Lubricants and Hydraulic Fluids: *Handling*

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CHAPTER 5

Lubricant Additives

5-1. Introduction. An additive is a material that imparts or reinforces a desirable property of the lubricant. Additives can enhance properties of the base oil and also suppress undesirable properties of the base oil. The overall performance of oil can be improved by introducing additives. However, 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. Virtually all lubricants contain additives to enhance existing properties or to impart new properties. Additives generally only comprise a small portion of the overall lubricant composition. This is typically from 1 to 30% of the overall composition. Figure 5-1 shows a typical lubricant composition.

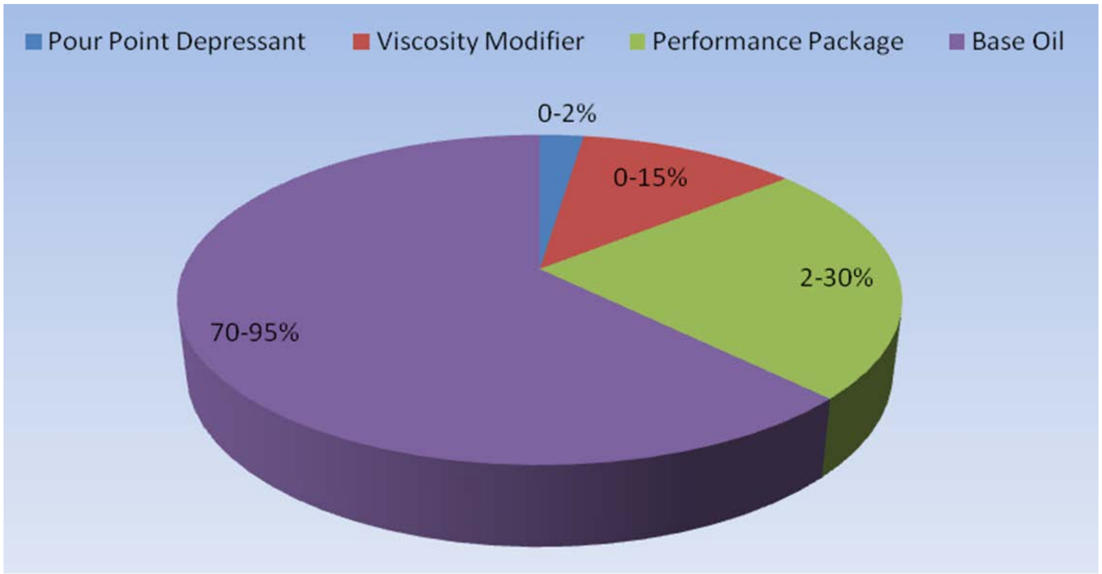

Figure 5-1. Typical Lubricant Composition.

5-2. Additive Classifications. Three general classifications of lubricant additives are surface protective additives, performance-enhancing additives, and lubricant protective additives. As the names imply, surface protective additives protect the bearing surfaces, performance-enhancing additives enhance the lubricant’s performance for particular applications, and lubricant protective additives prevent deterioration of the lubricant. These categories are summarized as:

- Surface-Protecting Additives. Extreme pressure (EP) additives, Antiwear (AW) additives, and rust inhibitors are included in this category. These additives coat the lubricated surfaces and prevent wear or rust.
- Performance-Enhancing Additives. Viscosity index improvers and antifoaming agents are examples. They make the lubricant perform in a desired manner for specific applications.
- Lubricant Protective Additives. An example is antioxidants. Antioxidants reduce the tendency of oil to oxidize and form sludge and acids.

5-3. Oil Classification. Oil is normally classified by viscosity grade (probably most common), additive package, by application or use, or by the producer's brand name. Some oils are classified as nonspecialized industrial oils.

a. 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 professional societies and organizations such as SAE, AGMA, and ISO. Each organization uses a different kinematic viscosity range numbering system. Chapter 4 of this manual further discusses viscosity and the professional societies that classify lubricants. Common professional organizations related to lubricants include:

- SAE (Society of Automotive Engineers).
- API (American Petroleum Institute).
- AGMA (American Gear Manufacturers Association).
- ISO (International Standards Organization).
- NLGI (National Lubricating Grease Institute).

b. Classification by Additive Package. Oil quality is established by the refining processes and additives are most effective if the oil is well refined. Table 5-1 lists the most common additives, which are discussed individually in the following paragraphs.

Table 5-1. Types of Additives.

Additive	**What It Does**	**How It Works**
Acid neutralizers	• Neutralize contaminating strong acids formed, e.g., by combustion of high sulfur fuels or by decomposition of active EP additives	• Are alkaline substances that neutralize acids that are formed
Antifoam or foam inhibitor	• Reduce surface foam • Prevents formation of stable foam	• Promotes combination of small bubbles, which in turn collapse more easily
Antioxidants or oxidation inhibitor	• Reduce oxidation • Inhibits varnish and sludge formation • Reduces viscosity increase resulting from oxidation • Reduces formation of corrosive acids	• Slows the rate of reaction with oxygen by interruption of chain reactions or by decomposing reactive peroxides

Additive	**What It Does**	**How It Works**
Antirust	• Reduce rusting of ferrous surfaces swept by oil	• Forms a film on ferrous parts thus protecting them from water or other destructive materials
Antiwear agents	• Reduce wear and prevent scuffing caused by metal-to-metal contact during conditions of mild boundary lubrication under steady load operating conditions	• Additive reacts chemically and forms a film on metal surfaces under normal operating conditions
Corrosion inhibitors	• Prevents corrosive attack on nonferrous metallic surfaces	• Forms a film on nonferrous metallic parts thus protecting them from attack by contaminants in the oil
Detergents	• Prevents oxidation products (gums) that have formed in the oil from sticking to metal parts at high temperatures, e.g., internal combustion engine • Neutralizes acidic contaminants	• Chemically react with oxidation products (gums) so that they remain soluble in the oil and do not stick to metal surfaces • Metallic base reacts with acid
Dispersant	• Keeps oxidation products separated and suspended in the oil, retards formation of sludge, and reduces soot related viscosity increase at low temperatures	• Additive absorbs on surface of gum particles or soot and inhibits agglomeration
Demulsifiers	• Loosens and breaks stable emulsions	• Lowers emulsion stability
Emulsifiers	• Promotes rapid mixing of oil and water promoting formation of a stable emulsion	• Reduces interfacial tension and permits intimate mixing of oil and water
EP agents	• Prevents welding and subsequent wear or seizure of contacting metal parts under extreme or shock load conditions	• Additive combines chemically with surface to from a surface film • Reaction usually occurs at high temperatures that result when asperities collide
Friction modifier	• Alters coefficient of friction	• Forms an easily shearable film on metal surfaces

Additive	**What It Does**	**How It Works**
Metal Deactivator	• Reduces the catalytic effect of metals on oxidation rate.	• Forms an inactive film on metal surfaces by combining with metallic ions.
Oiliness enhancers	• Reduce friction under boundary lubrication conditions. • Increase load-carrying capacity where limited by temperature rise by formation of mainly organic surface films.	• Forms a (metal-wetting) film on metal surfaces .
Pour point depressants	• Lowers the pour point of paraffinic oils and enables the lubricant to flow at low temperature.	• Changes the size and shape of wax crystals.
Rust inhibitor	• Prevent rusting of ferrous (iron or steel) machine parts.	• Forms a film on ferrous parts thus protecting them from water or other destructive materials.
Tackiness agents	• Reduce loss of oil by gravity, e.g., from vertical sliding surfaces, or by centrifugal force.	• Adding polymers composed of long-chain molecules or aluminum soaps of long-chain fatty acids increases the tackiness or adhesiveness of oils.
Viscosity modifier (VM) or viscosity index improvers	• Reduces rate of change of viscosity with temperature and makes possible the formulation of multigrade oils.	• Polymers uncoil as temperature rises, thus increasing their effective sizes and viscosity.

5-4. Surface Protective Additives. The primary purpose of surface additives is to protect lubricated surfaces. This category includes extreme pressure additives, rust, and corrosion inhibitors, tackiness agents, antiwear additives, and oiliness additives. 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. Rust inhibitors protect ferrous (iron or steel) parts by forming a film on the part that resists attack by water. 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. Corrosion inhibitors act in a similar way as rust inhibitors to protect nonferrous parts and also act to neutralize acids with a basic compound such as calcium carbonate. 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. EP 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. Extreme pressure additives react with the metal surfaces to form compounds that have lower shear strength than the metal. EP additives work by reacting with a metal to form a compound that acts as a protective layer on the metal's surface. This coating reduces friction, wear, scoring, seizure, and galling of wear surfaces. Because this layer is softer than the metal itself, under extreme pressure conditions, the compound layer wears away first, protecting the metal. As this layer is removed, the EP additive acts to form another layer. In contrast to the action of antiwear additives, EP additives control wear instead of preventing it. Some EP additives, because of their reactive nature, can be corrosive to brass or copper-containing alloys. To prevent excessive corrosion, most EP additives are activated by the heat of friction created during extreme pressure conditions, but do not react at room temperature. During extreme pressure conditions, the reaction is initiated by increased temperature caused by pressure between asperities on wearing 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. Tackiness agents act to increase the adhesiveness of an oil or grease.

