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England)**

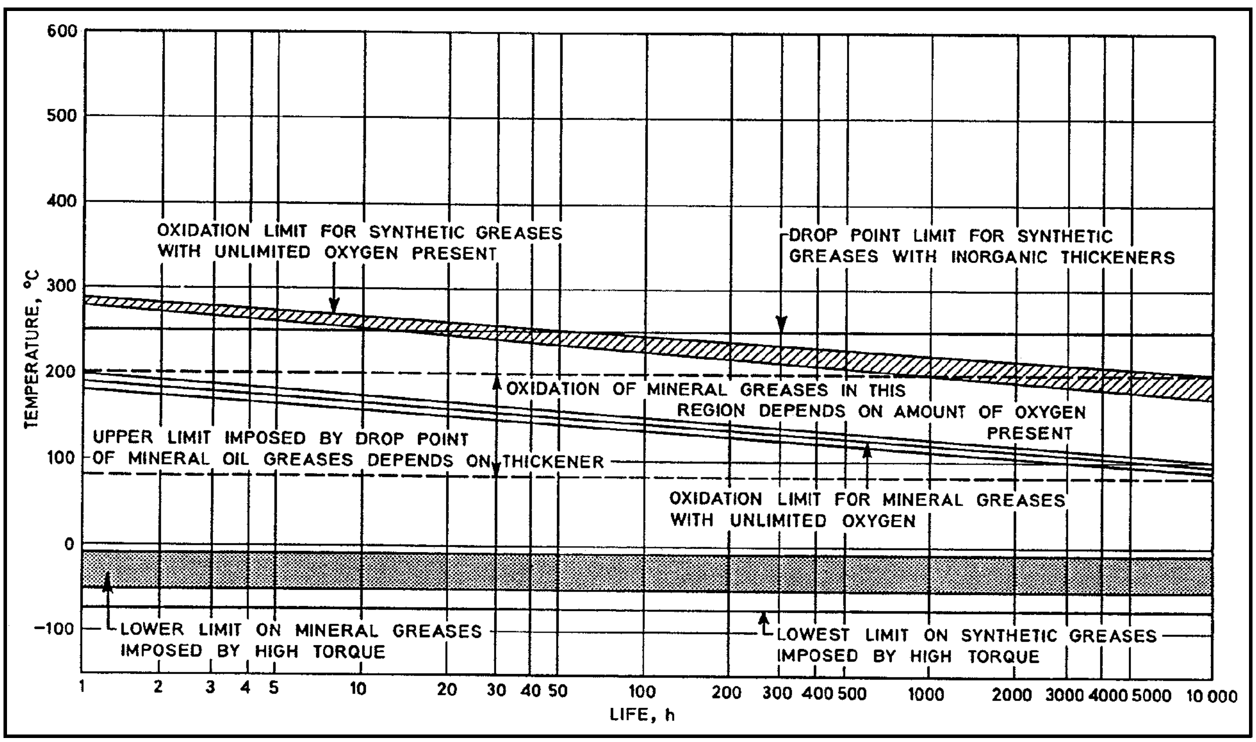
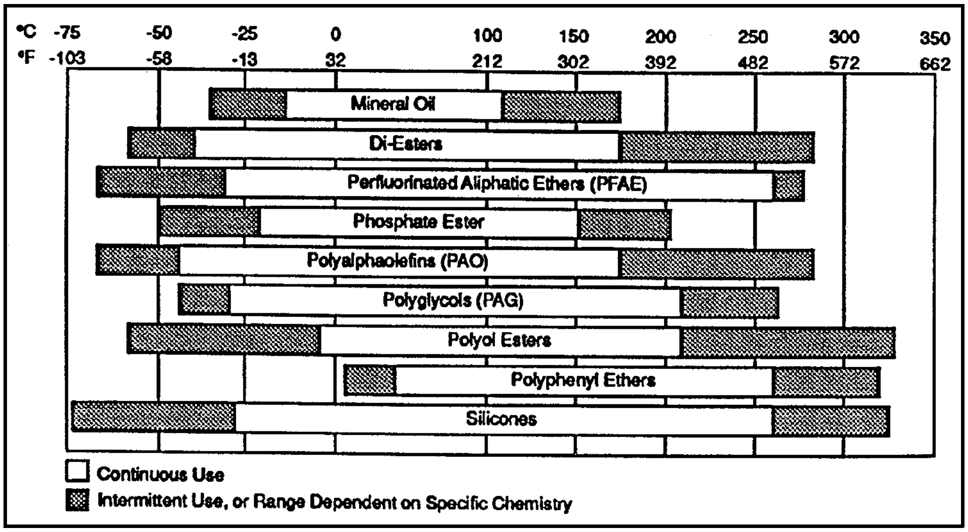



**Figure 12-3. Temperature limits for greases (Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England)**




**12-4. Base oil temperature limits (Reference: Booser, R.E., Reprinted with permission from CRC Handbook of Lubrication (Theory and Practice of Tribology); Volume II Theory and Design, Copyright CRC Press, Boca Raton, Florida)**

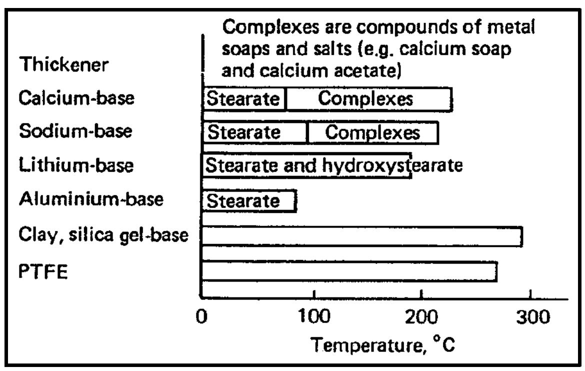



**Figure 12-5. Usable temperature range for greases (Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England)**

**Table 12-17**
**Lubricant Pour Point Temperatures**

| Type of Lubricant | Pour Point, ° C (°F) | |
|---|---|---|
| Mineral oil | -57 (min.) | (-70.6) |
| Diester | -60 | (-76.0) |
| Phosphate ester | -57 | (-70.6) |
| Silicate ester | -65 | (-85.0) |
| Di-siloxane | -70 | (-94.0) |
| Silicone | -70 | (-94.0) |
| Polyphenyl-ether | -70 | (-94.0) |
| Perfluorinated polyether | -75 to -90 | (-103 to -130) |

Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England

**Table 12-18**
**Temperature Limitations of Solid Lubricants**

| | Example | Practical Temperature Limit, ° C* | (°F) | Common Usages |
|---|---|---|---|---|
| 1. Boundary lubricants and extreme pressure additives (surface active) | Metal soap (e.g., stearate) | 150 | (302) | Metal cutting, drawing, and shaping; Highly-loaded gears |
| | Chloride (as Fe $Cl_3$) | 300 | (572) | |
| | Sulphide (as FeS) | 750 | (1382) | |
| | Phthalocyanine (with Cu and Fe) | 550 | (1022) | Antiseizure |
| 2. Lamellar solids and/or low shear strength solids | Graphite | 600 | (1112) | General, metal working, antiseizure, and antiscuffing |
| | Molybdenum disulphide | 350 | (662) | |
| | Tungsten disulphide | 500 | (932) | |
| | Lead monoxide† | 650 | (1202) | |
| | Calcium fluoride | 1000 | (1832) | |
| | Vermiculite | 900 | (1652) | Antiseizure |
| | PTFE | 250 | (482) | Low friction as bonded film or reinforced composite |

* The limit refers to use in air or other oxidizing atmospheres.
† Bonded with silica to retard oxidation.
Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

*a. Oil.* Oil is stored in active oil reservoirs, where it is drawn as needed, and in oil drums for replenishing used stock. Each mode has its own storage requirements.

(1) Filtered and unfiltered oil tanks. Most hydroelectric power plants use bulk oil storage systems consisting of filtered (clean) and unfiltered (dirty) oil tanks to store the oil for the thrust bearings, guide bearings, and governors. Occasionally the filtered oil tank can become contaminated by water condensation, dust, or dirt. To prevent contamination of the bearing or governor oil reservoirs, the filtered oil should be filtered again during transfer to the bearing or governor reservoir. If this is not possible, the oil from the filtered tank should be transferred to the unfiltered oil tank to remove any settled contaminants. The filtered oil storage tank should be periodically drained and thoroughly cleaned. If the area where the storage tanks are located is dusty, a filter should be installed in the vent line. If water contamination is persistent or excessive, a water absorbent filter, such as silica gel, may be required.

(2) Oil drums. If possible, oil drums should be stored indoors. Store away from sparks, flames, and extreme heat. The storage location must ensure that the proper temperature, ventilation, and fire protection requirements are maintained. Tight oil drums breathe in response to temperature fluctuations, so standing water on the lid may be drawn into the drum as it “inhales.” Proper storage is especially important when storing hydraulic fluids due to their hygroscopic nature. To prevent water contamination, place a convex lid over drums stored outdoors. Alternatively, the drums should be set on their side with the bungs parallel to the ground. The bungs on the drums should be tightly closed except when oil is being drawn out. If a tap or pump is installed on the drum, the outlet should be wiped clean after drawing oil to prevent dust from collecting.

*b. Grease.* Grease should be stored in a tightly sealed container to prevent dust, moisture, or other contamination. Excessive heat may cause the grease to bleed and oxidize. Store grease in clean areas where it will not be exposed to potential contaminants, and away from excessive heat sources such as furnaces or heaters. The characteristics of some greases may change with time. A grease may bleed, change consistency, or pick up contaminants during storage. To reduce the risk of contamination, the

**Table 12-19**
**Causes of Lubricant Deterioration and Their Prevention**

| Cause | Components Affected | Effect | Prevention |
|---|---|---|---|
| ATMOSPHERIC<br>Oxygen | Lubricants | Forms gums, resins, and acidic products with viscosity increase. | Use lubricant containing antioxidation additive. Keep in sealed containers. |
| | Engines and components | When moisture is present, causes corrosion, particularly to ferrous components. | Coat with lubricant or temporary protective. Wrap in airtight packages using vapor phase inhibitors. In sealed units, include desiccants. |
| | Cables and wires | Corrosion in the presence of water. | Coat with lubricant or temporary protective. |
| | Seals | Promotes slow cracking of natural rubber and some similar materials. Negligible normally at ambient temperatures. | Use of a different polymer. Do not store in a hot place. |
| Pollutants<br>(e.g., sulphur dioxide, hydrogen sulphide) | Engines and components<br>Cables and wires<br>Brakes and clutches | Rapid corrosion of most metals. | Store in sealed containers. Coat metals with temporary protective or lubricant. Filter air supply to remove pollutants. |
| Dust and Dirt | Lubricants | Increased rate of wear between bearing surfaces. | Keep covered or in containers. |
| | Engines and components<br>Cables and wires<br>Brakes and clutches | Increased rate of wear between bearing surfaces. Promotes corrosion in the presence of moisture | Keep covered or in containers |
| TEMPERATURE<br>Heat | Lubricants | Increases rate of deterioration as under "Oxygen." Will increase oil separation from greases. | Keep store temperature no higher than 20° C (68 °F) |
| | Seals | Increases deterioration rate as above. | |
| Cold | Lubricants | In water-containing materials (e.g., cutting oils and certain fire-resisting hydraulic oils) water could separate out. | Keep temperature above freezing point |
| HUMIDITY | Seals | Could become brittle. | |
| | Engines and components<br>Cables and wires | Promotes corrosion. More severe when ferrous and nonferrous metals present. See "Oxygen." | Coat metal parts with lubricant or temporary protective. |
| | Brakes and clutches<br>Belts and ropes<br>Seals | Promotes fungus/bacterial growth. | Store in dry location. |
| LIGHT | Lubricants | Promotes formation of gums, resins, and acidity. | Store in metal or opaque containers. |
| FUNGI/BACTERIA | Lubricants | Growth occurs at water/oil interface. | Keep water out of containers. In certain cases, biocides and fungicides can be added. |
| | Brakes and clutches<br>Belts and ropes<br>Seals | Surface covered and attacked by mold growth. | Store in dry location. Treat with biocide and fungicide. |
| VIBRATION | Engines and components | Ball bearings, and to a lesser extent roller bearings, suffer false brinelling. | Do not store where there is vibration. Resilient mountings can reduce effects of vibration. |

Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

**Table 12-20**
**Frequency of Inspection**

| Component | How Stored | Inspect |
|---|---|---|
| Lubricants | Bulk tanks | Each year, and when refilled. |
| | Sealed containers | Check annually for damage to containers. Limited tests for serviceability of contents after 3 years. |
| Engines and components | General storage<br>Packaged or sealed containers | Annually. Hand-turn engines where possible.<br>Two to four years. |
| Cables and wires<br>Brakes and clutches<br>Belts and seals | General storage | Visual inspection annually. |
| Ropes | General storage | Turn annually and test to destruction |
| Rot proofed | | Every 4 years |
| Untreated | | Every 2 years |
| Synthetic fiber | | Every 4 years |

Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

**Table 12-21**
**Relubrication and Reprotection**

| Component | How Stored | Inspection and Treatment |
|---|---|---|
| *In general:* | | |
| Engines and components | Coated with lubricant or temporary protective | Recoat annually. Lubricate when brought into use. |
| | Packaged or sealed containers | Replace VPI, desiccants, or lubricant every 2 to 4 years. |
| *Special items:* | | |
| Grease-packed ball and roller bearing | After prolonged or adverse storage, or if oil bleeding has occurred | Before use, clean out old grease with solvent,* remove surplus solvent, and replace with new grease. |
| Oil-impregnated porous metal bearings | After prolonged or adverse storage | Before use soak in warm oil of the same type as originally impregnated. |
| Small mechanisms in their own cases, e.g., watches, servos | Coated with lubricant | Relubricate every 4 years. |
| Small mechanisms and components, e.g., gas bearings, watch components | | These will require specialized cleaning and lubrication before being brought into use. |
| Cables and wires | | Replace every 2 to 3 years. |

* For example, paraffin, trichlorethylene.
*Note:* Traces of chlorinated solvents such as trichlorethylene, particularly in the presence of moisture, can cause corrosion of most metals. Therefore, after cleaning with chlorinated solvents all traces should be removed, ideally by blowing with warm dry air.
Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England

amount of grease in storage should not exceed a one-year supply. Before purchasing grease supplies, the manufacturer or distributor should be consulted for information about the maximum shelf life and other storage requirements for the specific grease.