e. Antiwear (AW) Agents. Antiwear additives work by coating a metal's surface. If light metal-to-metal contact is made, the heat from the friction melts the additives, forming a liquid layer between the surfaces. This molten additive layer, being softer than the metal, acts as a lubricant, preventing wear of the metal surfaces. Molecules of the antiwear compound are polar and attach (adsorb) themselves to metal surfaces or react mildly with the metal. Under boundary lubrication conditions (direct contact between metal asperities), 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 480 °F (250 °C). 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. EP additives should be considered under these conditions.

f. Detergents and Dispersants. Detergents and dispersants are used primarily in internal combustion engines to keep metal surfaces clean by preventing deposition of oxidation products. Detergents and dispersants are used primarily in engine oils to keep surfaces free of deposits and to keep contaminants dispersed in the lubricant. They provide high temperature cleanliness and control corrosive wear by neutralizing acids.

g. Compounded Oil or Lubricity Additives. Lubricity, also referred to as oiliness, with respect to lubricating oil, is defined as the ability of an oil to reduce friction between moving surfaces. Lubricity is also the ability of an oil to provide a lower coefficient of friction at a given viscosity. Lubricity additives, usually vegetable or animal fats, enhance lubricity by tenaciously adhering to the metal's surface, forming an adsorbed film of high lubricating value. A small amount of animal fat or vegetable oil added to a mineral or residual oil will reduce the coefficient of friction in situations where an extreme amount of sliding friction occurs without affecting the viscosity. This oil contains from 3% to 10% fatty or synthetic fatty oils. 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. A very common application is in worm gear systems.

h. Residual Oil. 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.

5-5. 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. Pour point depressants reduce viscosity and improve low temperature pumping ability.

b. Viscosity Modifier (VM) or 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. An emulsifier promotes the rapid mixing of oil and water to form a stable emulsion. Emulsifiers are used in motor oils to allow water, formed by combustion of fuel, to be kept in emulsion until engine heat can evaporate it. Emulsifiers are also used in soluble oils used in some metal working operations and in fire resistant hydraulic fluids. Emulsification is usually not a desirable property in most hydraulic fluids or turbine oils.

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

5-6. Lubricant Protective Additives.

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

(1) Oxidation inhibitors. Oxidation inhibitors, or antioxidants, lengthen a lubricant's service or storage life by increasing its oxidation resistance by binding the free oxygen in the oil or by neutralizing the catalytic effect of metals. 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 180 °F (82 °C), the oxidation rate is doubled for every 18 °F (10 °C) 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 such as a gearbox.

(2) Foam inhibitors. Foam inhibitors prevent lubricant foaming by decreasing the surface tension of air bubbles, allowing them to combine into large ones, which break more rapidly. 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. They also prevent forming persistent foam by reducing surface tension of entrained air or gas bubbles.

5-7. Specialized Classifications and Manufacturer Product Data.

There are a number of specialized lubrication applications that require various additives. The type and number of additives and the type of petroleum (paraffinic or naphthenic) may be varied to provide desirable qualities for a given application. Some of the more common specialty classifications 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.

a. General Purpose Oils and Turbine Oils. General purpose oils contain R&O (rust and oxidation) additives, AW agents, antifoam additives, 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. Chapter 9 of this manual discusses turbine oils in detail.

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.

c. Producer Brand Names. Oil producers often identify their products by names that may or may not be connected with standard classifications. 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 and specifications to determine the intended use, additives, and specifications.

d. Oil Producer’s Product Data and Specifications. 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 (Table 5-2). 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).

e. 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 104 and 212 °F (40 and 100 °C), SUS (saybolt viscosity) at 100 and 210 °F (37 and 98 °C), 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.

Table 5-2. 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 -4°F (20 °C), naphthenic below	• Antioxidant • Antirust • Antiwear • Pour point depressant • VI improver • Antifoam	• Minimum viscosity change with temperature • Minimum wear of steel/steel
Steam and gas turbines	Paraffinic or naphthenic distillates	• Antioxidant • 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

Type of Machinery	**Usual Base Oil Type**	**Usual Additives**	**Special Requirements**
Air compressor cylinders	Paraffinic or naphthenic distillates	• Antioxidant • Antirust	• Low deposit formation tendency
Gears (steel/steel)	Paraffinic or naphthenic	• Antiwear • EP Antioxidant • Antifoam • Pour point depressant	• Protections against abrasion and scuffing
Gears (steel/bronze)	Paraffinic	• Oiliness • 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 Dispersant • Antioxidant • Acid-neutralizer • Antifoam • Antiwear • Corrosion inhibitor	• Vary with type of engine thus affecting additive combination
Reference: Neale, M.J. 1995. A *Tribology Handbook*. Butterworth-Heinemann Ltd., Oxford, England.			

5-8. Precautions. Additives alone do not establish oil quality with respect to oxidation resistance, emulsification, pour point, and viscosity index. Lubricant producers do not usually state the compounds that 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 also that the differences may be significant when mixing different products.

a. Additive depletion. Certain precautions must be observed with regard to lubricant additives. Some additives, such as antiwear and extreme pressure additives and rust, oxidation, and corrosion inhibitors, are consumed as they are used. When all of a particular additive has been consumed, the lubricant is no longer capable of performing as originally intended. Usually this condition requires replacement of the lubricant, but in some cases, replenishment of the additive is possible. The lubricant manufacturer should be consulted before this is attempted. 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.

b. Additive Quantity. When using oil additives, more is not always better. As more additive is blended into the oil, sometimes there is no more benefit gained, and at times the performance actually deteriorates. In other cases, the performance of the additive does not improve, but the duration of service does improve. In addition, increasing the percentage of a certain additive may improve one property of an oil while at the same time degrade another. When the specified concentrations of additives become unbalanced, overall oil quality can also be affected. Some additives compete with each other for the same space on a metal surface. If a high concentration of an antiwear agent is added to the oil, the corrosion inhibitor may become less effective. The result may be an increase in corrosion-related problems.

c. After-Market Additives. There are a number of after-market lubricant additives that are marketed as solutions to many lubricating problems. The automotive industry is probably the most heavily marketed. These additives supposedly improve the lubricating qualities to the lubricant. There may be cases where these additives actually improve performance in some way or at least appear to improve performance. However, in many cases their usefulness is questionable at best. These additives may actually reduce a lubricant’s effectiveness by reacting with some of the additives already in the oil. The major lubricant manufacturers spend a great deal of time and money formulating their products to provide optimum performance for particular applications. If some additive is available that will improve a lubricant to the extent claimed by many of the after-market additive distributors, most lubricant manufacturers would have added it to their product. If a lubricant is not performing as it should, a different lubricant may be required, or some mechanical problem may exist. Before adding anything to a lubricant, the lubricant’s manufacturer should be consulted. The lubricant manufacturer can provide information on the possible benefits or consequences of the additive and determine whether a different lubricant is required.

d. 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.

e. Storage Stability (Shelf Life Precaution). Some oil formulations will degrade over time. If stored for long periods of time, some formulations may require mixing and retesting before use to determine if the lubricant still meets intended performance levels.

f. Oil Temperature. Oil temperature can affect the suspension of additives in the parent oil. Oils should be operated at temperatures according to the manufacturer’s guidelines. The maximum operating temperature should not be exceeded to avoid additive depletion. High temperatures can rapidly deplete additives in the lubricant. A secondary heat exchanger should be considered and added to the system that will limit operating temperatures.

g. Filtration. Filtration can remove unsuspended additives. Proper pairing of oil temperature and filtration is needed for a system. The filter system will have a preferred fluid temperature range that needs to be coordinated with the supplier operating temperatures that allow additives to stay suspended. Alternatively, the temperature of the oil should be raised to a re-suspension level before filtration to avoid stripping the oil.

h. Mixing Different Lubricants. The additive packages between lubricants from different manufacturers are not always compatible. This is primarily due to incompatibility between additives. When servicing an oil lubricating system, the existing and new oils must be compatible. Oils that are rated for similar applications but that were 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.

i. Substitution Chart. 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 do not suggest or imply that lubricants listed as being equivalent are identical or that the additive packages are compatible. The lists do indicate that the two lubricants are in the same class, have the same 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.

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CHAPTER 6

Filtration

6-1. Oil Filtration, Purification, and Water Control.

a. General. Contamination of hydraulic and lubrication systems is a major cause of machinery failure and affects component wear and reliability. Fluid cleanliness is critical to establish equipment reliability. Proper filtration improves fluid cleanliness, which results in longer fluid life. Also proper filtration makes equipment more reliable, and reduces the need for machinery maintenance, lowers component replacement costs, and lessens downtime. Most damage-causing particles in hydraulic and lubrication systems are smaller than 14µm (microns) and cannot be seen by the unaided eye (Note: 1 micron = 1 millionth of a meter or 25 microns is approximately equal to 0.001 in.).

b. Oil Contamination and Testing Program. Oil must be free of contaminants to perform properly. Most hydraulic and other lubrication systems use an inline filter to continually filter the oil while the system is operating to maintain the required cleanliness rating in accordance with the ISO standard discussed below. An examination and inspection of filter elements should be done on a periodic basis. This will allow and provide an indication for the proper service intervals of machinery and equipment. A lubrication testing and monitoring system shall be established, followed, periodically accessed, and adjusted for all hydropower plants, locks, dams, and other similar USACE facilities. Filter, flush, or purify oil periodically as dictated by the results of the oil testing program and per ASTM D6439. New oil should be filtered before being used in machinery especially hydraulic fluid, turbine oils, and gearbox oils. Water is the most common contaminant found in hydroelectric plants and is also commonly found in many other equipment lubrication systems such as gearboxes. 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, promote sludge formation and foaming, and restrict oil flow within the system. This chapter will provide some of the most common methods used to remove contaminants from oil. This chapter will also provide some general guidelines for flushing lubricating oil systems.

c. New Oil Filtration. In many cases, new oil can be the dirtiest oil in the system and plant. The containers used to store lubricants are often reused and may be subjected to many extreme conditions before they reach the end user. Lubricant manufacturers are not required to ensure the cleanliness of the lubricant they provide unless it is advertised as meeting a specified cleanliness rating, or the cleanliness rating is written into the lubricant purchase specification. For all hydropower plants (turbine oils), locks, dams, and other similar facilities, the cleanliness rating of new oil and lubricants should be written into the specification. In addition, the specifications should require testing and certification of the supplied oil before acceptance and installation of oil in the facility or system. The ISO cleanliness codes are discussed later in this chapter. Oil out of shipping containers is usually contaminated to a level above what is acceptable for most hydraulic systems. The oil from shipping containers typically has a cleanliness level about the same as ISO 4406 Code 23/21/19, and water content could be as high as 200 to 300 ppm. Most hydraulic systems require ISO cleanliness levels much lower than this. Routine analysis of new oils should be employed to ensure effective contamination control. New oil should be introduced to the system through sufficient filtration to meet minimum system cleanliness levels.

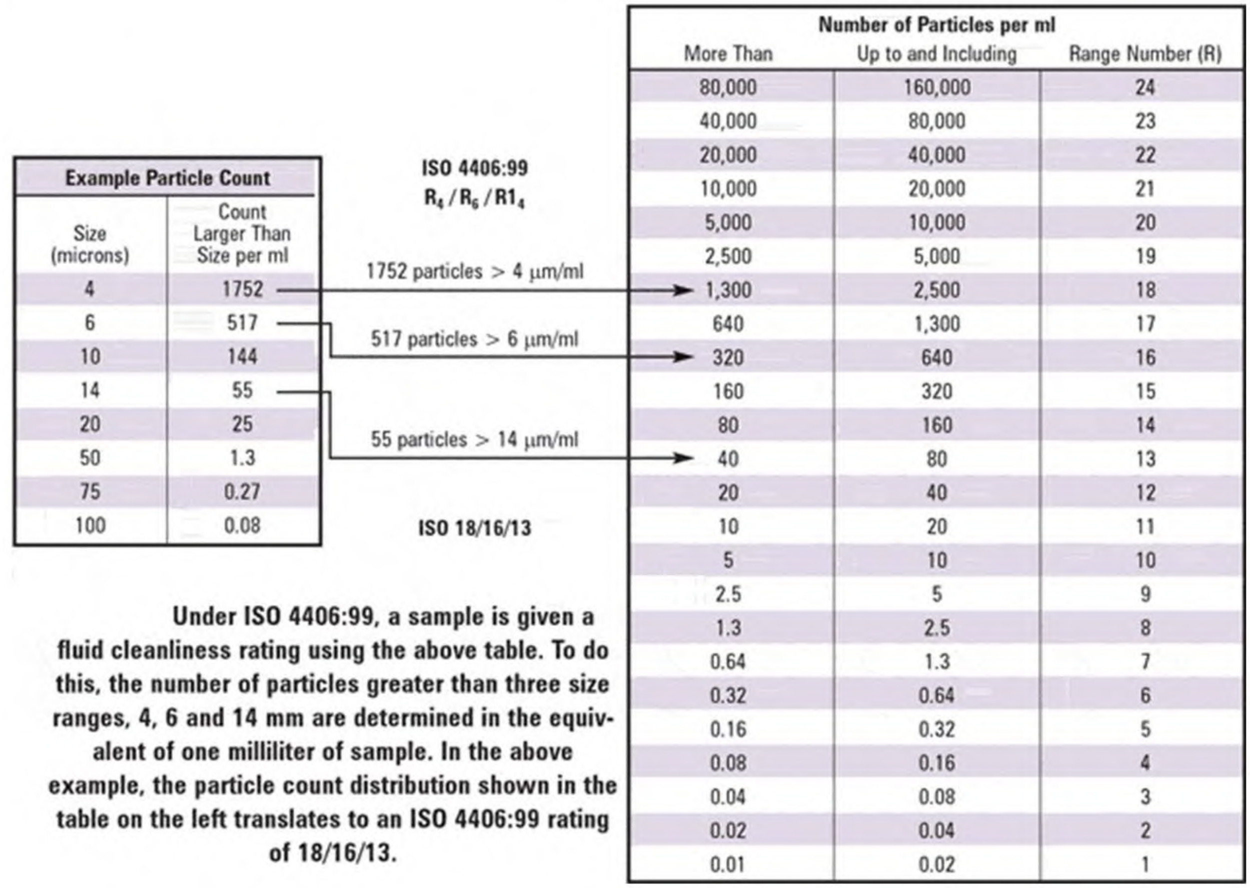
d. Oil Purification and Filtration. The terms oil "purification" and "filtration" are often used interchangeably. Filtration can be considered a primary means of contamination control and is often provided by the equipment manufacturer. This is typically done using mechanical filtration and media. It is intended to filter out the larger contaminants and particles. Oil purification is often referred to as secondary filtration above and beyond the initial primary filtration. It is intended to extend the life of the oil by cleaning it, filtering out the smaller contaminants, and removing water. The advantage of oil purification is not only that it extends the life of the oil, but also that it extends the life of the equipment by keeping oil clean. This chapter provides a general overview of filtration and purification and discusses several methods of oil filtration and purification. Chapter 9 includes more specific discussion on filtration related to turbine oils. Chapter 10 provides specific discussion on filtration related to hydraulic systems. Table 7-2 in Chapter 7 lists specific and targeted cleanliness codes for bearings, machinery, etc. The equipment manufacturer should also be consulted for their recommendation, especially for new equipment.

6-2. Methods for Particle Counting.

a. ISO 4406 (1999) "Hydraulic fluid power – Fluids – Method for coding the level of contamination by solid particles" is an internationally recognized standard that expresses the level of particulate contamination of a hydraulic fluid. This is the preferred standard for particle counting. This standard is also used to specify the required cleanliness level for other oils and systems. ISO 4406 is a hydraulic cleanliness rating system that is based on a number of contamination particles in a 1-milliliter (ml) 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. 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-ml sample for each size category. The first number represents the number of particles present measuring greater than 4µm. The second represents particles greater than 6µm and the third represents those greater than 14µm.

b. Other Standards for Measuring Contamination of Fluids. Other standards are available for particle counting, but are not as widely used. The SAE J1165 "Reporting Cleanliness Levels of Hydraulic Fluids," was and still is used extensively, but has been recently cancelled and superseded by ISO 4406. This classification system uses a two number system based on the number of contamination particles greater than 5 µm and 15 µm. It is important to have the testing firm document the standard they are using for contamination testing. Testing at USACE facilities should be done using the current three number ISO 4406 standard. Sometimes a testing firm will use the current ISO rating system, but only use two numbers. If only two numbers are used, then the 4µm number is deleted and the 6µm and 14µm numbers are used.

c. The ISO 4406 standard uses a three number system to classify system cleanliness, e.g., 18/16/13. As noted above, the first number represents the number of particles present measuring greater than 4µm, the second represents particles greater than 6µm, and the third represents those greater than 14µm (Figure 6-1). Table 6-1 lists the ISO 4406 range numbers. As the range number increases by one value, the number of particles in a sample of oil will double. On the range code, each number is double the range below. For example, an oil with a code of 19/17/14 should contain twice as many particles in each size category as the code of 18/16/13. For critical components, particle counting and testing should be repeated to confirm the ISO rating.



Example Particle Count

Size (microns)	Count Larger Than Size per ml
4	1752
6	517
10	144
14	55
20	25
50	1.3
75	0.27
100	0.08

ISO 4406:99
$R_4 / R_6 / R1_4$

1752 particles > 4 µm/ml

517 particles > 6 µm/ml

55 particles > 14 µm/ml

ISO 18/16/13

Under ISO 4406:99, a sample is given a fluid cleanliness rating using the above table. To do this, the number of particles greater than three size ranges, 4, 6 and 14 mm are determined in the equivalent of one milliliter of sample. In the above example, the particle count distribution shown in the table on the left translates to an ISO 4406:99 rating of 18/16/13.

Number of Particles per ml		
More Than	Up to and Including	Range Number (R)
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

Source: ***Noria Practical Handbook of Machinery Lubrication*** **(Noria 2011)**

Figure 6-1. ISO 4406:99 Method for Rating Fluid Cleanliness.

Table 6-1. ISO 4406 Range Numbers.