## 12-13. Safety and Health Hazards

Safety considerations related to lubricants include knowledge of handling and the potential hazards. With this information, the necessary precautions can be addressed to minimize the risk to personnel and equipment.

*a. Material safety data sheets.* When handled properly, most lubricants are safe, but when handled improperly, some hazards may exist. Occupational Safety and Health Administrtion (OSHA) Communication Standard 29 CFR 1910.1200 requires that lubricant distributors provide a Material Safety Data Sheet (MSDS) at the time lubricants are purchased. The MSDS provides essential information on the potential hazards associated with a specific lubricant and should be readily accessible to all personnel responsible for handling lubricants. The lubricant's MSDS should provide information on any hazardous ingredients, physical and chemical characteristics, fire and explosion data, health hazards, and precautions for safe use.

*b. Fire, explosion, and health hazards*

(1) Oils. Although lubricating oils are not highly flammable, there are many documented cases of fires and explosions. The risk of an explosion depends on the spontaneous ignition conditions for the oil vapors (see Figures 12-6 and 12-7). These conditions can be produced when oils are contained in enclosures such as crankcases, reciprocating compressors, and large gear boxes.

(2) Hydraulic fluids. Hydraulic systems are susceptible to explosion hazards. A leaking hose under high pressure can atomize hydraulic fluid, which can ignite if it contacts a hot surface. Use of fire-resistant hydraulic fluids significantly reduces the risk of an explosion. Use of water-based hydraulic fluids can prevent ignition by forming a steam blanket at the hot spot or ignition source. Synthetic fluids are less flammable than mineral oils. Under normal circumstances, synthetic fluid will not support combustion once the ignition source has been removed. Table 12-22 summarizes the properties of water-based and synthetic hydraulic fluids and notes special precautions that must be taken when they are used.

(3) Health hazards. Lubricants also present health hazards when in contact with skin. Health hazards associated with lubricants include :

- Toxicity--Some additives contained in mineral oils may be toxic.
- Dermatitis--May be caused by prolonged contact with neat or soluble cutting oil.
- Acne--Mainly caused by neat cutting and grinding oils.
- Cancer--May be caused by some mineral oil constituents.

Material Safety Data Sheets for products should be reviewed carefully by personnel to ensure that the proper handling procedures are used.

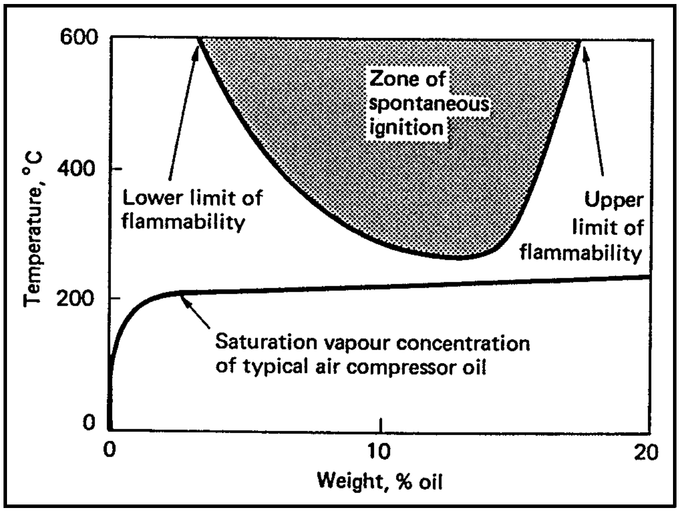



**Figure 12-6. Spontaneous ignition limits for mineral oil vapor air mixtures at atmospheric pressure (Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England)**

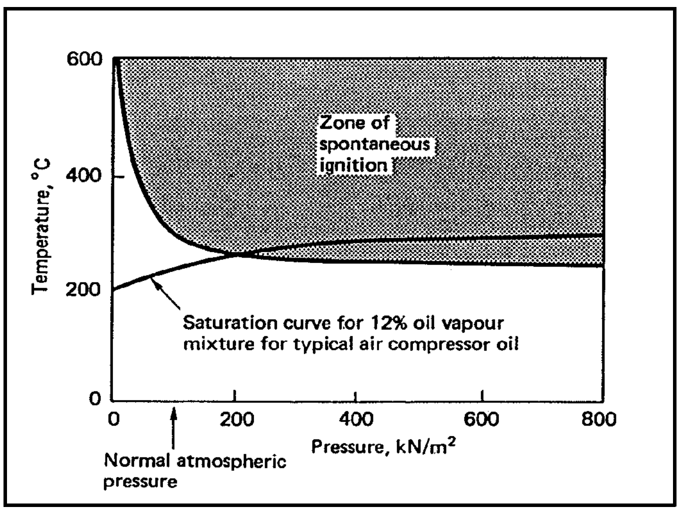



**Figure 12-7. Spontaneous ignition limits for 12% mineral oil vapor as a function of pressure (Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England)**

## 12-14. Environmental Regulations

*a. Development of environmental regulations.*

(1) Legislation passed by Congress is termed an Act of Congress. The responsibility for developing rules or regulations to implement the requirements of the Acts is given to various agencies of the Federal

**Table 12-22**
**Fire-Resistant Hydraulic Fluids**

| | ***Water-containing Fluids*** | | | ***Synthetic Fluids*** | |
|---|---|---|---|---|---|
| | ***Soluble-oil Emulsions (2% Oil)*** | ***Water-in-oil Emulsions (40% Water)*** | ***Water-glycol Blends (45% Water)*** | ***Phosphate Esters*** | ***Phosphate-ester Chlorinated Hydrocarbon Blends*** |
| **Maximum system temperature, °C (°F)** | **65 (149)** | **65 (149)** | **65 (149)** | **100 (212)** | **100 (212)** |
| Restrictions on materials used in normal oil systems: | | | | | |
| (*I*) Internal paints | None | None | Special paints required | Special paints required | Special paints required |
| *(ii)* Rubber seals | None | None | Normally no problem | Special seals required | Special seals required |
| *(iii)* Materials of construction | None | None | Avoid magnesium, zinc, and cadmium plating | Avoid aluminum rubbing contacts | Avoid aluminum rubbing contacts |
| Lubrication: | | | | | |
| *(I)* Rolling bearings - apply factor to load for design calculations | Not suitable | 2.0 | 2.5 | 1.2 | 1.2 |
| *(ii)* Gear | Not recom-mended | Limit pressure to 3.5 $MN/m^2$ (500 $lbf/in^2$) | Limit pressure to 3.5 $MN/m^2$ (500 $lbf/in^2$) | Satisfactory | Satisfactory |
| Maintenance | --- | Water content must be maintained* | Water content must be maintained | Should be kept dry | Should be kept dry |
| Cost relative to mineral oil | --- | 1.5-2 | 4-5 | 5-7 | 7-9 |

* Some separation of water droplets may occur on standing. The emulsion can, however, be readily restored by agitation. Care must be taken to avoid contamination by water-glycol or phosphate-ester fluids as these will cause permanent breakdown of the emulsion.
Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

Government such as the Environmental Protection Agency (EPA). The proposed regulations developed by these agencies are published daily in the Federal Register. After publication, the public is permitted to review and comment on the proposed regulations. All comments are evaluated after the specified review time (30 days, 60 days, etc.) has passed. The comments may or may not result in changes to the proposed regulations, which are published in the Federal Register as the final rules.

(2) The final rules from the Federal Register are compiled annually in the Code of Federal Regulations (CFR). The CFR is divided into 50 titles, numbered 1 through 50, which represent broad areas subject to Federal regulation. Title 40, “Protection of the Environment” contains regulations for the protection of the environment. References to the CFR are made throughout this subchapter. Copies of the CFR are not appended to this manual but can be obtained from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402.

(3) The general format for identifying a specific regulation in the CFR involves the use of a combination of numbers and letters. For example, 40 CFR 112.20, "Facility Response Plans,” indicates that the regulation is found in Title 40 of the CFR. It is further identified as Part 112. A part covers a

specific regulatory area, and can range in length from a few sentences to hundreds of pages. The number 20 that follows the decimal point indicates a given section where the specific information is found. A section also may range in length from a few sentences to many pages. Although not shown in this example, the section number may be followed by a series of letters and numbers in parentheses to further identify individual paragraphs.

(4) The regulations discussed in this subchapter are current at the time (1997) of writing. However, new regulations are being proposed and promulgated continuously. In addition, state or local regulations may be more restrictive than the Federal regulations, and must be reviewed carefully.

*b. Water quality regulations.* The Environmental Protection Agency (EPA) has developed water pollution regulations under legal authority of the Federal Water Pollution Control Act, also known as the Clean Water Act. These regulations are found in 40 CFR Subchapter D, “Water Programs,” and encompass Parts 100 through 149. Prominent parts of the regulation addressing oil pollution of the water are 40 CFR 110 “Discharge of Oil”; 40 CFR 112 “Oil Pollution Prevention”; and 40 CFR 113, “Liability Limits for Small Onshore Storage Facilities.”

(1) Reportable oil discharge. 40 CFR 110 requires the person in charge of a facility that discharges “harmful oil” to report the spill to the National Response Center (800-424-8802). The criteria for “harmful oil” discharges are:

(a) Discharges that violate applicable water quality standards.

(b) Discharges that cause a film or sheen upon or discoloration of the surface of the water or adjoining shorelines. Sheen means an iridescent appearance on the surface of the water.

(c) Discharges that cause a sludge or emulsion to be deposited beneath the surface of the water or adjoining shorelines.

(2) Spill Prevention Control and Countermeasures (SPCC) Plan. 40 CFR 112 requires regulated facilities that which have discharged or could reasonably discharge harmful oil into navigable U.S. waters or adjoining shorelines to prepare and implement a Spill Prevention Control and Countermeasures Plan. The regulation applies to nontransportation related facilities provided:

- The facility’s total above-ground oil storage capacity is greater than 5000 liters (1320 gallons), or the above-ground storage capacity of a single container is in excess of 2500 liters (660 gallons), or the total underground storage capacity of the facility is greater than 160,000 liters (42,000 gallons).

- Facilities which, due to their location, could reasonably expect spilled oil to reach U.S. waters.

(a) General requirements. 40 CFR 112.7 provides guidelines for preparing and implementing an SPCC plan. The SPCC plan is to follow the sequence outlined in the section and includes a discussion of the facility’s conformance with the appropriate guidelines. Basic principles to embody in an SPCC plan are:

- Practices devoted to the prevention of oil spills such as plans to minimize operational errors and equipment failures that are the major causes of spills. Operational errors can be minimized by training personnel in proper operating procedures, and increasing operator awareness of the imperative nature of spill prevention. Equipment failures can be minimized through proper construction, preventive maintenance, and frequent inspections.

- Plans to contain or divert spills or use equipment to prevent discharged oil from reaching navigable waters. When it is impracticable to implement spill containment measures, the facility must develop and incorporate a spill contingency plan into the SPCC plan.

- Plans to remove and dispose of spilled oil.

(b) Specific requirements

- Time limits. Prepare the SPCC within 6 months from startup. Implement the plan within 12 months from startup, including carrying out spill prevention and containment measures. Extensions may be authorized due to nonavailability of qualified personnel or delay in construction or equipment delivery beyond the control of the owner or operator. (40 CFR 112.3)

- Certification. A registered professional engineer must certify the SPCC and amendments. (40 CFR 112.3)

- Plan availability. Maintain a complete copy of the SPCC at an attended facility or at the nearest field office if the facility is not attended at least 8 hours per day. (40 CFR 112.3)

- Training. Conduct employee training on applicable pollution control laws, rules and regulations, proper equipment operation and maintenance to prevent oil discharge, and conduct spill prevention briefings to assure adequate understanding of the contents of the SPCC plan. (40 CFR 112.7)

- Plan review. Review the SPCC at least once every three years. (40 CFR 112.5)

- Amendments. Certified amendments to the SPCC are required when:

  - The EPA Regional Administrator requires amendment after a facility has discharged more than 3785 liters (1000 gallons) of oil into navigable waters in a single spill event or discharged oil in harmful quantities into navigable waters in two spill events within any 12-month period. (40 CFR 112.4)

  - There is a change in design, construction, operation, or maintenance that affects the potential for an oil spill. (40 CFR 112.5)

  - The required 3-year review indicates more effective field proven prevention and control technology will significantly reduce the likelihood of a spill. (40 CFR 112.5)

(3) Facility response plans. 40 CFR 112.20 requires facility response plans to be prepared and implemented if a facility, because of its location, could reasonably be expected to cause substantial harm to the environment by discharging oil into or on navigable waters or adjoining shorelines. This regulation applies to facilities that transfer oil over water to or from vessels and have a total oil storage capacity greater than 160,000 liters (42,000 gallons), or the facility's total oil storage capacity is at least 3.78 million liters (1 million gallons) with conditions. Most Corps of Engineers civil works facilities do not fall under these categories.