Number of Particles per ml		ISO 4406 Range Number
Greater Than	**Less Than**	
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

Number of Particles per ml		
Greater Than	**Less Than**	**ISO 4406 Range Number**
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

d. Hydraulic Components. Chapter 10 provides a discussion of hydraulic systems in more detail. Hydraulic systems are especially vulnerable to particle contamination. Many hydraulic system failures are a direct result of fluid contamination. Proper filtration reduces operating costs and improves reliability of hydraulic machinery. In a hydraulic system, the liquid is both a lubricant and a power-transmitting medium that is also under high pressure. The presence of solid contaminant particles in the liquid interferes with the ability of the hydraulic fluid to lubricate and causes wear to the components. The extent of contamination in the fluid has a direct bearing on the performance and reliability of the system. Table 6-2 shows some typical required ISO ratings for hydraulic machinery. Chapter 10 provides some more specific requirements. As noted above, Table 7-2 in Chapter 7 also lists more specific and targeted cleanliness codes for bearings, machinery, etc. Also, as previously noted, the equipment manufacturer should be consulted for their recommendations for required cleanliness ratings, especially for new equipment. In new hydraulic system installations, it is important to flush and clean the system before it is operated. The reader should refer to UFGS 35 05 40.14, *Hydraulic Power Systems for Civil Works Structures* (May 2014) for hydraulic cleaning and flushing requirements. ASTM D6439 also provides guidelines for flushing and cleaning hydraulic systems.

Table 6-2. Typical Required ISO Ratings for Hydraulic Equipment.

Components	**ISO Code**
Servo control valves	16/14/11
Proportional valves	17/15/12
Valve and piston pumps/motors	18/16/13
Directional and pressure control valves	18/16/13
Gear pumps/motors	19/17/14
Flow control valves, cylinders	20/18/15
Source: Courtesy of Vickers Hydraulics.	

6-3. Filter Ratings and General Discussion.

a. Beta rating. The Beta rating expresses the separating effectiveness of a filter. Beta ratings are an important piece of information for selecting filter elements. These ratings give an idea of how efficient a filter element will be at removing various particle and contamination sizes. It provides a method of comparing filter performance based on efficiency. This is done using the Multipass test, which counts the number of particles of a given size before and after fluid passes through a filter. The Beta rating comes from the ISO 16889 standard. ISO 16889, "Hydraulic fluid power - Filters - Multipass method for evaluating filtration performance of a filter element," is an industry standard used to evaluate filter element performance. During the Multipass test, fluid is circulated through the circuit under precisely controlled and monitored conditions. The differential pressure across the test element is continuously recorded, as a constant amount of contaminant is injected upstream of the element. The test provides a method to determine the filtration efficiency, using what is called the "beta ratio." The beta ratio is in turn used to calculate the filtration efficiency.

(1) The Beta Ratio equals the ratio of the number of particles of a minimum given size (in microns) upstream of the filter to the number of particles of the same size and larger found downstream, i.e., the higher the Beta Ratio the higher the capture efficiency of the filter; the lower the Beta Ratio, the worse the efficiency. As the particle size becomes larger, it is generally easier for a filter to remove it. Therefore, for larger particle sizes, the Beta Ratio is usually larger. The Beta Ratio then, βx, = Number of Particle X size upstream/Number of Particles X size downstream.

(2) Assume that 50,000 particles >10 μm were counted upstream of the filter and 250 particles >10 μm were counted downstream of the filter. The Beta Ratio would be $\beta 10(c) = 50000/250 = 200$. A Beta rating of $\beta 2=200$ means that, for every 200 particles greater than 2 microns that entered the

filter, only one particle would leave the filter. For most equipment in hydroelectric power plants, a β5 = 200 filter is sufficient, but if cleaner oil is desired, a β2=200 can be used. Before using extremely fine filters, the oil manufacturer should be contacted to verify a recommendation for a minimum filter rating. Some additives may be filtered out of the oil if the filter medium is too fine.

(3) The efficiency of the filter can be calculated directly from the Beta Ratio. The efficiency is stated as (βx-1/βx) x 100. A Beta 1000, 5-micron filter is thus said to be 99.99% efficient at removing 5 micron and larger particles. A Beta Ratio of 200 would have an efficiency of 99.5%.

(4) Caution must be exercised when using Beta Ratios since they do not take into account field operating conditions such as pressure surges and changes in temperature, which can affect real life performance. A filter's Beta Ratio also does not give any indication of its dirt-holding capacity, the total amount of material that can be trapped by the filter throughout its life, nor does it account for how the capture efficiency changes over time. Nevertheless, Beta Ratios are an effective way of gauging the expected performance of a filter.

(5) The ISO standard for Multipass filter testing (ISO 16889) has changed to require filter manufacturers to determine the average particle sizes that yield Beta Ratios equal to 2, 10, 75, 100, 200, and 1000, again using the multipass test stand approach. The new standard gives a better interpretation of a filter's overall performance.

b. Absolute Rating. Filter manufacturers will sometimes provide an absolute rating. An absolute rating means that no particles greater than a certain size will pass through the filter, based on the maximum pore size of the filtering medium. It can also be considered the diameter of the largest hard spherical particle that will pass through a filter under specified test conditions. This is an indication of the largest opening in the filter elements. However, most particles in oil are not spherical. A general industry definition for absolute rating is to state the micron size at which the filter achieves a Beta Rating of 75 or is 98.7% efficient.

c. Nominal Rating. "Nominal rating" is not an industry standard, but an arbitrary value assigned by the filter manufacturer. The nominal rating value indicates 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.

d. Filter Sizing. Filter sizing is critical. One of the easiest ways to prolong the filter change-out interval is by simply over sizing the filter. Never use coarse filters in an attempt to obtain longer filter life. If contamination levels are high and it is necessary to change filters often, obtain and install larger filters of the same quality to increase dirt capacity. Filters can also be installed in parallel to increase dirt-holding capacity. Another option is to use a series of filters with the higher micron contaminants removed first. It is important to size filters for cold startup oil viscosity. This can be from 3 to 30 times the operation viscosity, and can cause pressure drop upstream of the filter. Suction strainers and filters must be oversized. Install off-line filtration, kidney filtration, or use filter carts to further filter and purify the oil and control small contaminants.

e. Differential Pressure Indicators. Filters should be provided with a differential pressure indicator. The viscosity of the oil and flow rate will determine the pressure drop across a filter.

The normal situation is for the differential pressure across a filter to increase with time. This indicates particles are collecting on the filter elements and reducing the size of the pores in the filter and increasing the efficiency. However, it is not a good practice to schedule filter replacement by relying solely on reading of a differential pressure across the filter, because it fails to indicate the following conditions: bypass valve stuck open, ruptured filter media, or a faulty differential pressure indicator. The cleanliness of the oil must be checked if the pressure differential across a filter has dropped. This indicates the efficiency of the filter has decreased and the ISO 4406 particle count of the oil has increased. This type of scenario also could indicate either a filter of poor quality or the filter is failing.

f. Filter Replacement and Oil Testing. The Particle Counting Test (ISO 4406) is the best method to use in the process of scheduling filter replacement and checking the system's efficiency and contamination of oil. A portable particle could be used for an onsite analysis. The instrument allows personnel to have instantaneous information of the efficiency for all filtration systems at their powerhouse or lock and dam site.

g. Gearbox Filtration. If replacing the oil in a gearbox, make sure to drain the oil within 15 minutes of shutdown. Also, pre-filter any new oil. Alternatively, instead of draining the oil, periodically filter the oil with a portable filtration cart while the machine is operating. Another option is to use a dedicated kidney filter discussed below. Site staff should sample and analyze the oil periodically to determine if it needs to be changed. This strategy will reduce the overall cost of maintenance and extend the life of the gearbox. New gearboxes should be cleaned and flushed per ASTM D6439.

6-4. Filtration and Purification.

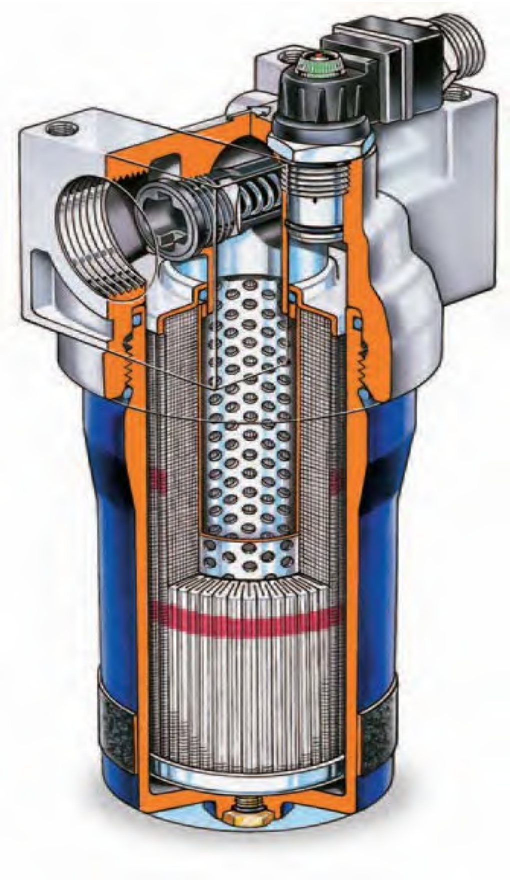
a. Gravity Filtration. Gravity filtration or purification is the separation or settling of contaminants that are heavier than the oil. Gravity separation occurs while oil is in storage, but is usually not considered an adequate means of purification for most applications. Other filtration methods should also be used in addition to gravity separation.

b. Mechanical Separation – Filter Media (Most Common). Particulate removal is typically done with mechanical filters. Mechanical filtration removes contaminants by forcing the oil through a filter medium with holes smaller than the contaminants. Mechanical separation uses either full flow or depth filtration to filter and purify the oil. These types of filters are very simple to operate and maintain. Mechanical filters with fine filtration media can remove particles as small as 1 micron, but filtration under 5 microns is not recommended because 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.