(4) Liability limits. 40 CFR 113 establishes size classifications and associated liability limits for small onshore oil storage facilities with fixed capacity of 160,000 liters (1000 barrels, or 42,000 gallons) or less that discharge oil into U.S. waters and removal of the discharge is performed by the U.S. Government. Unless the oil discharge was a result of willful negligence or willful misconduct, the table in 40 CFR 113.4 limits liability as follows:

(a) Above-ground storage.

| Size Class | Capacity (barrels) | Limit (dollars) |
|---|---|---|
| I | Up to 10 | 4,000 |
| II | 11 to 170 | 60,000 |
| III | 171 to 500 | 150,000 |
| IV | 501 to 1,000 | 200,000 |

(b) Underground storage.

| Size Class | Capacity (barrels) | Limit (dollars) |
|---|---|---|
| I | Up to 10 | 5,200 |
| II | 11 to 170 | 78,000 |
| III | 171 to 500 | 195,000 |
| IV | 501 to 1,000 | 260,000 |

*c. Soil quality regulations.* Regulations regarding oil contamination of soil vary from state to state. State and local laws and regulations should be reviewed for guidelines on preventing and handling soil contamination from oil spills.

# Chapter 13
# Lubricant Specifications and Selection

## 13-1. Introduction

Proper selection of a lubricant depends on understanding the lubricating regime (i.e., film, mixed, boundary), established conventions of classifications, and an ability to interpret and apply the producer’s product data specifications to the equipment. Without this background, it is impossible to make an informed selection or substitution.

## 13-2. Lubricant Classification

Professional societies and organizations have established classifications for oil and grease. The most widely encountered systems are those of the following organizations:

- SAE (Society of Automotive Engineers)
- API (American Petroleum Institute)
- AGMA (American Gear Manufacturers Association),
- ISO (International Standards Organization)
- NLGI (National Lubricating Grease Institute).

*a. Oil classification.* Oil is normally classified by viscosity grade, additives, use, or by the producer's brand name. Some oils are classified as nonspecialized industrial oils.

(1) Classification by viscosity grade. Classification according to viscosity is the most prevalent method of describing oils, and the most common classification systems are those of the SAE, AGMA, and ISO. Each organization uses a different kinematic viscosity range numbering system.

(2) Classification by additives.

(a) Oil may be further classified according to the additives included in the oil to enhance its performance properties as follows:

- Inhibited or RO (rust and oxidation inhibited)
- AW (antiwear)
- EP (extreme pressure)
- Compounded
- Residual.

The first three classes are discussed throughout this manual and require no further explanation; they contain the indicated additives. Compounded oil contains from 3 to 10 percent fatty or synthetic fatty oils. It is also called steam cylinder oil. The added fat reduces the coefficient of friction in situations where an extreme amount of sliding friction occurs. A very common application is in worm gear systems. Compounded oil may be composed of either a normal mineral oil or a residual oil, depending on the desired viscosity.

(b) Residual compounds are heavy-grade straight mineral oils or EP oils. These compounds are normally mixed with a diluent to increase ease of application. After application, the diluent evaporates, leaving a heavy adhesive lubricant coating. Residuals are often used for open-gear applications where tackiness is required to increase adhesion. This type of heavy oil should not be confused with grease. Residual oil with lower viscosity is also used in many closed-gear systems. Compounded oil may contain residual oil if the desired viscosity is high.

(3) Classification according to use. This system of classification arises because refining additives and type of petroleum (paraffinic or naphthenic) may be varied to provide desirable qualities for a given application. Some of the more common uses are:

- Compressor oils (air, refrigerant).
- Engine oils (automotive, aircraft, marine, commercial).
- Quench oils (used in metal working).
- Cutting oils (coolants for metal cutting).
- Turbine oils.
- Gear oils.
- Insulating oils (transformers and circuit breakers).
- Way oils.
- Wire rope lubricants.
- Chain lubricants.
- Hydraulic oils.

(4) Nonspecialized industrial oil. This classification includes oils that are not formulated for a specific application and are frequently referred to as “general purpose oil” in the manufacturer’s product literature. These oils are generally divided into two categories: general purpose and EP gear oils.

(a) General purpose oils. General purpose oils contain R&O additives, AW agents, antifoamants, and demulsifiers. They may be used in mechanical applications where a specialized oil is not required. Their ISO viscosity ranges from about 32 to around 460. These oils are often referred to as R&O oils or hydraulic oils although they may contain other additives and are not intended exclusively for hydraulic use.

Some of these oils are more highly refined and provide longer life and better performance than others. These are usually referred to as “turbine oils” or premium grades. Although used in turbines, the name “turbine oil” does not mean their use is restricted to turbines, but refers to the quality of the oil.

(b) EP gear oils. These oils generally have a higher viscosity range, from about ISO grade 68 to around 1500, and may be regarded as general purpose oils with EP additives. Although commonly used in gear systems, these oils can be used in any application where their viscosity range and additives are required. Gear oils should not be confused with SAE gear oils that are specially formulated for automotive applications; automotive oils are not discussed in this manual.

(5) Producer brand names. Oil producers often identify their products by names that may or may not be connected with standard classifications. For example, a name such as Jo-Lube 1525, a product of Jonell Oil, tells nothing of its class. However, Conoco's Dectol R&O Oil 32 indicates that it is an R&O oil with an ISO viscosity of 32. Regardless of how much information may be implied by the brand name, it is insufficient to select a lubricant. A user must refer to the producer’s information brochures to determine the intended use, additives, and specifications.

(6) Oil producer’s product data and specifications

(a) Product data. Oil producers publish product information in brochures, pamphlets, handbooks, or on the product container or packaging. Although the amount of information varies, it generally includes the intended use, the additives (AW, EP, R&O, etc.), oil type (i.e., paraffinic, naphthenic, synthetic, compounded, etc.), and the specifications. Some producers may identify the product by its usage classification such as those noted above, or they may simply note the machinery class where the product can be used. Often, both methods of identification are used. Intended use designations can be misleading. For example, fact sheets for three different oils by the same producer indicate that the oils can be used for electric motors and general purpose applications. However, all three are not suitable for every application of this equipment. One oil contains no oxidation inhibitors and is intended for use where the oil is frequently replaced. The second is an R&O oil with the usual antifoaming and demulsifying agents. AW agents are also included. The third is a turbine oil similar to the second except that the refining method and additive package provide greater protection. One turbine viscosity grade, ISO 32, is treated to resist the effects of hydrogen used as a coolant in generators. Failure to notice these differences when evaluating the data can lead to incorrect application of these lubricants. Producers do not usually list additives. Instead, they indicate characteristics such as good antiwear qualities, good water resistance, or good oxidation resistance. These qualities are not inherent in oil or contained in sufficient quantities to provide the degree of protection necessary. Therefore, the user is safe in assuming that the appropriate agent has been added to obtain the given quality. Product literature also gives the oil type (i.e., paraffinic, naphthenic, residual compounded, or synthetic).

(b) Producer specifications. Producer specifications amount to a certification that the product meets or exceeds listed physical characteristics in terms of specific test values. The magnitude of chemical impurities may also be given. Producers vary somewhat in the amount of information in their specifications. However, kinematic viscosity (centistokes) at 40 and 100 °C (104 and 212 °F ), SUS (saybolt viscosity) at 37 and 98 °C (100 and 210 °F ), API gravity, pour point, and flash point are generally listed. Other physical and chemical measurements may also be given if they are considered to influence the intended use.

*b. Grease classifications.*

(1) Characteristics. Grease is classified by penetration number and by type of soap or other thickener. Penetration classifications have been established by NLGI and are given in Chapter 5. ASTM D 217 and D 1403 are the standards for performing penetration tests. A penetration number indicates how easily a grease can be fed to lubricated surfaces (i.e., pumpability) or how well it remains in place. Although no method exists to classify soap thickeners, the producer indicates which soap is in the product. The type of soap thickener indicates probable water resistance and maximum operating temperature and gives some indication of pumpability. Although these are important factors, they are not the only ones of interest. These simple classifications should be regarded as starting requirements to identify a group of appropriate grease types. The final selection must be made on the basis of other information provided in the producer's specifications. Viscosity of the oil included in a grease must also be considered.

(2) Producer’s product data for grease. Producers also provide information and specifications for grease in brochures, pamphlets, handbooks, or on the product container or packaging. Grease specifications normally include soap thickener, penetration, included oil viscosity, and dropping point. The producer may also include ASTM test information on wear, loading, lubrication life, water washout, corrosion, oil separation, and leakage. Grease additives are not usually stated except for solid additives such as molybdenum disulfide or graphite, or that an EP additive is included. If EP or solid additives are used, the producer will often state this emphatically and the product name may indicate the additive.

## 13-3. Principles of Selection

*a. Manufacturer recommendations.*

(1) The prime considerations are film thickness and wear. Although film thickness can be calculated, the wear properties associated with different lubricants are more difficult to assess. Lubricants are normally tested by subjecting them to various types of physical stress. However, these tests do not completely indicate how a lubricant will perform in service. Experience has probably played a larger role than any other single criterion. Through a combination of testing and experience, machine manufacturers have learned which classes of lubricants will perform well in their products.

(2) Professional societies have established specifications and classifications for lubricants to be used in a given mechanical application. For example, AGMA has established standard specifications for enclosed and open-gear systems. These specifications have been developed from the experience of the association’s membership for a wide range of applications. Thus, any manufacturer has access to the collective knowledge of many contributors.

(3) It should be noted that the equipment manufacturer's recommendation should not necessarily be considered the best selection. Individual manufacturers may have different opinions based on their experience and equipment design. The concept of “best” lubricant is ambiguous because it is based on opinion. Despite this ambiguity, the manufacturer is probably in the best position to recommend a lubricant. This recommendation should be followed unless the lubricant fails to perform satisfactorily. When poor performance is evident, the manufacturer should be consulted for additional recommendations. This is especially critical if the equipment is still under warranty.

(4) Although some manufacturers may recommend a specific brand name, they can usually provide a list of alternative lubricants that also meet the operating requirements for their equipment. One of the recommended lubricants should be used to avoid compromising the equipment warranty if it is still in effect. Physical qualities (such as viscosity or penetration number), chemical qualities (such as paraffinic or naphthenic oils), and applicable test standards are usually specified.

*b. Lubricant producer recommendations.*

(1) When manufacturers recommend lubricants for their products in terms of specifications or required qualities rather than particular brand names, the user must identify brands that meet the requirements. Following the suggestions given in this chapter may help the user identify appropriate products. When a user is uncertain, lubricant producers should be consulted to obtain advice on products that comply with the required specifications.

(2) Many lubricant producers employ product engineers to assist users in selecting lubricants and to answer technical questions. Given a manufacturer's product description, operating characteristics, unusual operating requirements, and lubricant specification, product engineers can identify lubricants that meet the manufacturer's specifications. Viscosity should be the equipment manufacturer’s recommended grade. If a recommendation seems unreasonable, the user should ask for verification or consult a different lubricant producer for a recommendation. These products will probably vary in quality and cost. The application should dictate lubricant selection. This will help prevent the unnecessary purchase of high-priced premium quality lubricants when they are not required.

*c. User selection.*

(1) The user should ensure that applicable criteria are met regardless of who makes the lubricant selection. Selection should be in the class recommended by the machinery manufacturer (R&O, EP, AW, etc.) and be in the same base stock category (paraffinic, naphthenic, or synthetic). Furthermore, physical and chemical properties should be equal to or exceed those specified by the manufacturer. Generally, the user should follow the manufacturer's specification. Additional factors to be considered are shown in Tables 13-1, 13-2, and 13-3. Each of these tables uses different criteria that can be beneficial when the user is selecting lubricants.

(2) If the manufacturer’s specifications are not available, determine what lubricant is currently in use. If it is performing satisfactorily, continue to use the same brand. If the brand is not available, select a brand with specifications equal to or exceeding the brand previously used. If the lubricant is performing poorly, obtain the recommendation of a product engineer. If the application is critical, get several recommendations.

(3) Generally, the user will make a selection in either of two possible situations:

! Substitute a new brand for one previously in use.

! Select a brand that meets an equipment manufacturer's specifications. This will be accomplished by comparing producer's specifications with those of the manufacturer.

Product selection starts by using a substitution list maintained by most lubricant producers. A substitution list usually shows the products of major producers and the equivalent or competing product by other producers. Substitution lists are useful but they have limitations. They may not be subdivided by classes of lubricants. Furthermore, it is difficult to do more than compare a lubricant of one producer with one given by the publishing producer. For example, consider three producers called A, B, and C. Producer A’s substitution list may compare B’s products with A’s, or C’s with A’s. However, B and C cannot be compared unless A has a product equivalent to both B and C. A user would need substitution lists from many producers to be able to effectively select more than one option. Many producers claim they do not have a substitution list, or are reluctant to provide one. As noted in Chapter 11, the chart of

**Table 13-1**
**Factors Affecting Lubricant Selection**

| Element | Type | Size | Material | Operating Temperature | Operating Conditions | Velocity | Remarks |
|---|---|---|---|---|---|---|---|
| Bearings | Plain, needle roller, ball | Shaft diameter | | | | rev/min | |
| Chain drives | Links; number and pitch | PCD of all wheels and distance between centers | | | | Chain speed ft/min | |
| Cocks and valves | Plug, ball, etc. | | Fluid being controlled | | | | Depends on properties of the fluid |
| Compressors | BHP, manufacturer's name | | | Gas temperature | Max gas pressure | rev/min | |
| Couplings | Universal or constant velocity | | | | | rev/min | |
| Cylinders | | Bore, stroke | Cylinder, piston, rings | Combustion and exhaust gas temperature | Combustion and exhaust gas pressure | Crank speed, rev/min | |
| Gears | Spur, worm, helical, hyperbolic | BHP, distance between centers | | | Radiated heat and heat generated | rev/min | Method of lubricant application |
| Glands and seals | Stuffing box | | Fluid being sealed | | | | Depends on design |
| Hydraulic systems | BHP Pump type (gear, piston vane) | | Hydraulic fluid materials 'O' rings and cups, etc. | | | | Lubricant type adjusting to loss rate |
| Linkages | | | | Environmental heat conditions | | Relative link speeds, ft/s, angular vel., rad/s | |
| Ropes | Steel hawser | Diameter | | | Frequency of use and pollution, etc. | | |
| Slideways and guides | | | | | | Surface relative speed, ft/min | |

Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

"Interchangeable Industrial Lubricants" and "Guide to Synthetic Lubricants" published by Plant Engineering Magazine (PEM) can be helpful. The PEM charts correlate products of many producers. The chart of synthetic lubricants correlates products by category (class).

(4) A substitution list or chart is valuable because it correlates the array of brand names used by producers. Furthermore, it eliminates producers who do not have the desired product in their line. A substitution list should be regarded as a starting point to quickly identify potential selections. The lists

**Table 13-2**
**Types of Additive Oil Required for Various Types of Machinery**

| Type of Machinery | Usual Base Oil Type | Usual Additives | Special Requirements |
|---|---|---|---|
| Food processing | Medicinal white oil | None | Safety in case of ingestion |
| Oil hydraulic | Paraffinic down to about -20 °C (-4 °F), naphthenic below | Antioxidant<br>Antirust<br>Antiwear<br>Pour point depressant<br>VI improver<br>Antifoam | Minimum viscosity change with temperature; minimum wear of steel/steel |
| Steam and gas turbines | Paraffinic or naphthenic distillates | Antioxidant<br>Antirust | Ready separation from water, good oxidation stability |
| Steam engine cylinders | Unrefined or refined residual or high-viscosity distillates | None or fatty oil | Maintenance of oil film on hot surfaces; resistance to washing away by wet steam |
| Air compressor cylinders | Paraffinic or naphthenic distillates | Antioxidant<br>Antirust | Low deposit formation tendency |
| Gears (steel/steel) | Paraffinic or naphthenic | Antiwear, EP<br>Antioxidant<br>Antifoam<br>Pour point depressant | Protections against abrasion and scuffing |
| Gears (steel/bronze) | Paraffinic | Oiliness<br>Antioxidant | Reduce friction, temperature rise, wear, and oxidation |
| Machine tool slideways | Paraffinic or naphthenic | Oiliness; tackiness | Maintains smooth sliding at very low speeds. Keeps film on vertical surfaces |
| Hermetically sealed refrigerators | Naphthenic | None | Good thermal stability, miscibility with refrigerant, low flow point |
| Diesel engines | Paraffinic or naphthenic | Detergent<br>Dispersant<br>Antioxidant<br>Acid-neutralizer<br>Antifoam<br>Antiwear<br>Corrosion inhibitor | Vary with type of engine thus affecting additive combination |

Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

do not suggest or imply that lubricants listed as being equivalent are identical. The lists do indicate that the two lubricants are in the name class, have the name viscosity, and are intended for the same general use. The chart of interchangeable industrial lubricants lists the following categories:

- General purpose lubricants
- Antiwear hydraulic oil
- Spindle oil

**Table 13-3**
**Importance of Lubricant Properties in Relation to Bearing Type**

| | Type of Component | | | | | |
|---|---|---|---|---|---|---|
| **Lubricant Property** | **Plain Journal Bearing** | **Rolling Bearing** | **Closed Gears** | **Open Gears, Ropes, Chains, etc.** | **Clock and Instrument Pivots** | **Hinges, Slides, Latches, etc.** |
| 1. Boundary lubricating properties | 1 | 2 | 3 | 2 | 2 | 1 |
| 2. Cooling | 2 | 2 | 3 | - | - | - |
| 3. Friction or torque | 1 | 2 | 2 | - | 2 | 1 |
| 4. Ability to remain in bearing | 1 | 2 | - | 1 | 3 | 1 |
| 5. Ability to seal out contaminants | - | 2 | - | 1 | - | 1 |
| 6. Temperature range | 1 | 2 | 2 | 1 | - | 1 |
| 7. Protection against corrosion | 1 | 2 | - | 2 | - | 1 |
| 8. Volatility | 1 | 1 | - | 2 | 2 | 1 |

Note: The relative importance of each lubricant property in a particular class of component is indicated on a scale from 3 = highly important to - = quite unimportant.
Reference: Neale, M.J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England.

! Way oil

! Extreme pressure gear oil

! Worm gear oil

! Cling-type gear shield (open gears)

! General purpose extreme pressure lithium based grease

! Molybdenum disulfide extreme pressure grease.

(5) Spindle and way oils are not widely used. One of the last three classes on the list is a special preparation for open gears and the other two are classes of grease. General purpose oils, antiwear hydraulic oils, and EP gear oils are best described by comparison with the nonspecialized industrial oils discussed earlier. Nonspecialized oils contain a category called general purpose oils. This term is also used in the PEM list but it differs from the previously described general purpose oil category in that the additives may not be the same. In some cases, brand names indicate that EP additives have been included. In other cases, AW is indicated but not R&O. This raises the possibility that R&O additives are not present. AW hydraulic oil is a general purpose oil, but its antiwear properties are sufficient to pass the Vickers vane test for hydraulic applications when this is required.

(6) The EP gear oils should correspond to those described under nonspecialized industrial oils except that EP additives are included and viscosities may be as high as ISO 2200. The EP classification of gear oil should not be confused with the SAE gear oil classification which is for use in automotive gear systems. SAE gear oils are formulated differently and are not discussed in this manual.

(7) While grease preparation varies greatly among producers, only two types are given in the PEM list: No. 2 lithium EP and molybdenum disulfide EP No. 2. These are the two most widely used industrial greases. The name molybdenum disulfide designates lubricant type, and does not reflect the type of soap, but the soap will usually be lithium. While both types are intended to provide extra protection against wear, one contains EP additives and the other contains molybdenum disulfide.

(8) Lithium greases are the most widely used, but calcium, aluminum, polyurea, and sodium-calcium are also used. Furthermore, greases ranging from NLGI 00 to No. 3 are used. Consequently, in many cases, the PEM tables will not be useful for selecting greases.

(9) The cling-type gear shield lubricants are residual oils to which a tackiness agent has been added. They are extremely adhesive and so viscous that solvents are added to permit application. After application, the solvent evaporates leaving the adhesive viscous material. Some products contain no solvent and must be heated to reduce viscosity for application.

(10) Compounded oils are not included in the list as a separate class. When this type of oil is required, producers must be contacted directly.

(11) Ultimately, information brochures provided by the producers must be examined to verify the following:

(a) Viscosity. The product viscosity meets the manufacturer's recommendation or is the same as a previously used lubricant that performed well. When a grease is considered, the viscosity of the included oil should be the same as the previous lubricant.

(b) Intended use. The product's intended use, as given by the producer, corresponds to the application in which the lubricant will be used.

(c) Class of lubricant. The class of lubricant is the same as that recommended by the equipment manufacturer or the same as a previously used lubricant that performed well. If the manufacturer recommended an R&O, AW, or EP oil, or a No. 2 lithium grease, that is what should be used.

(d) Specification. The product specifications are equal to or better than those recommended by the equipment manufacturer or those of a previously used lubricant that performed well.

(e) Additives. The product additives perform the required function even though they may not be chemically identical in several possible alternative lubricants.

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## 13-4. Specification Types

Current government policy encourages use and adoption of nongovernment specifications and standards instead of developing new or updating existing federal and military specifications. Types of specifications, in order of usage preference are: (1) Nongovernment specifications; (2) Commercial Item Descriptions; and (3) Federal and military specifications.

*a. Nongovernment.* Federal and military specifications are being replaced by specifications and industry standards developed by trade associations such as SAE, AGMA, and API and professional private-sector organizations and technical societies such as ISO, ANSI (American National Standards Institute), and ASTM. Nongovernment specifications and standards (NGS) should not be confused with lubricant producer standards. NGS promote competition and usually provide a broad base of suppliers, whereas producer-specific standards tend to limit competition to a single supplier.

*b. Commercial item description.* A Commercial Item Description (CID) is an indexed, simplified product description that describes by salient function or performance characteristics, available and acceptable commercial products that meet the government's needs. These items include references to ASTM, ANSI, and other industry standards. CIDs are issued by the General Services Administration (GSA) and are listed in the GSA "Index of Federal Specifications, Standards and Commercial Item Descriptions."

*c. Federal and military.* New Federal specifications are developed and existing specifications are updated to establish requirements for commercial products only if specific design, performance, interface, or other essential characteristics are not described adequately by nongovernment standards or Commercial Item Descriptions. Federal Specifications are issued by the General Services Administration and are listed in the GSA "Index of Federal Specifications, Standards and Commercial Item Descriptions." New military specifications are developed and existing specifications are updated to establish requirements for military-unique products or commercial products that must be substantively modified to include military-unique requirements. If a nongovernment standard exists that contains the basic technical requirements for a product or process, it is referenced in the military specification, and the military specification contains only those additional requirements needed by the Department of Defense. Military specifications are issued by the Department of Defense and are listed in the "Department of Defense Index of Specifications."

*d. Proprietary.* Proprietary specifications refer to specifications owned by an oil producer or used for acquisition of a product from a lone source.

(1) Oil producer. Some proprietary specifications contain confidential trade secrets, and are developed and exclusively controlled by a lubricant producer. Producer specifications published in company brochures, pamphlets, and handbooks contain nonproprietary information and are described in subparagraph 132-*a*(6) Oil Producers' Product Data and Specifications.

(2) Acquisition. Sometimes a proprietary specification is used as an acquisition method to specify a product that is available from only one source. It identifies a product by manufacturer's brand name, product number, type, or other unique designation. A specification can be considered proprietary even if brand name is not stated but the product is available from only one source. Specifying by product name is suitable and advantageous when a specific product has proven successful or its use is specified by an equipment manufacturer as an equipment warranty condition. Disadvantages to specifying a product by brand name are that it eliminates competition and the purchaser may pay a premium price.

## 13-5. Lubricant Consolidation

*a. General.* Older machines tend to operate at slow speeds and light loads. These machines also tend to have large clearances and few lubricating points. Lubrication of such older machines is not as critical, comparatively speaking, as for modern machines that operate at higher speeds, under heavier loads, and with closer mechanical tolerances. A common maintenance practice is to have inventories of several types of lubricant to service both older and newer versions of similar equipment (e.g., speed reducers). This problem is further aggravated by the different types of unrelated equipment operating at a complex facility (e.g., turbines, speed reducers, ropes and chains, etc.), each requiring lubrication. Consolidation of lubricants is usually undertaken to reduce inventories, storage requirements, safety and health hazards, and cost. Consolidation, done properly, is a rational approach to handling the lubrication requirements at a facility while reducing the total number of lubricants in the inventory.

*b. Manufacturer's recommendations.* Manufacturers may recommend lubricants by brand name or by specifying the lubricant characteristics required for a machine. Depending on the machine, lubricant specifications may be restrictive, or they may be general, allowing considerable latitude. Usually the manufacturer's warranty will be honored only if the purchaser uses the lubricants recommended by the manufacturer. Voiding the terms of a warranty is not advisable, so the specified lubricants should be used until the warranty has expired. After warranty expiration the machine and its lubrication requirements may be included in the consolidation list for the facility.

*c. Consolidation considerations.* Consolidation of lubricants requires careful analysis and matching of equipment requirements and lubricant properties. Factors that influence selection of lubricants include operating conditions, viscosity, viscosity index, pour point, extreme pressure properties, oxidation inhibitors, rust inhibitors, detergent-dispersant additives, etc. With a grease, consideration must also include composition of the soap base, consistency, dropping point, pumpability. There are several precautions that must be followed when consolidating lubricants.

(1) Characteristics. Consideration should be given to the most severe requirements of any of the original and consolidated lubricants. To prevent equipment damage, the selected lubricant must also have these same characteristics. This is true for greases.

(2) Special requirements. Applications with very specific lubricant requirements should not be consolidated.

(3) Compatibility. Remember that some lubricant additives may not be compatible with certain metals or seals.

*d. Consolidation procedure.* Consolidation may be accomplished through the services of a lubricant producer or may be attempted by facility personnel who have knowledge of the equipment operating characteristics and lubricating requirements, and an ability to read lubricant producer's product data.