(1) A number of different filter media are available. The job of the media is to capture particles and allow the fluid to flow through. For fluid to pass through, the media must have holes or channels to direct the fluid flow and allow it to pass. Filter media is a porous mat of fibers that alters the fluid flow stream by causing fluid to twist, turn, and accelerate during passage (Figure 6-2). The fluid changes direction as it comes into contact with the media fibers. As the fluid flows through the media, it changes direction continuously as it works its way through the maze of media fibers. As it

works its way through the depths of the layers of fibers, the fluid becomes cleaner and cleaner. Generally, the thicker the media, the greater the dirt-holding capacity it has. Course media will have lower pressure drop, but less efficiency. Fine media will have greater pressure drop, but more efficiency.

(2) There are two common types of filters: surface or membrane filters and depth filters. Surface filters simply trap particles on the surface or face of the filter. Depth filters allow the oil to flow throughout the body or depth of the filter and trap particles throughout the media. Common filter media include cellulose fiber, glass fiber, and synthetic media. The efficiency depends on pore sizes and their depth.



Source: Courtesy of Parker Hydraulic Filtration.

Figure 6-2. Typical Mechanical Filter for a Hydraulic System.

(3) Cellulose media are primarily used in low pressure applications. They have low initial cost. Cellulose fibers are actually wood fibers, microscopic in size and held together by resin. Fibers are irregular in both shape and size. Cellulose often has lower Beta ratings, which means there are smaller pores in the media. Smaller media pores will cause more flow resistance, resulting in higher pressure drop.

(4) Fiberglass media have moderate initial cost. They have high capture efficiency and dirt-holding capacity. Generally they have more pores per square inch and consistent pore size and dirt-holding capacity. They have a higher dirt-holding capacity and tolerate high temperatures.

(5) Synthetic fibers are smooth, rounded, and provide the least resistance to flow. Their consistent shape allows for control of the fiber size and distribution pattern throughout the media mat to create the smoothest, least inhibited fluid flow. Consistency of fiber shape allows the maximum amount of contaminant-catching surface area and specific pore size control. The result is media with predictable filtration efficiencies at removing specified contaminants and maximum dirt-holding capacity. The low resistance of synthetic media to fluid flow makes it ideal for use with synthetic fluids, water glycols, water/oil emulsions, hydraulic fluids, and petroleum-based fluids. Synthetic fibers also perform better in the harsh environments that tend to destroy cellulose filters.

(6) Maintenance considerations. Install inline filters in an area that one can easily and readily access the filter media and any indicator (such as a delta-P indicator) to promote proper maintenance. For example, only add a filter in the pump suction line if it is placed where it does not require draining of a reservoir, and has a delta-P indicator that is visible. It is far worse to have a clogged filter starve and fail the pump than to have some particles enter the pump.

c. Centrifugal Separation. Centrifugal filtration is gravity separation accelerated by the centrifugal forces developed by rotating the oil at high speed. These systems use a spinning bowl or disc to separate both water and solid contamination from the oil. They use heat and full flow media to aid in purifying the oil. 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. Centrifugal systems can be complicated to operate and are difficult to maintain and usually require special training. Instead of filtering the mixture of solid and liquid particles, the mixture is centrifuged to force the (usually) denser solid to the bottom, where it often forms a firm cake. The liquid above can then be decanted. This method is especially useful for separating solids that do not filter well, such as gelatinous or fine particles. This type of filtration usually does not work well with high viscosity oils.

d. Coalescence Purification. A coalescing filter system uses special cartridges to combine small, dispersed water droplets into larger drops. These systems bring water molecules together with each other for gravity to separate the water from the oil and to allow for draining the water off of the system. They use full flow or depth media to aid in purifying the oil. 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. Coalescing systems are simple to operate and maintain, but are not always reliable. Temperature, flow rate, and oil type affect coalescing efficiency. This type of system does not work well with hydraulic oils and some turbine oils (Type II).

e. Adsorptive Separation (Chemical Process). 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 many oil additives, this method should not be used for turbine oil purification.

f. Electrostatic Separation (Electrostatic Filter). This type of system can purify oil to very low ISO contamination levels. The operation is based on the electrostatic principle of opposite attraction. It removes all charged particles regardless of their size. Unlike conventional filtration, electrostatic filtration has the ability to remove sub-micron sized particulate without the need for expensive absolute rated filtration media. This technology works on the principle of electrostatic and electromagnetic attraction of positively and negatively charged particles for sub-micron cleaning to ISO levels of 10/7/0. It is commonly used on transformer oils.

g. Vacuum Dehydration. A vacuum dehydration system (Figure 6-3) 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 100º F to 140º F (38ºC to 60º C). 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. Vacuum dehydration can be complicated to operate and does require special training. This system is usually easy to maintain and is very effective for water removal. It is capable of removing dissolved water down below 5 ppm. These systems are always coupled with media-based filtration. They are useful for not only removing free and emulsified water, but also can remove dissolved water. This system is useful in hydraulic systems, gear oils, lubrication oils, and turbine oils (regardless of base oil type). Vacuum dehydration does not work well with high viscosity oils.

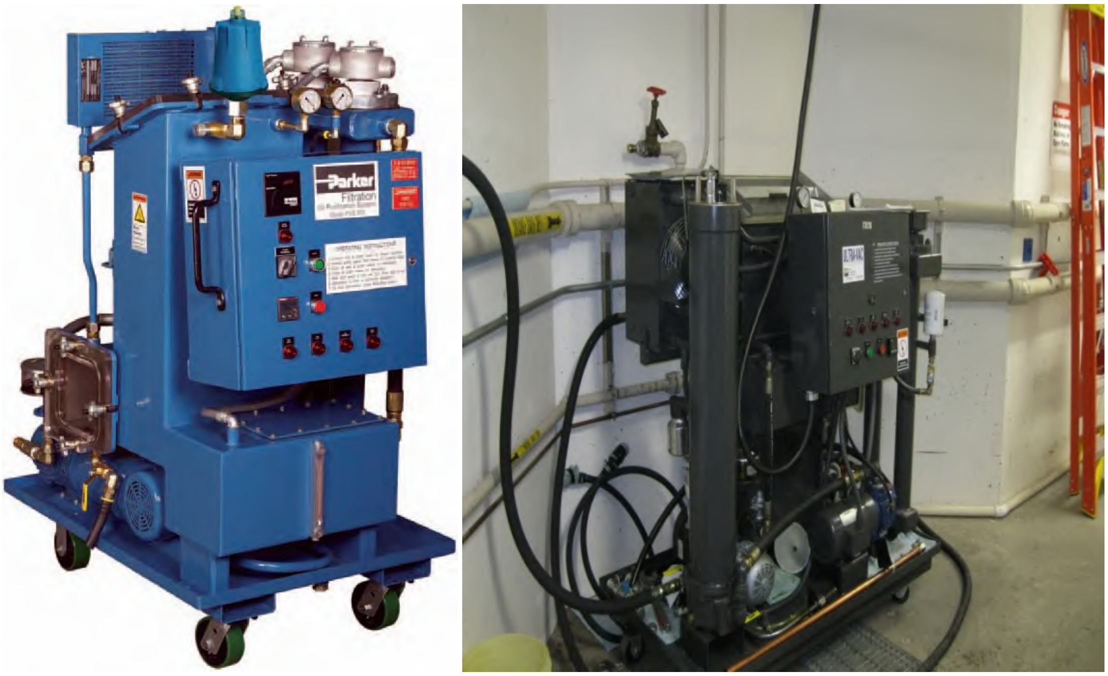


Figure 6-3. Vacuum Dehydrator.

h. Off-Line Filtration Kidney Loop. One very effective way of ensuring thorough fluid conditioning is with a dedicated off-line circulation loop, or “kidney” loop. This system uses a separate circulation pump that runs continuously, circulating and conditioning the fluid. Multiple stages and types of filters can be included in the circuit, as well as heat exchangers and inline immersion heaters. A sampling valve for testing the oil can also be incorporated into the kidney loop system. Kidney loop filtration has been used effectively in many applications such as turbine systems, vacuum pumps, and gear boxes (Figure 6-4).

Figure 6-4. Kidney Filter for a Gearbox.

i. Benefits of Off-Line Filtration. There are many benefits of off-line filtration. This type of filtration can be used to filter the first full tank of fluid to the desired cleanliness levels before the main system pump is started. The off-line (bypass) system is not only capable of achieving a low level of contamination, but by using this system for topping-up, it can eliminate the dangers inherent to the normal methods of adding fluid. Changing the element does not involve stopping the main system so filter maintenance can be planned, scheduled, and carried out at designated time. If the system is left running continuously, it provides a complete tank of very clean fluid ready for every startup. Since most off-line filtrations systems are additions to existing or off-the-shelf system, the user should ensure the proper location of system fluid removal and reintroduction ports to promote the best circulation of fluid without impact to the primary system.

j. Filter Carts. When using a filter cart, the oil is taken from a dirty sump, filtered, and returned to the dirty sump. The cleanliness of the filtered oil is diluted by the dirty oil still residing in the tank. To overcome the dilution effect, the tank volume must pass through the filter approximately seven times to achieve the equivalent of single-pass filtration (where the oil is pumped from one container to another through a filter). For example, with a 30-gallon tank and a filter cart that pumps at 5 gallon gallons per minute (gpm) (18.93 L/min), the cart will need to operate for 42 minutes to equal single-pass filtration (30 gallons multiplied by 7, divided by 5 gpm; or 113.5 L multiplied by 7, divided by 18.93 L/min).