(1) Lubricant supplier. The preferred method for consolidating lubricants is to retain the services of a qualified lubrication engineer. All major oil companies have engineers available to help users with lubrication problems. There are also numerous independent lubricant suppliers with the necessary personnel and background to provide assistance. Ultimately, the knowledge, experience, integrity, and reputation of the lubricant supplier are the best assurance that the products recommended will meet the lubrication requirements for the equipment. The supplier must be given a list of equipment, along with any information about the operating characteristics, ambient conditions, and lubrication requirements. The engineer can use this information to consolidate lubricating requirements where possible, and to isolate equipment with highly specific requirements that cannot be consolidated. The primary disadvantage with this approach is that the lubricant supplier will, in all probability, recommend only those products within the company's product line. If this is a major concern, the services of an independent lubricating engineer or tribologist, not affiliated with any supplier, may be retained.

(2) Consolidation by in-house personnel.

(a) In-house personnel should begin the consolidation process by preparing a spreadsheet identifying equipment, lubricating requirements, lubricant characteristics, and brand names. The equipment should be sorted by type of lubricant (oil, hydraulic fluid, synthetics, biodegradable, grease) required. Under each type, the properties of each lubricant should be grouped such as oil viscosity, detergent-dispersant requirements, EP requirements, rust and oxidation inhibitors, NLGI grade of grease, viscosity of oil component in the grease, pumpability, etc. See Figure 13-1 for an example of a spreadsheet showing the essential features.

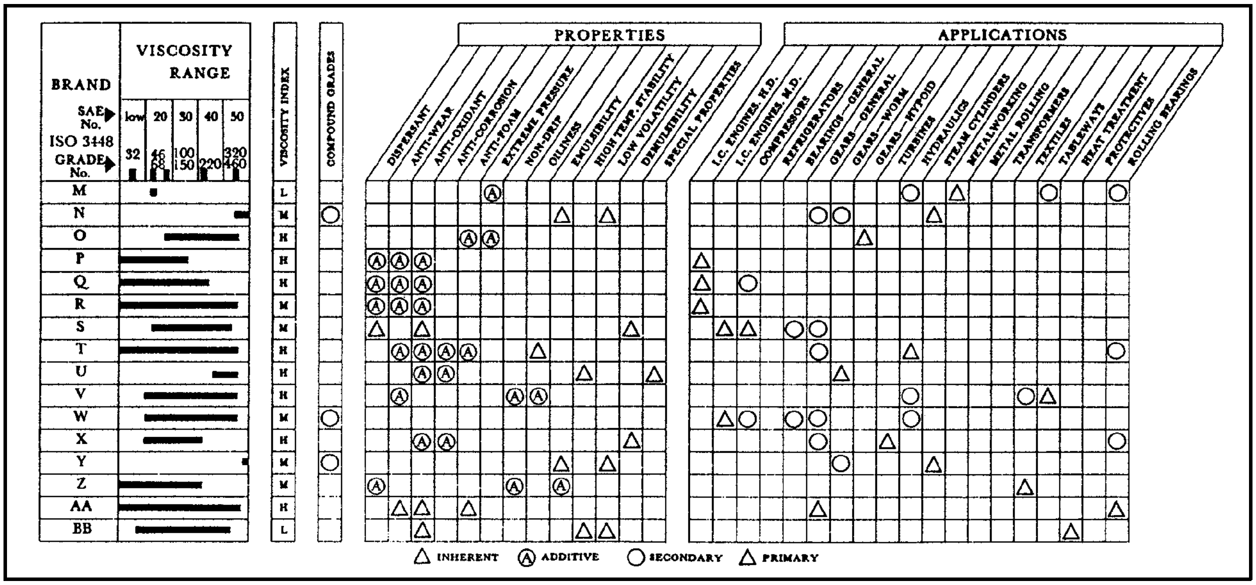


**Figure 13-1. Lubricant consolidation chart (Reference: Neale, M. J., Lubrication: A Tribology Handbook. Butterworth-Heinemann Ltd., Oxford, England**

(b) At this stage, viscosity grouping can be made. For instance, if three similar oils have viscosities of 110, 150, and 190 SUS at 100 °F, the 150 may be used as a final selection. If one of the original oils was rust and oxidation inhibited, the final product should also have this property. A second group of oils with viscosities of 280, 330, and 350 SUS at 100 °F could be reduced to one oil having a viscosity in the neighborhood of 315 SUS at 100 °F. As shown in Figure 13-1, the goal is to identify the viscosity requirements and range for various equipment and see if a single lubricant can span the range. If the range can be covered, then consolidation is possible. However, recall that paragraph 13-3 included a warning that the lubricant viscosity for a machine must comply with the manufacturer's requirements. Obviously, an exact match of viscosity for all equipment cannot be accomplished with the same lubricant when consolidation is the goal. Lubricants with vastly different viscosity requirements must not be consolidated.

(3) Use higher quality lubricants. Another alternative for consolidation is to use higher grade lubricants that are capable of meeting the requirements of various machinery. Although the cost of high-grade lubricants is greater, this may still be offset by the benefits of consolidation (e.g., reduction in the number of different lubricants needed, reduction in inventory-management requirements, possible price discounts for purchasing certain lubricants in greater quantity, etc.).

(4) Use multipurpose lubricants. Multipurpose lubricants and other general purpose oils can be applied to a wide range of equipment and help reduce the number of lubricants required. Although some lubricants are not listed as multipurpose they may be used in this capacity. For example, assume two lubricants by the same producer: one is listed as an R&O turbine oil and the other as a gear oil.

Examination of product literature shows that the R&O turbine oil can also be used in bearings, gear sets, compressors, hydraulic systems, machine tools, electric motors, and roller chains while the gear oil can also be used in circulating system, chain drives, plain and antifriction bearings, and slides. These oils may be suitable for use in a consolidating effort. Producers often have similar application overlaps in their product lines.

# Appendix A
# References

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D 95, Test Methods for Water in Petroleum Products and Bitumenous Materials by Distillations.

D 97, *Standard Test Methods for Pour Point of Petroleum Oils*.

D 130, Method for Detection of Copper Corrosion from Petroleum Products by the Copper Strip Tarnish Test.

D 217, *Standard Test Methods for Cone Penetration of Lubricating Grease*.

D 445, Test Methods for Kinematic Viscosity of Transparent and Opaque Liquids (and the Calculation of Dynamic Viscosity).

D 566, *Standard Test Method for Dropping Point of Lubricating Grease*.

D 664, Test Method for Neutralization Number by Potentiometer Titration.

D 665, Test Method for Rust-Preventing Characteristics of Inhibited Mineral Oil in the Presence of Water.

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D 942, *Standard Test Method for Oxidation Stability of Lubricating Greases by the Oxygen Bomb Method.*

D 943, *Standard Test Method for Oxidation Characteristics of Inhibited Mineral Oils.*

D 972, *Standard Test Method for Evaporation Loss of Lubricating Greases and Oils*.

D 974, *Test Method for Neutralization Number by Color-Indicator Titration.*

D 1092, *Standard Test Method for Measuring Apparent Viscosity of Lubricating Greases.*

D 1263, *Standard Test Method for Leakage Tendencies of Automotive Wheel Bearing Greases*.

D 1264, *Standard Test Method for Determining the Water Washout Characteristics of Lubricating Greases.*

D 1401, *Test Method for Water Solubility of Petroleum Oils and Synthetic Fluids.*

D 1403, *Standard Test Method for Cone Penetration of Lubricating Grease Using One-Quarter and One-Half Scale Cone Equipment.*

D 1500, *Test Method for ASTM Color of Petroleum Products (ASTM Color Scale).*

D 1742, *Standard Test Method for Oil Separation from Lubricating Grease During Storage.*

D 1743, *Standard Test Method for Determining Corrosion Preventive Properties of Lubricating Greases.*

D 1744, *Test Method for Water in Liquid Petroleum Products by Karl Fischer Reagent.*

D 1831, *Standard Test Method for Roll Stability of Lubricating Grease*.

D 2161, *Method for Conversion of Kinematic Viscosity to Saybolt Universal Viscosity or to Saybolt Furol Viscosity*.

D 2265, *Standard Test Method for Dropping Point of Lubricating Grease Over Wide-Temperature Range*.

D 2266, *Standard Test Method for Wear Preventive Characteristics of Lubricating Grease (Four-Ball Method)*.

D 2270, *Standard Test Method for Calculating Viscosity Index From Kinematic Viscosity at 40 and 100 °C*.

D 2272, *Rotating Bomb Oxidation Test (RBOT).*

D 2509, *Standard Test Method for Measurement of Extreme Pressure Properties of Lubricating Grease (Timken Method)*.

D 2595, *Standard Test Method for Evaporation Loss of Lubricating Greases Over Wide-Temperature Range*.

D 2596, *Standard Test Method for Measurement of Extreme-Pressure Properties of Lubricating Grease (Four-Ball Method)*.

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D 3232, *Standard Test Method for Measurement of Consistency of Lubricating Greases at High Temperatures*.

D 3336, *Standard Test Method for Performance Characteristics of Lubricating Greases in Ball Bearings at Elevated Temperatures*.

D 3847, *Standard Specification for Mineral Insulating Oil Used in Electrical Apparatus - Type II Mineral Oil - Practice for Rubber-Directions for Achieving Abnormal Test Temperatures.*

D 4048, *Standard Test Method for Detection of Copper Corrosion from Lubricating Grease*.

D 4049, *Standard Test Method for Determining the Resistance of Lubricating Grease to Water Spray*.

D 4059, *Test Method for Analysis of Polychlorinated Biphenyls in Insulating Liquid by Gas Chromatography Method.*

D 4170, *Standard Test Method for Fretting Wear Protection by Lubricating Greases*.

D 5864, *Standard Test Method for Determining Aerobic Aquatic Biodegradation of Lubricants or Their Components*.

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# Appendix B
# Survey of Locks and Dams for Lubricants

**Lock Gates - Miter**

| Lock and State | Temp Range °C (°F) | Lubrication for Sector Gears | Freq of Lubrication, Method | Lubrication for Pintles, Gudgeon Pin | Freq of Lubrication, Method | Lubrication for Strut Arms | Freq of Lubrication, Method | Comments |
|---|---|---|---|---|---|---|---|---|
| Aberdeen, MS | | | | Exxon EP0 winter Exxon EP1 summer | Monthly Air gun | Exxon EP0 winter Exxon EP1 summer | Monthly Air gun | |
| Cheatham, TN | | Chevron Open Gear Lube SP | Weekly Spray | Keystone Velox 3 | Monthly Air gun | | | |
| Dashields, PA | -36.6 to 3.5 (-25 to 95) | Dubois Chem MP2 | Monthly Brush | Lubriplate 630 AA | Monthly Gun | | | |
| Hiram M. Chittenden, WA | 12.2 to 37.7 (10 to 100) | Certified Lube Trac Plus and Dynaco Tacky Lube Open Gear Grease | Weekly Spray | Water | | | | Certified and Dynaco work great |
| John T. Meyers, OH | | Keystone Moly 29 | As neces. 2 to 4 mo Calk. gun | Amoco Super Permalube grease | Weekly Elec gun | Dixon 271 Graphite grease | 6 months | |
| Lock and Dam No. 12, IA | -28.8 to 37.7 (-20 to 100) | Lubriplate 1242 | Weekly Brush | Lubriplate 1242 | 2 weeks Gun | Lubriplate 1242 | 2 weeks | White, easy to clean up with putty knife and towel. Almaplex 1275 falls off when cold, didn't hold film. |
| Lock No. 8, WI | -40 to 48.8 (-40 to 120) | Lubricating Eng. Pyroshield 5100 | 2-weeks Spray or Paddle | Mobil EAL 102 | Weekly Gun | | | No problems with biode-gradable EAL. |
| Lock and Dam No. 7, MN | -45.5 to 37.7 (-50 to 100) | Lubrication Eng. Pyroshield 5182 and 5100 | 2 weeks Calk. gun Spray | Mobil Mobilux EP 2 | Monthly Gun | Mobil Mobilux EP 2 | | |
| Lock and Dam No. 18, IL | -28.8 to 40.5 (-20 to 105) | Amoco Amovis 8-X | Weekly Brush | Amoco Ryotec EP | 2 weeks Gun | | | |
| Lockport, IL | -28.8 to 48.8 (-20 to 120) | Hydrotex Copper Coat Gear Grease | 6 months Manual | Mobil Mobilith SHC 220 | Monthly Gun | Mobil Mobilith SHC 220 | Gun | Mobilith- Good in cold temperature. |
| Marmet, WV | -28.8 to 43.3 (-20 to 110) | Chesterton 715 Spraflex | | Kendall L-427, Shell Alvania 2 | Monthly Gun | | | |
| McAlpine, KY | -40 to 43.3 (-40 to 110) | Chevron Open Gear Lubricant SP | Weekly Spray | Keystone Velox 3 | Weekly Elec gun | Dixon 271 graphite grease | Gun | Chevron works very well. Keystone stains clothes permanently. |