6-5. Water Contamination and Removal.

a. A number of techniques exist to prevent water or moisture ingression or to remove water once it is present in a hydraulic or lubrication oil system. The best choice of technique for removal depends on the whether or not the water exists as a separate phase (dissolved or free), and also on the quantity of water present. For example, the presence of water or moisture can be reduced or prevented from entering a fluid reservoir through the use of bladder type reservoir isolators, absorptive or desiccant breathers, or active venting systems. Water can enter a system through worn seals or through reservoir openings. Condensation is also a prime water source. As the fluids cool in a reservoir or tank, water vapor will condense on the inside surfaces. A simple "crackle" test will give some indication of the level of water in the oil. However, the oil should be tested to give a true reading of water contamination.

b. In an oil lubrication system, water is present in either a dissolved form, emulsified form, or a free form. All new lubricating oils will have some level of dissolved water, typically 50 to 100 ppm. The saturation point of an oil at a given temperature is the maximum amount of water the oil will dissolve (Table 6-3). Water contamination can be dissolved (completely mixed with the oil) and the fluid may look clear at lower water content, below the saturation point. At higher water content levels, above the saturation point, the water is "free" or "emulsified" and the fluid looks milky. The saturation point varies greatly depending on the type of lubricating oil. Free water will eventually settle to the bottom of a reservoir or tank since its density is higher than that of oil. The temperature of the oil has a significant role in how much water can be dissolved. The higher the oil temperature, the more water that can be dissolved in the oil. When draining off water from a reservoir, the oil should be allowed to cool.

Table 6-3. Typical Saturation Points of Different Fluids. Note That These Can Vary Greatly Depending on Temperature and Type of Oil.

Fluid Type	**PPM**	**Percent**
Hydraulic Fluid	300	0.03%
Lubrication Fluid	400	0.04%
Transformer Fluid	50	0.005%

c. Methods of Water Control. Prevent moisture from entering a fluid reservoir by using absorptive breathers or active venting systems (Table 6-4). For free water in smaller amounts, use water absorbing filters or active venting. Free water may collect and settle to the tank bottom where it can be simply drained out. Vacuum dehydration, coalescence, and centrifuge methods are more extreme methods of water control. However, for large quantities of water, vacuum dehydration, coalescence, and centrifuges are appropriate techniques for water removal. Each of these techniques operates on different principles and has various levels of water removal effectiveness. Gravity separation can also be considered another method of water control.

Table 6-4. Water Prevention and Removal Techniques.

Technique	**Usage**	**Prevents Humidity Ingression**	**Removes Dissolved Water**	**Removes Free Water**	**Removes Large Quantities of Free Water**	**Limit of Water Removal**
Bladder Type Reservoir Isolator	Prevention	Y				N/A
Adsorptive Passive breather	Prevention	Y				N/A
Active Venting system	Prevention and removal	Y	Y	Y		Down to <10% saturation
Water-Absorbing Cartridge Filter	Removal			Y		Down to <100% saturation
Cartridge	Removal			Y	Y	Down to <100% saturation
Coalescer	Removal			Y	Y	Down to <100% saturation
Vacuum Dehydrater	Removal		Y	Y	Y	Down to <-20% saturation
Source: Courtesy of Donaldson Hydraulic Filtration 101.						

(1) Gravity separation. Because water generally has a higher specific gravity than lubricating and hydraulic oils, water tends to settle at the bottom of the reservoir, given sufficient resident time in a still environment. Increasing the fluid's temperature and employing a cone-shaped separating tank improve the effectiveness of gravity separation. High fluid viscosity, oxidation byproducts, and polar additives and impurities inhibit the effective separation of oil and water. Gravity separation alone does not remove tightly emulsified or dissolved water.

(2) Centrifuge separation. As discussed previously, by spinning the fluid, the difference in specific gravity between the fluid and the water is magnified. Centrifugal separators remove free water more quickly than do gravity separators. They also remove some emulsified water depending on the relative strength of the emulsion vs. the centrifugal force of the separator. Centrifugal separators do not remove dissolved water. They are an excellent option for continuous decontamination of fluids with excellent demulsibility (water-separating characteristics).

(3) Coalescing separation. Coalescing separators help small droplets of water combine to form large ones so they will drop out of the oil more easily. This is achieved because large droplets have less surface contact with the fluid than an equal volume of water dispersed as tiny droplets. Coalescing separators are more effective when the oil's viscosity is low, making them an ideal solution for removing water from fuel. Coalescing separators do not remove dissolved water.

(4) Absorbent polymer separation. Free and emulsified water is collected by super absorbent polymers impregnated in the media of certain filters. The water causes the polymer to swell and remain trapped in the filter's media. They are not well suited for removing large volumes of water, but they are a convenient way to maintain dry conditions in systems that do not normally ingest a lot of water. These filters do not remove dissolved water.

(5) Vacuum dehydration. This technique effectively removes free, emulsified, and dissolved water. It is one of the only systems that will remove dissolved water. These devices effectively

remove water at a temperature that does not cause much damage to the base oil or additives. There is some risk of additive vaporization with this technique. Vacuum dehydration is used extensively in hydroelectric plants.

d. Effects of Water. New oils will typically have 50 ppm to 100 ppm dissolved water. Water in lubricating oil has a number of detrimental effects. It affects both the oil and equipment. Water will eventually breakdown the base oil and additives. It creates sludge and acids in the oil. For the machinery components, water will create rust and corrosion. In high enough concentrations, it will damage filters. Water promotes oxidation of the lubricant's base oil. It hydrolyzes (chemically attacks) additives, compromises their performance, and washes them out of oil. It produces highly corrosive byproducts. A water-degraded lubricant cannot fully lubricate and protect the machinery components, which leads to excessive wear and failure.

(1) Rust and corrosion. Water directly attacks iron and steel surfaces to produce iron oxides. Water teams up with acid in the oil to increase the corrosive potential in the attack of ferrous and nonferrous metals. Rust and corrosion lead to rapid surface deterioration since rust particles are also abrasive. Abrasion also exposes fresh nascent base metal, which is more easily corroded in the presence of water and acid.

(2) Cavitation. If the vapor pressure of water is reached in the low pressure regions of a machine, such as the suction line of a pump, the preload region of a journal bearing, etc., the vapor bubbles expand. When the vapor bubble is exposed to sudden high pressure, such as in a pump or the load zone of a journal bearing, the water vapor bubbles quickly contract (implode) and simultaneously condense back to the liquid phase. The water droplet can then impact a small area of the machine's surface with great force in the form of a needle-like micro-jet, which causes localized surface fatigue and erosion (Figure 6-5). Water contamination also increases the oil's ability to entrain air, thus increasing gaseous cavitation.

Figure 6-5. Cavitation Damage on a Hydraulic Pump.

(3) Rolling element bearings and film strength loss. Water greatly affects rolling bearings and decreases their lifespan. Water contamination increases contact fatigue (spalling failure) caused by surface-to-surface rolling contact in elastohydrodynamic (EHD) contact region of rolling element bearings and also the pitch line of a gear tooth. The strength of the lubricating film occurs because the oil's viscosity increases as pressure increases. Water does not possess this property. Its viscosity remains constant (or drops slightly) as pressure increases. As a result, in these high pressure zones, hydrogen-induced wear occurs, causing embrittlement and blistering. A small amount of water in the contact zone of bearings will cause loss of the oil film and damage to the bearing surface.

6-6. <u>Cleaning and Flushing</u>. New hydraulic systems, turbine systems, and gearboxes need to be cleaned and flushed before going into operation. The manufacturing process of hydraulic systems can leave behind machine slag and residue. Hydroelectric turbine systems need to be cleaned and flushed during oil replacement. After the emergence of new paraffinic (Group II) oils, flushing became one of the most important steps in turbine oils replacement process. ASTM D6439 provides a general guide for cleaning and flushing these systems. The benefits of filtration and purification of oil lubrication systems can be significantly reduced if the lubricating systems are not initially cleaned to a level that will prevent component damage on initial startup after manufacturing or rebuilding.

a. Thorough cleaning and flushing is required to minimize and remove contaminants during fabrication, rebuilding, or installation of hydraulic, turbine, and other mechanical systems. Because contaminants will remain from these processes, it is necessary to flush and purify the system to remove them before startup. In new systems, the emphasis is on the removal of contaminants introduced during manufacture, storage, field fabrication, and installation. In operational systems, the emphasis is on the removal of contaminants that are generated during operation. Failure of systems and components can also occur during machinery operation, which can also introduce contaminants.

b. Flushing is an important part of preventive maintenance for all rotational equipment and systems. Flushing oil lubrication and hydraulic systems should be designed as a part of the lifelong maintenance program. A means for flushing these systems should be included in the design phase and incorporated into the plans and specifications. Once samples from the system indicate the specified cleanliness level has been reached, continue flushing for at least 30 more minutes at turbulent flow. This increases the probability of removing adherent particles from tube walls. The flushing fluid should be compatible with the fluid used during normal system operation. Perform new cleaning and hot oil flushing after component changes, assembly, disassembly, or similar procedures have occurred. The original filters in the system should not be used as flushing filters. Dedicated flushing filters should be used. The flushing filter is important for two essential reasons. First, it determines the final cleanliness level, and second, it determines the rate at which this level can be reached.

c. Reservoirs. This is one of the most difficult components of a system to flush. The system reservoir should be cleaned manually then filled with flushing fluid. Use a flushing pump with an inline filter to circulate and flush the reservoir.

d. Cylinders, Accumulators, Motors, and Pumps. Clean these separately. The components that have bidirectional movement must be actuated to full movement (stroke) to achieve volume flow of at least 10 times their internal volume. Hydraulic manifolds, blocks, motors, reservoirs, assemblies, and components should be delivered clean according to a specific procedure. If not delivered clean, they must be flushed separately.

e. Cleaning and Flushing Methods. There are a number of cleaning and flushing methods in industry. Some of the more common methods are listed below.