**Lock Gates - Miter**

| Lock and State | Temp Range °C (°F) | Lubrication for Sector Gears | Freq of Lubrication, Method | Lubrication for Pintles, Gudgeon Pin | Freq of Lubrication, Method | Lubrication for Strut Arms | Freq of Lubrication, Method | Comments |
|---|---|---|---|---|---|---|---|---|
| McNary, OR | Below -17.7 to 37.7 (0 to 100+) above water | Keystone Moly 29 | 2 to 4 weeks, Manual caulk gun | Husk-ITT LVI-50 NT Grease | Each gate operation, every 4 hours, auto Farval | Husk-ITT LVI-50 NT Grease | 6 months Manual gun | Enclosed gears-Texaco Cepheus 150 change 10 years. LVI-50 Biodegradable food grade |
| Newburgh, IN | 26.1 to 37.7 (-15 to 100) | Keystone Moly 29 | Monthly Caulk gun | Valvoline 612 EP | Weekly Pwr gun | Dixon 271 | | |
| Old Hickory, TN | -6.6 to 35 (20 to 95) | Chevron Open Gear Lubricant SP and Keystone Moly 29 | Monthly Spray, paddles | Keystone Velox 3 | Monthly Gun | | | May be hard to purchase Velox 3 in future. |
| Port Allen, LA | -28.8 to 40.5 (20 to 105) | B & R Open Gear | As needed Weekly Spray | Certified Lab. Premalube Red | Weekly Gun | Certified Lab. Premalube Red | Weekly Gun | B&R stays on, few drips. Certified is very tacky, works well in wet/high pressure environment. |
| Robert C. Byrd, WV | | Chesterton Sprayflex Gold | Monthly Spray | Unocal 76 Redtac 2 | Monthly Gun | Dixon 270 graphite grease | 3 months Gun | Chesterton-Good adhesion in wet conditions |
| Smithland, IL | | Keystone Moly 29 | Monthly Paddles | British Petroleum Ener-grease LS-EP2 | Weekly Gun | Dixon graphite grease | | |
| Starved Rock, IL | -34.4 to 43.3 (-30 to 110) | Bowman Dist. Barnes Grp. Part No. 19464 Open Gear & Fifth Wheel | 6 months Spray | Chevron Ultra-Duty Grease EP NLGI 2 | Pintles-daily, Gudgeon Mo. Gun | Chevron Ultra-Duty Grease EP NLGI 2 | | Enclosed gears |
| Winfield, WV | | | | Kendall L-427 | | | | |

**Lock Gates - Sector**

| Lock and State | Temp Range °C (°F) | Lubrication for Pintles, Gudgeon Pin | Freq of Lubrication | Comments |
|---|---|---|---|---|
| Bayou Boeuf, LA | | Certified Premalube | Weekly Gun | |

**Lock Gates - Vertical Lift and Submergible Vertical Lift**

| Lock | Temp Range °C (°F) | Lubrication for Hoist Wire Rope | Freq of Lubrication | Lubrication for Open Gears | Freq of Lubrication | Lubrication for Enclosed Gears | Lubrication for Other Equipment or Comments | Freq of Lubrication |
|---|---|---|---|---|---|---|---|---|
| Lockport, IL | -28.8 to 48.8 (-20 to 120) | Stainless steel | None | | | Mobil SHC 630 | Told not to lube wire ropes | |
| Lower Monu-mental, WA | -28.8 to 40.5 (-20 to 105) | Chemsearch High Core | 3 months Manual | Tribol Molub-Alloy 412-1 Open Gear | 3 months Manual | Texaco Meropa 150 | | |

**Culvert Valves - Reverse Tainter and Tainter**

| Lock and State | Temp Range °C (°F) | Lubrica-tion for Trunnion | Freq of Lubrication, Method | Lubrication for Hoist Wire Rope, Chains | Freq of Lubrica-tion, Method | Lubri-cation for Open Gears | Freq of Lubrica-tion, Method | Lubrica-tion for Enclosed Gears | Other |
|---|---|---|---|---|---|---|---|---|---|
| Aberdeen, MS | | Exxon EP0 winter Exxon EP1 summer | Monthly Gun | | | | | | |
| Cheatham, TN | | Keystone Velox 3 | Monthly Air gun | Chevron Open Gear Lube SP | Monthly Spray | Chevron Open Gear Lube SP | Monthly Spray | | |
| John T. Meyers, OH | | Amoco Super Permalube grease | Monthly Elec gun | | | | | | |
| Lock No. 8, WI | -40 to 48.8 (-40 to 120) | Mobil EAL 102 | Weekly Gun | Rope - Lubriplate L0135-063 | Yearly Spray | | | Mobil SHC 630 | Seals - Mobil EP1, EAL 101, mo, gun |
| Lock and Dam No. 7, MN | -45.5 to 37.7 (-50 to 100) | Shaeffer's 271 Synthetic H-1 | Monthly Gun | | | | | Mobil SHC 630 | Cam limit switch - Mobilgear 629 |
| Lock and Dam No. 12, IA | -28.8 to 37.7 (-20 to 100) | Lubriplate 1242 | 2 Weeks Gun | Stainless steel | None | Lubriplate 1242 | Brush | Lubricating Eng. Almasol 607 SAE 90, yearly | |
| Lock and Dam No. 18, IL | -28.8 to 40.5 (-20 to 105) | Amoco Ryotek EP | 2 weeks Gun | Rope-Drumund Core | 6 months Spray | Amoco Ryotek EP | 2 weeks Gun | Mobil SHC 630 | |
| Lower Monumental, WA | -1.6 to 32.2 (35 to 90) | Mountain Oil DY-80 | Weekly Gun | | | | | Texaco Meropa 150, 3 months | |
| McAlpine, KY | -40 to 43.3 (-40 to 110) | Keystone Velox 3 | Weekly Elec gun | | | | | | |
| McNary, OR | Below 47.7 to 37.7 (0 to 100+) | Husk-ITT LVI-50 | Daily Manual Farval | | | | | | |
| Newburgh, IN | 26.1 to 37.7 (-15 to 100) | Valvoline 612 EP | Monthly Pwr gun | | | Keystone Moly 29 | | | Rollers, Wheels-Valvoline 612 EP |
| Old Hickory, TN | -6.6 to 35 (35 to 65) | Keystone Velox 3 | Monthly Gun | | | | | | |
| Port Allen, LA | -28.8 to 40.5 (20 to 105) | Certified Prem-I-Lube Red | Weekly Gun | | | | | | |

**Culvert Valves - Reverse Tainter and Tainter**

| Lock and State | Temp Range °C (°F) | Lubrica-tion for Trunnion | Freq of Lubrication, Method | Lubrication for Hoist Wire Rope, Chains | Freq of Lubrica-tion, Method | Lubri-cation for Open Gears | Freq of Lubrica-tion, Method | Lubrica-tion for Enclosed Gears | Other |
|---|---|---|---|---|---|---|---|---|---|
| Robert C. Byrd, WV | | Unocal 76 Redtac 2 | Monthly Gun | Stainless rope | None | | | | Cylinder rod guide Chesterton Sprayflex Gold |

**Culvert Valves - Stoney**

| Lock and State | Temp Range °C (°F) | Lubrica-tion for Roller Trains | Freq of Lubrication | Lubrication for Hoist Wire Rope, Chains | Freq of Lubrica-tion | Lubrication for Open Gears | Freq of Lubrica-tion | Lubrication for Enclosed Gears | Other |
|---|---|---|---|---|---|---|---|---|---|
| Hiram M. Chittenden, WA | 12.2 to 37.7 (10 to 100) | | | | | Certified Lube Trac Plus Dynaco Tacky Lube | 3 times per week Spray | TexacoTexclad 23/week, paddle | |
| Marmet, WV | -28.8 to 43.3 (-20 to 110) | Kendall L-427 | | | | | | Mobil SHC 634 | |

**Culvert Valves - Butterfly and Slide**

| Lock and State | Temp Range °C (°F) | Type | Trunnion | Freq of Lubrication, Method | Lubrication for Wheels, Rollers | Freq of Lubrica-tion, Method | Lubrication for Open Gears | Freq of Lubrica-tion, Method | Lubrica-tion for Enclosed Gears |
|---|---|---|---|---|---|---|---|---|---|
| Dashields, PA | -31.6 to 35 (-25 to 95) | Butterfly | | | Lubriplate 630 AA | Monthly Gun | | | |
| Lockport, IL | -28.8 to 48.8 (-20 to 120) | Slide | | | Mobil Mobilith SHC 220 | Monthly Gun | | | |
| Starved Rock, IL | -34.4 to 43.3 (-30 to 110) | Slide | | | Chevron Ultra-Duty Grease EP NLGI 2 | | | | |

| Dam Gates - Roller | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Lock and Dam** | **Temp Range °C (°F)** | **Lubrication for Hoist Chain** | **Freq of Lubrica-tion** | **Lubrication for Open Gears** | **Freq of Lubrica-tion** | **Lubrication for Enclosed Gears** | **Lubrication for Other Equipment or Comments** | **Freq of Lubrica-tion** |
| Lock and Dam No. 7, MN | -45.5 to 37.7 (-50 to 100) | Mobil EAL 224H Hydraulic Oil | 6 months Spray | Lubrication Eng. Pyroshield 5182 and 5100 and Mobiltac 375 NC | 6 months Spray Brush | Mobil Mobilube HD 80w90, annually | | |
| Lock and Dam No. 12, IA | 28.8 to 37.7 (-20 to 100) | Lubricating Eng. Quinplex Plate Oil #10 | 6 months Spray | Lubriplate 1242 | 6 months Gun | Lubricating Eng. Almasol 607 SAE 90 | | |
| Lock No. 8, WI | -40 to 48.8 (-40 to 120) | Mobil EAL 102 | 2 / year Gun | Mobil EAL 102 | 2 / year Brush | Shaeffers SYN 75-90 | Pillow blk bearings EAL 102 | 2 / year |
| Marmet, WV | -28.8 to 43.3 (-20 to 110) | Chesterton 715 | 3 months Spray | Chesterton Gold | 3 months Spray | Gear Oil 85-140 | Wire rope Chesterton 715 | 3 months |
| Robert C. Byrd, WV | | Chesterton Sprayflex Gold | Spray | Chesterton Sprayflex Gold | 6 months Spray | Mobil SHC 634 ISO VG 460 | | |

**Dam Gates -Tainter**

| Lock and Dam | Temp Range °C (°F) | Lubrication for Trunnions | Freq of Lubrication, Method | Lubrication for Hoist Wire Rope, Chains | Freq of Lubrication, Method | Lubrication for Open Gears | Freq of Lubrication, Method | Lubrication for Enclosed Gears |
|---|---|---|---|---|---|---|---|---|
| John T. Meyers, OH | | Amoco Super Permalube grease | 4 mo. or after submer. | | | Keystone Moly 29 | As need 6 to 12 mo calk. gun | Helical - Gulf 100<br>Worm - Mobil - SHC 634 |
| Lock and Dam No. 12, IA | -28.8 to 37.7 (-20 to 100) | Lubriplate 1242 | 6 months Gun | Chains - Lubricating Eng. Quinplex Plate Oil #10 | 6 months Spray | Lubriplate 1242 | 6 months Gun | Lubricating Eng. Almasol 607 SAE 90 |
| Lock and Dam No. 7 | -45.5 to 37.7 (-50 to 100) | Mobil Mobilux EP 2 | 6 months | Mobil EAL 224H Hydraulic Oil | 6 months | Lubrication Eng. Pyroshield 5182 and 5100 and Mobiltac 375 NC | 6 months | Mobil Mobilube HD 80w90, annually |
| Lock No. 8, WI | -40 to 48.8 (-40 to 120) | Mobil EAL 102 | 6 months Gun | Chains - Mobil EAL 102 | Yearly Gun | Mobil EAL 102 | 2 / year Brush | Shaeffers SYN 75-90, as needed |
| Lock and Dam No. 18, IL | -28.8 to 40.5 (-20 to 105) | Amoco Ryotek EP | 2 weeks Gun | Rope - Drummond Core | 6 months Spray | Amoco Amovis 8-X | Weekly Brush | Mobil SHC630 |
| McAlpine, KY | -40 to 43.3 (-40 to 110) | Keystone Velox 3 | 6 months Gun | | | Keystone Moly 29 (Excel staying power) | Yearly Calk. gun | Mobil SHC 634 |
| Newburgh, IN | -26 to 37.7 (-15 to 100) | Valvoline 612 EP | 4 months Pwr gun | Stainless rope | Inspect monthly | Keystone Moly 29 | 3 mo. more if used freq | Amoco Gear Lube SAE 90 |
| Starved Rock, IL | -34.4 to 43.3 (-30 to 110) | Chevron Ultra-Duty Grease EP NLGI 2 | 6 months Gun | | | Bowman Dist. Barnes Grp. Part No. 19464 Open Gear&Fifth Whl | 6 months Spray | Mobil SHC 630 |

**Dam Gates - Vertical Lift**

| Lock | Temp Range °C (°F) | Lubrication for Hoist Wire Rope | Freq of Lubrica-tion, Method | Lubrication for Open Gears | Freq of Lubrica-tion, Method | Lubrication for Enclosed Gears | Lubrication for Other Equipment or Comments | Freq of Lubrica-tion, Method |
|---|---|---|---|---|---|---|---|---|
| **Aberdeen,** MS | | Lubriplate Gearshield Extra Spray | 3 months Spray | Lubriplate Gearshield Extra Spray | 3 months Spray | | Seals - Royal Oil Grease NLGI 1 | 3 months Gun |
| Lower Monumental, WA | 28.8 to 40.5 (-20 to 105) | Chemsearch High Core | 3 months Manual | Tribol Molub-Alloy 412-1 Open Gear | 3 months Manual | Texaco Meropa 150 | Wheels - Mountain Oil DY-80 | |
| McNary, OR | | Chevron Rust Preventive EPS 254105 | Yearly Paint brush | Keystone Moly 29 | Yearly Caulk gun | Mobil Mobilgear 632 Change 8 years | Wheels - Texaco Novatex 1 | Grease pump |

**Hydraulic Fluids**

| Lock | Hydraulic Fluids For: Lock Gates | Hydraulic Fluids For: Culvert Valves | Hydraulic Fluids For: Dam Gates | Operation Press bar (psi) | Frequency of Change or Testing | Pump Type | Filter, Freq of Change |
|---|---|---|---|---|---|---|---|
| Aberdeen, MS | Shell Telus 22 | Shell Telus 22 | | | | | |
| Bayou Boeuf, LA | Shell Tellus No. 46 Superior Ind. Turb. 1651 (Biodegradable) | | | 17.2 to 34.6 (250 to 500) | | Nachi-Fujikoshi semi swashplate style - PVS | Fairey Arlon 200 series, yearly or as indicator requires |
| Cheatham, TN | Shell Tellus No. 32 | Shell Tellus No. 32 | | 24.1 (350) | | Vickers vane 45V50A1A2 00880 | Vickers 100FF 1F 11, yearly |
| Dashields, PA | Army Hydraulic Oil - 2075 | Army Hydraulic Oil - 2075 | | 27.6 (400) | | Racine var vane | Magnatech, 3 mo. |
| John T. Meyers, OH | Amoco Industrial No. 32 | Amoco Industrial No. 32 | | 67.6 (980) | Test annually | Delaval IMO worm gear | Cuno GPS (culvert)Cuno PV2 (rest)-Turn daily |
| Lockport, IL | Amoco #68 | Amoco #100 Synthetic | | Lock 55.2-82.7 (800-1200) Culvert 552-96.5 (800-1400) | Analysis - 6 months | 2-stage rotary vane pump | Schroeder line #TF-1-2A10-S Element A10 |
| Lower Monumental, WA | Texaco Regal R&O 32 | Texaco Regal R&O 32 | Texaco Regal R&O 32 | 48.3 (700) lock and dam. 51.7 (750) valves | | | Yearly |
| Marmet, WV | Mobil DTE 24 | | Comment: Have several hydraulic fluids for diff equip. Seeking to consolidate. | 103.4 (1500) | | Var displ piston | 3 micron, 3 mo |
| McAlpine, KY | Mobil DTE 13M | Mobil DTE 13M | Bukhead crane hydraulics- Chevron ISO 32 | 62.1-68.9 (900-1000) for Mobil | | Screw | Cuno 12569, drain sed monthly/ |
| McNary, OR | | Texaco Regal 32 | Head gates - Chevron Grade E Mil-H-5606E | Culvert- 17.2 (250) Dam-199.9 (2900) | | | Culvert filter change 6 months Dam filter change monthly |
| Newburgh, IN | Amoco AW 32 | Amoco AW 32 | | 75.8 (1100) | | Screw const deliv | Cuno PV-2 auto clean |
| Old Hickory, TN | Shell Telus 32 | Shell Telus 32 | | 10.3-41.4 (150-600) | Test 6 months | Vickers model V460 | Fairey Arlon 370-L-210A, 2 mo. or as needed |
| Port Allen, LA | Lubriplate HO 1 | Lubriplate HO 1 | | 10.3-87.2 (150 to 1250) | Test 6 months | Var disp gear | Wix 51071 and 51092, yearly |
| Robert C. Byrd, WV | Unocal 76 Unax AW 32 | Unocal 76 Unax AW 32 | | 120.7 (1750) | Test yearly | Vickers | Vickers, 6 months |

**Hydraulic Fluids**

| Lock | Hydraulic Fluids For: Lock Gates | Hydraulic Fluids For: Culvert Valves | Hydraulic Fluids For: Dam Gates | Operation Press bar (psi) | Frequency of Change or Testing | Pump Type | Filter, Freq of Change |
|---|---|---|---|---|---|---|---|
| Smithland, IL | | | Bulkhead Crane Jeffery Unit cone drive Gulf Harmony 115 HD 680 | | | | |
| Starved Rock, IL | | Chevron Clarity Hydraulic Oil AW ISO 46 | | | 6 months | Vickers 2-stage vane | Schroeder A10, 6 months |
| Winfield, WV | Mobil DTE 11M | Mobil DTE 11M | Mobil DTE 11M | 144.8 (2100) | | | |

**Environmentally Acceptable Lubricants**

| Lock/Location | Lubricant | Comments |
|---|---|---|
| Bayou Boeuf, LA | Superior Ind. Turbine 1651 | Yes. Biodegradable hydraulic oil seemed to do a good job in our old equipment and will be used in new equipment when warranty is out. Food grade grease will not hold up under EP or exposed to weather as well as petroleum or synthetic. |
| Bayou Boeuf, LA | | Biodegradable hydraulic oil seemed to do a good job and will be used as soon as new equip. warranty runs out. Food grade will not hold up under water or exposed to weather as well as petroleum or synthetic. |
| Dashields, PA | Dubois Chem - MPG-2 | Satisfactory |
| Greenup, WV | | Yes. When the equipment was pulled out of the water, a black “fungus” looking substance coated it. |
| Hiram M. Chittenden, WA | Mobil EAL Hydraulic Fluid | Yes. So far so good. Used in floating plant equipment, cranes etc. |
| John T. Meyers, OH | | Yes. Good comparison with petroleum or synthetic lubricants. |
| Lock No. 8, WI | Mobil EAL 101 and 102 | Working out fine. No problems yet. EAL 102 not avail in grease gun tubes. |
| Lock and Dam No. 7 | | Yes. Not as good as petroleum or synthetic but adequate. Recently have tried Mobil EAL 224H on chains. |
| Lock and Dam No. 12, IA | Cenpeco Special Chain Penetrant | Yes. Used for 3 years on dam roller and tainter gate chains to prevent river contamination. No problems but too early to tell if they are doing as well as the old petroleum oil used for many years. |
| Lock and Dam No. 18 | | No. Tried food grade and found it to be a poor lubricant. |
| Lockport, IL | | No. Actively seeking EALs for wire rope. Other locks have tried biodegradable hydraulic oil and had poor results. |
| Lower Monumental, WA | | Have been unable to find environmentally acceptable lubricants that will work in our environment. Used food acceptable grease that works well but will not work in grease gun or automatic Farval units. |
| Marmet, WV | | Yes. Experienced bacterial growth. |
| McNary, OR | | Yes. Husk-ITT LVI-50 on lock gates and culvert valves. We have been phasing in LVI-50 since 1987 and have not seen any evidence of inadequate lubrication since changing to it. Also use Husk-ITT 15A14 Lube Oil on pump oil lube bearings. |
| Old Hickory, TN | | Have tested food grade lubricants on open gears, miter block (gates), and wire ropes. Grease does not hold up in environment. When time to replace seal bearings, will replace greaseable bearings with nongreaseable Thordon bearings. |
| Port Allen, LA | | No. Informed by sales people that food grade or environmentally acceptable are not as good as petroleum or synthetic for our application. |
| Wheeler Aux. Lock | Mobil EAL 100H | Satisfactory on culvert valve and miter gate machinery after 5 years of service. |
| Big Cliff Dam | Mobil EAL 101 | Satisfactory on turbine wicket gate bushings after 1 year. |
| Huxtable Pumping Plant | Mobil EAL 102-EP | Satisfactory in right angle gear box. |
| Wheeler Aux. Lock | Mobil EAL 224H | Satisfactory in miter gate hydraulic system. |

**Environmentally Acceptable Lubricants**

| Lock/Location | Lubricant | Comments |
|---|---|---|
| Petti Bone Floating Snag Vessel | Mobil EAL 224H | Satisfactory in hydraulic systems after 5 years. Spills congeal on surface of water making cleanup easier. |
| Carri Tuck Multipurpose Vessel | Mobil EAL 224H | Satisfactory. Using 3-year replacement cycle but may not be necessary. |
| Jordan Lake Intake Tower | Mobil EAL 224H | Satisfactory after 6 years of service in hydraulic system. Can see spill on concrete because of extreme black biological growth. Change-over was easy . |
| Wilmington District Repair Facility | Mobil EAL 224H | Four years service on crane. Installed heater and cooler to address temperature extremes. |
| Olmsted Prototype Wicket Dam | Mobil EAL 224H | Hydraulic fluid thickened in cold weather. |
| Crane Barges Fry & Merritt | Mobil EAL 224H | In service in cranes for 4 years. Immersion heaters used at low temperatures. |
| Ballard Locks | Mobil Envirosyn H | Satisfactory. Change-over was easy. |
| Huxtable Pumping Plant | Mobil EAL 224H | Satisfactory. |

**Lubrication for Additional Equipment 1**

| Lock | Floating Mooring Bits | Tow Haulage Gear Box | Tow Haulage Bearings | Tow Haulage Cable | Compressor | Bubbler | Crane Cables |
|---|---|---|---|---|---|---|---|
| Cheatham, TN | Keystone Velox 3 | Valvoline Hydro-Lube SAE 80w90 | | | | | |
| Dashields, PA | Lubriplate 630 AA | Mobil DTE Ex Heavy | Certified Lube-Trac + | Certified CCx 77 | | | |
| John T. Meyers, OH | | | | | | | Chemsearch High Core |
| Lock No. 8, WI | | Shaeffers SYN 75-90 | Mobil EAL 102 | | Rotary-Roots Dresser ISO VG 220 | LuBest Titan 999 | |
| Lock and Dam No. 12, IA | | Lubricating Eng. Almasol 607 SAE 90 | Lubriplate 1242 | | | | |
| Lower Monumental, WA | Mountain Oil DY 80 | | | | | | |
| Marmet, WV | Kendall L-427, Shell Alvania 2 | | | | | | |
| McAlpine, KY | Mobil SHC 460 | | | | | | Fluid Film WRO Rust & corrossion |
| McNary, OR | Husk-ITT LVI-50 NT Grease, monthly w/gun | | | | | | |
| Old Hickory, TN | Keystone Velox 3, monthly w/gun | | | | | | |
| Robert C. Byrd, WV | Unocal 76 Redtac 2, 6 months w/gun | | | | | | |
| Smithland, IL | British Petroleum Energrease LS-EP2, 6 mo. w/gun | | | | | | Chemsearch |
| Starved Rock, IL | | | | | Ingersoll-Rand SSR H-IF Food Grade Coolant, 2000 hours | | |

**Lubrication for Additional Equipment 2**

| Lock | Generator-Deisel-Detroit, Onan | Encoder Chains in Buildings | Stiff-leg Derrick Gear Boxes | Stiff-leg Derrick Wire Rope | Stoplog Hoist Gear Boxes | Blower - Roots Universal | Turbine Wicket Gates |
|---|---|---|---|---|---|---|---|
| John T. Meyers, OH | Amoco 300-30 wt | | | | | | |
| Lock and Dam No. 7 | | | | | | Mobilith SHC 220 and Mobil SHC 630 every 2000 hours or yearly | |
| Lockport, IL | | UZ Engineered Products Chain & Cable Lubri-Tec # 190118 spray, mo. | | | | | |
| McNary, OR | | | | | | | Husk-ITT LVI-50, 2 days, auto Farval |
| Port Allen, Lock | | | Shell 85W90 gear | Certified CCx97 grease, clear, no mess, rope absorbs | Shell 85w90 gear | | |
| Starved Rock, IL | Chevron 400 Multigrade SAE 15W-40, 6 months | | | | | | |

# Appendix C
# SPECIFICATION FOR TURBINE OIL

## GUIDANCE ON THE USE OF THIS SPECIFICATION

The specification below is for zinc and chlorine-free petroleum-based turbine oils for use at hydroelectric power plants in generator and turbine bearings, Kaplan turbine hubs, and governor systems. For additional guidance, reference Chapter 11, Engineer Manual EM 1110-2-1424, Lubricants and Hydraulic Fluids for Civil Works Project

Compatibility between new oil and in-service oils must be evaluated and determined by lab testing. Only oils found to be compatible will be mixed with in-service oil or used as replacement oil. The compatibility testing is necessary because the new oils currently readily available on the market are formulated with different base oils than the in-service oils, and their additives may not be fully compatible with additives of the in-service oils. This specification shall be used for the procurement of all turbine oils, whether purchased for initial installation, filling rehabbed hydroelectric units, or for use as additional turbine oil at operating projects.

There are essentially two viscosity grades of turbine oil for hydro turbines, ISO 68 and ISO 100, their characteristics requirements are listed in TABLE 2. The following criteria should be used in choosing these oils for the powerhouse.

1. New powerhouses should use turbine oil of the viscosity that is outlined in the design specifications.
2. Powerhouses that use ISO 68 oil in their Kaplan turbine runner hubs and are experiencing a stick/slip problem with their blade operating mechanism should investigate a changeover to ISO 100 turbine oil.
3. Powerhouses using ISO 68 oil with no problem should continue to use that oil.

The method of shipment, type of containers, delivery dates, delivery point, delivery point of contact, and other required information should be included in appropriate sections of the contract specifications.