(1) Filtration carts. This is the probably the simplest of the flushing strategies. Because many machines, gearboxes, etc. have no onboard filtration, the use of filter carts and oil reclamation equipment not only can clean the oil (drawing down the contaminant level), but can also remove loosely deposited sludge and sediment.

(2) High turbulence, high fluid velocity, low oil viscosity. The approach involves increasing fluid velocity up to turbulent levels (sometimes two to four times the normal flow rates) and/or reducing oil viscosity during the flush. The Reynolds number should exceed 4000. Typically, a Reynolds number in the range of 4,000 to 6,000 is generally targeted. By circulating hot oil or a flushing fluid through the piping of a system at a very high flow rate, turbulent flow can be achieved that dislodges particles that would otherwise cling to the walls during laminar flow. These particles are then removed from the piping as the fluid is circulated through a series of high efficiency flushing filter elements. Typically, filter elements are replaced throughout the flushing process.

(3) Hot oil flushing. This strategy is similar to the high turbulence and high velocity approach listed above. In addition, it increases oil solvency to aid in the scrubbing of tenacious deposits. Target temperatures range from 175 to 195 °F (79.4 to 90.6 °C). Generally speaking, the required cleanliness level to target during hot oil flushing is half the level during normal operation. For example, if the normal operation level is ISO 15/13/11, flush to an ISO14/12/10. Requirements for cleanliness levels of both solid particles and moisture should be achieved. The coldest part in the flushing loop should have a minimum temperature of 122 °F (50 °C). This can be achieved by using a minimum flushing fluid supply of 140 °F (60 °C). In certain cases, this can be achieved only by insulating certain parts of the loop.

(4) Pulsating oil flow. This involves rapidly changing oil flow rates. This in turn can help dislodge contaminants.

(5) Mechanical cleaning and tools. This tactic is used for wet sumps, gear boxes, and reservoirs that have a convenient access to hatches and clean-out ports. One option is to use a wand or nozzle on the end of a flushing hose to create high velocity oil flow to blast away deposits. Alternatively, a wand can be used like a vacuum that can be effective at picking up bottom sediment on the sump floor. Mechanical cleaning can also involve the use of scrapers, brushes, abrasives, and sometimes an ultrasonic bath. Machine components can also be washed one at a time using a parts-cleaning station and chemicals.

(6) Chemical cleaning. System components can be chemically cleaned. Chemically active cleaning compounds, typically caustics and acids, help remove the most adherent organic and inorganic surface deposits. The oil must first be removed completely from the system. Following the flush, the cleaning chemicals should be thoroughly rinsed from the system. Always consult machine and lubricant suppliers before using chemical flushes.

CHAPTER 7

Oil Monitoring and System Sampling and Testing

7-1. Description.

Oil sampling is the most critical aspect of oil analysis. Failure to obtain a representative oil sample impairs all other oil analysis efforts. Oil sampling and testing can be performed for several different purposes including:

- Purchasing new oil to verify oil properties.
- Testing the health of in-service oil.
- Testing oil after reconditioning such as filtration or dehydration.

a. The most common application is testing in-service oil. Oil monitoring serves as a maintenance tool to not only check the condition of the oil, but the condition of the machinery. It can be used as a way to prevent failures, or sometimes as a way to do a failure analysis. This chapter is intended for hydraulic oil, lubricating oil, compressors, engines (e.g., Figure 7-1), gear oil, and turbine oil. This chapter does not cover transformers since they require insulating (not lubricating) oil.

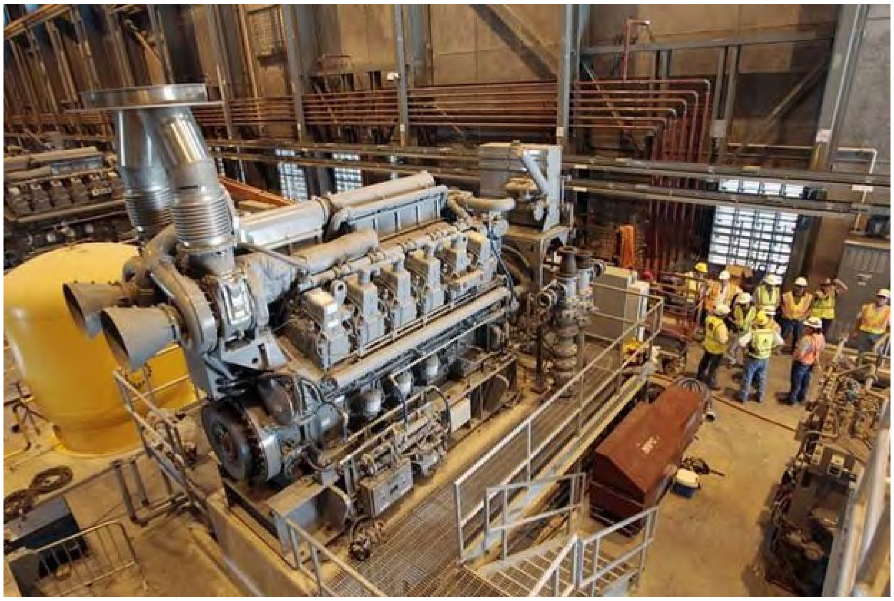


Figure 7-1. Diesel Engine for Pump Drive.

b. For turbine oils, the general requirements for testing in ASTM D4378, "In-Service Monitoring of Mineral Turbine Oils for Steam, Gas, and Combined Cycle Turbines," are a good starting point. However, there is some tailoring that is needed to make it more suitable for hydro applications. ASTM D6224, "In-Service Monitoring of Lubricating Oil for Auxiliary Power Plant Equipment," provides useful guidance for auxiliary systems including hydraulic systems, compressors, engines, and gears (e.g., Figure 7-2).

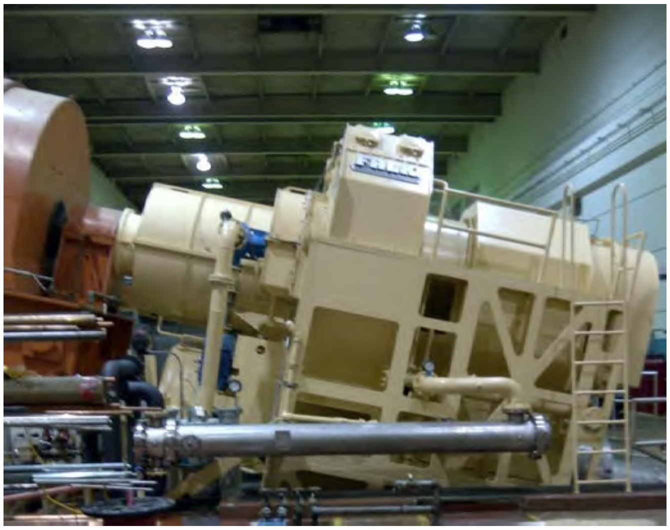


Figure 7-2. Gear Box (2:33,800 hp)

7-2. Guidelines for When to Sample.

All USACE facilities, including navigation sites, field sites, and hydropower sites, shall establish an oil sampling and testing program for their equipment. This chapter provides some guidelines on sampling frequency and testing requirements. Establishing an appropriate sampling frequency depends on several factors:

- Is a predictive or proactive strategy being used?
- What is the age of the machine?
- What is the age of the oil?
- What are the consequences of failure?
- How severe is the environment and what is the life expectancy of the lubricant?
- Has there been a history of oil related issues?

a. There is no one correct answer that applies to all systems. Most users will probably want a more simplified answer to this question. In ASTM D6224, the default recommended frequency for most types of industrial systems is 3 months. For civil works features such as locks and dams, a minimum sampling frequency of once per year should be established. On certain systems, where more information about the system is available, this sampling frequency can be refined.

b. One example would be turbine oil. Each subsystem, the bearings, the governor, and the turbine have its own unique characteristics. As far as oxidation, the thrust bearing has the most severe environment. However, if excessive foam is passing through the pumps, there can be more oxidation occurring in the governor system. For each of these systems, a once per year sampling is recommended. Life expectancy of the lubricant in this application is 20 to 40 yrs. On a system with more extreme operating conditions, the rate of change of properties will be faster, and the sampling frequency must be more frequent.

c. Enclosed Gear Boxes. AGMA 9005-E02, Annex E and F, provides some guidance for gear boxes or gear reducers. The higher the operating speed, the more often sampling and testing should be performed. Sump/splash lubricated gear drives many times do not have a filtration system. In these cases, the lubricant may need to be changed on a time scheduled basis to minimize the presence of particulate and/or water contamination. Routine oil sampling and condition analysis, when practical, are beneficial for all enclosed gear drives. The oil should be replaced when its degradation or level of contamination exceeds predetermined limits.