The turbine oil shall meet or exceed the chemical and physical requirements specified in TABLE 2. Additional characteristics or changes in listed values should not be included in the specifications without prior consultation with the technical proponent of the specification. The Corps' Districts/Projects may perform Quality Assurance (QA) tests on samples taken at the delivery point. The QA tests should include, as a minimum, the viscosity, acid number, elemental spectroscopy, and oxidation stability. Samples shall be taken from each bulk shipment and from not less than 10 percent of the drums taken at random from drum shipments. Such samples shall be not less than 4 L (1 gal), which may be stored in more than one sample container, and a portion of each sample shall be saved for later confirmation tests in the event that the results from the first tests indicate that the oil does not meet the specification requirements.
When soliciting for new contracts or orders using this specification for purchase of turbine oil that will be mixed with the in-service oil or as a replacement oil, the government should require all offerors to provide a 1-gallon sample of the proposed oil, which must meet the requirements of this specification in order to be eligible for award. The solicitation must include the following language - The Government may test this oil for compatibility with the in-service oil prior to awarding the Contract by sending a portion (1 qt) of new oil in an unmarked container, and a sample of in-service oil to a lab. The remaining

quantity of new oil should be retained by the Government for possible further testing. Compatibility testing should be performed at no charge to the bidders.

The Districts/Project office can contact Hydroelectric Design Center (HDC) for information on sources of testing services.

**SPECIFICATION FOR TURBINE OIL**

TURBINE OIL

TABLE OF CONTENTS



1. GENERAL

This specification covers zinc and chlorine-free rust and oxidation inhibited (R&O) mineral oils for use in hydraulic turbine and generator bearings, Kaplan turbine hubs, hydraulic-turbine governors, and other applications, where high-grade lubricating oil having anti-corrosion, anti-oxidation, and anti-foaming properties is required.

2. REFERENCES

The publications listed below form a part of this specification to the extent referenced. The publications are referred to in the text by basic designation only.

AMERICAN SOCIETY FOR TESTING AND MATERIALS (ASTM)

| | |
|---|---|
| ASTM D 92 | (2002b) Flash and Fire Points by Cleveland Open Cup |
| ASTM D 97 | (2004) Pour Point of Petroleum Oils |
| ASTM D 130 | (2004) Corrosiveness to Copper from Petroleum Products by Copper Strip Test |
| ASTM D 445 | (2004e1) Kinematic Viscosity of Transparent and Opaque Liquids (and the Calibration of Dynamic Viscosity) |
| ASTM D 664 | (2004e1) Acid Number of Petroleum Products by Potentiometric Titration |
| ASTM D 665 | (2003) Rust-Preventing Characteristics of Inhibited Mineral Oil in the Presence of Water |
| ASTM D 892 | (2003) Foaming Characteristics of Lubricating Oils |

| | |
|---|---|
| ASTM D 943 | (2004a) Oxidation Characteristics of Inhibited Mineral Oils |
| ASTM D 1401 | (2002) Water Separability of Petroleum Oils and Synthetic Fluids |
| ASTM D 2270 | (2004) Calculating Viscosity Index from Kinematic Viscosity at 40 and 100 Degrees C |
| ASTM D 2272 | (2002) Oxidation Stability of Steam Turbine Oils by Rotating Pressure Vessel Oxidation Test |
| ASTM D 3427 | (2003) Air Release Properties of Petroleum Oils |
| ASTM D 4057 | (2000) Manual Sampling of Petroleum and Petroleum Products |
| ASTM D 4177 | (2000) Automatic Sampling of Petroleum and Petroleum Products) |
| ASTM D 6304 | (2004ae1) Water in Petroleum Products, Lubricating Oils, and Additives by Coulometric Karl Fisher Titration |

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO)

| | |
|---|---|
| ISO 4406 | (1999) Coding the Level of Contamination by Solid Particles |
| ISO 11171 | (1999) Calibration of Automatic Particle Counters for Liquids |

3. SUBMITTALS
Government approval is required for submittals with a "G" designation; submittals not having a “G” designation are for information only. When used, a designation following the “G” designation identifies the office that will review the submittal for the Government. The following shall be submitted:

3.1. DATA

Data of Chemical and Physical Characteristics of Turbine Lubricating Oil, G [, _____ ]

The Contractor shall furnish [ _____ ] copies of certified test data, which show that the oil meets or exceeds characteristics values specified in TABLE 2. The certified test data shall be submitted for approval 30 days before the oil delivery.

3.2. SAMPLES

A gallon of proposed turbine oil, G [, _____ ] The prospective bidder shall send one gallon of oil to the Government along with the bid. This oil shall be closely representative to the oil being offered in the bid. The Government plans to send a quart of this oil in an unmarked container to an independent laboratory for compatibility testing with the in-service oil. The compatibility testing will be performed at no charge to the prospective bidder. If the submitted oil sample is found to be incompatible with the in-service oil, this oil will not be further considered in the Contract awarding process.

4. TURBINE OIL CHARACTERISTICS AND REQUIREMENTS

4.1 GENERAL PROPERTIES

The turbine oil should be a blend of virgin petroleum-based stocks plus additives, free of zinc and chlorine, resulting in a high-grade turbine oil having anti-rust, anti-oxidation and anti-foaming properties suitable for use in hydraulic turbines, generator bearings, Kaplan turbine hubs and related applications.

4.2 VISCOSITY
The oil viscosity should fall within the range as specified in TABLE 2.

4.3 CHEMICAL AND PHYSICAL CHARACTERISTICS

The turbine oil shall conform to the requirements established in TABLE 2 when tested according to the standards indicated there.

4.4 DEGRADATION

The physical and chemical properties of the oil shall not be degraded (changed from specified values in TABLE 2) by filtration through two-micron mechanical type filters, by centrifugal purification, or by vacuum type purifier, all of which have been designed for turbine oil.

4.5 HOMOGENEITY

Additive agents shall remain uniformly distributed throughout the oil at all temperatures above the pour point and up to 120 ºC (250 ºF). When the oil is cooled below the pour point, it shall regain homogeneity while standing at temperatures of 5 ºC (10 ºF) above the pour point, and retain clear and bright appearance.

4.6 COMPATIBILITY

Before the oil is being purchased for addition to existing (in-service) oil or as replacement oil, the Government will perform an independent compatibility testing of the two oils (new and in-service oil). The testing shall be performed in accordance with paragraph COMPATIBILITY TESTING and evaluated in accordance with paragraph APPEARANCE RATING PROCEDURE. If wish to conduct the test, potential suppliers shall contact the Contracting Officer to obtain a representative sample of the in-service oil required. The paragraphs COMPATIBILITY, COMPATIBILITY TESTING, and APPEARANCE RATING PROCEDURE are not applicable for new construction.

5. TESTING

5.1 COMPATIBILITY TESTING

The following testing procedure shall be used for evaluation of compatibility between new and in-service oils (for convenience, new oils are called “A” oils, and in-service oils are called “B” oils):

a. Prepare separately 300 ml of each mixture of the following ratios: 90:10, 50:50, and 10:90 of the two oils (A and B) to be evaluated for compatibility. The two constituent oils (100:0, and 0:100) shall be tested concurrently.

b. Stir each mixture vigorously in a laboratory glass mixer (minimum volume capacity of one quart) for 30 minutes, and immediately transfer to a glass beaker of suitable size for each mixture. Use a suitable rubber spatula, and squeegee the remaining oil into the glass beaker.

c. Heat the beakers with the mixtures in the oven at 65 ºC (150 ºF) for 168 hours (± 1 hour).

d. Remove the beakers from the oven and allow to cool to room temperature.

e. Observe the oil samples according to the procedure described in paragraph 5.2, Appearance Rating Procedure. If any of the oil mixtures tested display an incompatible result, conclude the test and report that the new oil is not acceptable for use. If the results are satisfactory, proceed to the next section.

f. Cool the beakers with the oil mixtures to 0 ºC (32 ºF) and keep them at this temperature for 24 hours.

g. Remove beakers from the cooler and bring to room temperature.

h. Observe the oil samples according to the procedure described in paragraph 5.2. Appearance Rating. If any of the oil mixtures tested displays an incompatible result, the new shall be reported as incompatible, and as such, not acceptable for use.

5.2 APPEARANCE RATING PROCEDURE

Set up the appearance-rating test using a 150-Watt reflector flood lamp.

a. SEDIMENT RATING

Hold the sample beaker vertically few inches above the flood lamp, without disturbing the sample, approximately ten inches in front of your eyes. View the sample beaker from the different directions, angles and distances from the light source bottom. Assign the observed sediment rating according to TABLE 1.

b. FLUID RATING

View the sample beaker from the side, looking directly through the oil mixture. Assign a fluid rating according to TABLE 1. If the samples are too dark to rate for fluid appearance, they may be rated by tilting samples on side and observing the material adhering to the beaker.

TABLE 1

| CODES FOR RATING COMPATIBILITY OF COMPOUNDED OILS | | | |
|---|---|---|---|
| Fluid Rating | Sediment Rating | Description | Result of Evaluation |
| 0 | - | Absolutely Bright | Pass |
| 1 | - | Bright | Pass |
| 2 | - | Very Slight Cloudiness | Fail |
| 3 | - | Moderate Cloudiness | Fail |
| 4 | - | Heavy Cloudiness | Fail |
| 5 | - | Detectable Floc | Fail |
| 6 | - | Heavy Floc | Fail |
| - | 0 | No Sediment | Pass |
| - | 1 | Very Slight Sediment | Fail |
| - | 2 | Slight Sediment | Fail |
| - | 3 | Heavy sediment | Fail |
| - | 4 | Appreciable More Sediment Than 3 | Fail |

5.3 TESTING PHYSICAL AND CHEMICAL CHARACTERISTICS OF OIL

Chemical and physical tests shall be conducted in accordance with the Standards listed in TABLE 2.

TABLE 2

CHEMICAL AND PHYSICAL CHARACTERISTICS REQUIREMENTS AND TEST METHODS FOR RUST AND OXIDATION (R&O) INHIBITED ISO 68 & 100 TURBINE OILS

| Chemical and Physical Characteristics | Requirements | | Test Method |
|---|---|---|---|
| | ISO 68 Oil | ISO 100 Oil | |
| Viscosity at 40 °C, centistokes (cSt) | 65-70 | 95-102 | ASTM D 445 |
| Viscosity Index, minimum | 98 | 95 | ASTM D 2270 |
| Flash Point, minimum, °C (°F) | 204 (400) | 210 (410) | ASTM D 92 |
| Pour Point, maximum, °C (°F) | -9 (16) | -9 (16) | ASTM D 97 |
| Acid Number (AN) mg KOH/g, maximum | 0.15 | 0.15 | ASTM D 664 |
| Oxidation Stability by Rotating Pressure Vessel Oxidation Test (RPVOT), minutes, minimum | 500 | 500 | ASTM D 2272 |
| Oxidation Characteristics, mg KOH/g, maximum | 0.5* | 0.5* | ASTM D 943 |
| Rust Preventive Characteristics, Procedures “A” | Pass | Pass | ASTM D 665 |

| | | | |
|---|---|---|---|
| and “B” | | | |
| Water Content, parts per million (ppm), maximum | 250 | 250 | ASTM D 6304 |
| Water Separability of Petroleum Oil | 40-40-0 (30) | 40-40-0 (60) | ASTM D 1401 |
| Corrosion from Oil by Copper Strip Tarnish Test | Classification 1 | Classification 1 | ASTM D 130 |
| Foaming characteristics<br><br><u>After 5 minutes blowing period:</u><br>Sequence 1, foam volume in milliliters (ml), maximum<br>Sequence 2, foam volume in ml, maximum<br>Sequence 3, foam volume in ml, maximum<br><br><u>After 10 minutes settling period:</u><br>Sequence 1, foam volume in ml, maximum<br>Sequence 2, foam volume in ml, maximum<br>Sequence 3, foam volume in ml, maximum | 100<br>50<br>100<br><br>10<br>0<br>10 | 100<br>50<br>100<br><br>10<br>0<br>10 | ASTM D 892 |
| Air Release Properties, minutes, maximum | 30 | 60 | ASTM D 3427 |
| Cleanliness, ISO Code Particle Count, particle sizes of greater than 4, 6, and 14 µm (c) | 17/15/12 (c) | 17/15/12 (c) | ISO 4406-99 (ISO 11171 Cal.) |
| Appearance | Clear & Bright | Clear & Bright | Visual Observation |

*  At the conclusion of the 1,000 hours test, measured AN should be 0.5 or less. In addition, at that point, the oil and water phases shall be examined for evidence of sludge and catalyst metal corrosion. Permitted maximum level of total sludge in the oil after 1000 hours is 50 mg/kg.

6. PRE-DELIVERY TESTING

The Contractor shall test the oil or a sample blend for all chemical and physical characteristics set forth in TABLE 2, and provide the certified test results as well as one gallon sample of the oil to the Government at least thirty days prior to delivery.

The Contractor may conduct compatibility testing of the oil or sample blend. The Government will provide a sample of in-service oils for such purposes on request.

The Government will conduct compatibility testing of the sample, and notify the contractor of the results prior to purchasing of the oil.

7. DELIVERY

The Contractor shall deliver the oil according to the delivery requirements specified elsewhere in the contract.

8. INSPECTION AND ACCEPTANCE.

At the point of oil delivery, the Government will obtain samples in a manner specified in ASTM D 4057 or ASTM D 4177, and may perform such tests as are deemed necessary to determine whether the oil meets the specifications values listed in TABLE 2. The delivered oil will remain in a storage tank (if applicable) and will not be used until the test results are received from the laboratory. Should the oil fail any test, the Contractor shall be responsible for disposing of the delivered oil and replacing the oil at its own expense.