7-3. <u>How To Sample</u>. The sample(s) taken must be representative of the oil in the system. The procedures must ensure that samples can be taken without adding contaminants to the sample. Consistent sampling procedures are necessary for consistent repeatable results. Oil samples should be collected when the machine is running under normal conditions. This ensures that insoluble material is suspended evenly throughout the system. Contact the lab to determine the volume of sample that they need. The information below summarizes sampling methods. For more detailed information, consult ASTM D4057-2006, “Standard Practice for Manual Sampling of Petroleum and Petroleum Products.”

a. Oil Sample Bottles. Samples should be taken in a suitable sample bottle. To be suitable, the bottle must be clean. Visual inspection should verify that there is no contamination. If there is any doubt, flush the bottle with the sample fluid. Normally, the best solution is to obtain sample bottles from the test lab. The lab can supply “Clean” bottles that contain less than 100 particles (>10µ) per milliliter of bottle volume. “Super Clean” bottles contain less than 10 particles (>10µ) per milliliter of bottle volume. “Ultra Clean” bottles contain less than one particle (>10µ) per milliliter of bottle volume. The bottle must have chemical resistance to the fluid being sampled. Bottles and packaging must be suitable for the shipping and handling method used. The bottle volume must be adequate for the tests performed. It is best to verify required volume with the lab beforehand.

b. Sample Labels. A sample bottle must be properly labeled for identification. The equipment must be identified uniquely. Labels should contain at least the following minimum information: Customer name, location, machine identification, date, type of oil, sampling location.

c. Sampling of New Oil Deliveries. A sample of the new lubricant is required to establish conformance with the contract and to establish a baseline for new oil properties. Samples must accurately represent the in-service oil, not tank low spots or other anomalies that may have radically different test results. New oil might be delivered in drums, totes, or tankers. Inspection of the drums, totes, or tankers may be necessary to determine whether one sample or multiple samples from the shipment are necessary. If contamination is suspected, it may be necessary to sample from all the containers or all of the compartments from the tanker, or at different points of pumping out the full tank. For tankers especially, flush the sampling port adequately to ensure a representative sample. Different compartments of the tank may have contained different fluids or may have received different levels of cleaning.

d. Proper oil sampling is critical to an effective oil analysis program. Without a representative sample, further oil analysis endeavors are futile. There are two primary goals in obtaining a representative oil sample. The first goal is to maximize data density. The sample should be taken in a way that ensures that there is as much information per milliliter of oil as possible. This includes criteria such as cleanliness and dryness of the oil, depletion of additives, and the presence of wear particles being generated by the machine. The second goal is to minimize data disturbance. The sample should be extracted so that the concentration of information is uniform, consistent, and representative. It is important to make sure that the sample does not become contaminated during the sampling process. This can distort and disturb the data, making it difficult to distinguish what was originally in the oil from what came into the oil during the sampling process.

7-4. Where to Sample. Sampling ports should be located downstream of the components that wear and away from areas where particles and moisture ingress. Return lines and drain lines heading back to the tank offer the most representative levels of wear debris and contaminants. Once the fluid reaches the tank, the information becomes diluted.

a. Filters and separators remove contaminants. Therefore, they can remove valuable data from the oil sample. Sampling valves should be located upstream of filters, separators, dehydrators, and settling tanks unless the performance of the filter is being specifically evaluated.

b. In drain lines where fluids are mixed with air, sampling valves should be located where oil will travel and collect (Figure 7-3). On horizontal piping, this will be on the underside of the pipe. Sometimes oil traps, like goose necks, must be installed to concentrate the oil in the area of the sampling port. Circulating systems where there are specific return lines or drain lines back to a reservoir are the best choice for sampling valves. The best way to ensure that the fluids are turbulent and mixed is to sample from elbows instead of straight lengths of pipe. The best sampling locations are highly turbulent areas where the oil is not flowing in a straight line, but is turning and rolling in the pipe.

Courtesy of Noria Corporation and *Machine Lubrication* Magazine.

Figure 7-3. Sample Valve in an Ideal Location.

c. Sampling Location. The primary sampling port is the location where routine oil samples are taken for monitoring oil contamination, wear debris, and the chemical and physical properties of the oil. Possible locations include:

(1) Dipping from the tank. Oil samples can be taken by dipping from the tank. Lubricant should be thoroughly circulated before the sample is taken. All sample components must be absolutely clean for this method to minimize risk of sample contamination. Avoid the bottom and

surface of the tank. An ideal location is near the return line. An acceptable location is near the suction line or in the mid-elevations of the tank.

(2) Oil return line sampling port. For circulating systems, the preferred location for oil samples is on a single return line before entering the sump or reservoir. Flushing of the port is critical and sufficient flushing must be done to ensure that contamination in the port is removed.

d. Sampling from high pressure lines. Sampling from high pressure lines should be done using a Minimess sampling valve (Figure 7-4). Taking a sample from a high pressure hydraulic system requires the use of tools that ensure the safety of the technician drawing the sample. Pressure-reducing valves are widely used to reduce the system pressure to a safe level for drawing an oil sample. These valves are used in association with standard sampling accessories. Typically, a short micro-bore hose (2 mm nominal bore size) connects the sample port to the handheld pressure-reducing valve. The pressure-reducing valve then reduces the pressure from up to 5000 psig to an acceptable output pressure as low as 50 psig. A sample port adapter and clean sample tube are then attached to the outlet of the pressure-reducing valve.

Figure 7-4. Minimess sample Valve.

e. Secondary Sampling Methods. These are to be used for measuring contamination and wear debris contributed by individual components, and can be located anywhere on the system to isolate upstream components. Contamination and wear debris contributed by individual components will be found by:

(1) Sampling from a Line. The line should contain lubricating oil that is free flowing and not deadheaded. For instance, the lines in a bearing header, an active filter, and active heat exchanger are free flowing; the lines to a gauge cabinet are deadheaded. In equipment with dual filters or heat exchangers, the inactive filters or heat exchangers do not have flowing fluid and are not suitable

sampling points. When using a sampling line, it is necessary that the line has been thoroughly flushed before taking a sample. Adequate amount of flushing will depend on sampling line dimensions, length, and diameter. Test values obtained will differ depending on the sample locations. Use caution when comparing sample results from different sample points. Samples should be taken in the same manner each time to allow reliable trending of oil properties.

(2) Tapping from a reservoir. The lubricating oil must be thoroughly agitated in the reservoir and the tap line flushed before a sample can be taken.

f. An oil sample is probably not representative if: (1) the system oil is hot while the sample is cold, (2) the oil in the system is one color or clarity in a sight glass while the sample is a different color or clarity, and (3) the viscosity of the reservoir oil is different from that of the sample when both are at the same temperature. Note that, on occasion, a sample may be requested that will not be representative. At that time, sampling instructions, as specified by the requestor, must be followed. For example, a sample might be taken off the top or the bottom of a tank to check for contamination. In all cases, the sample point should be marked on the sample bottle.

7-5. Test Requirements. The tests to be performed depend on the application. Table 7-1 lists recommended tests for equipment common in civil works. Adjustments can be made based on the specific application. It is also acceptable to follow the guidance of ASTM D6224 for tests to be performed.

Table 7-1. Test Requirements.

Requirement	**Standard**
Gear oils. Also see AGMA 9005-E02 for further requirements	
Spectrochemical by ICP	ASTM D5185
Viscosity at 104 and 212 °F (40 and 100 °C)	ASTM D445
Water by Karl Fischer	ASTM D6304
Total Acid Number	ASTM D664
Oxidation Stability (EP oils)	ASTM D2893
Air Compressors	
Spectrochemical by ICP	ASTM D5185
Water by Karl Fischer	ASTM D6304
Viscosity at 104 and 212 °F (40 and 100 °C)	ASTM D445
Total Acid Number	ASTM D664
Grease	
Oxidation Stability	ASTM D942
Apparent Viscosity	ASTM D1092

Requirement	**Standard**
Extreme Pressure Properties (4 ball method)	ASTM D2596
Spectrochemical by ICP	ASTM D5185
Hydraulic Oil	
Spectrochemical by ICP	ASTM D5185
Water by Karl Fischer	ASTM D6304
Viscosity	ASTM D445
Total Acid Number	ASTM D664
Particle Count	ISO D4406
Infrared Spectrometry	ASTM E2412
Hydro turbine oils	
Viscosity Measurement at 104 and 212 °F (40 and 100 °C)	ASTM D445
Total Acid Number	ASTM D664
Spectrochemical by ICP	ASTM D5185
Particle Count	ISO 4406
Water by Karl Fischer	ASTM D6304
Viscosity Index (Calculated)	ASTM D2270
Foaming Characteristics	ASTM D892
Water Separability of Oils @ 129 °F (54 °C)	ASTM D1401
Rust Preventive Characteristics	ASTM D665
Copper Corrosion by Copper Strip	ASTM D130
Oxidation Stability (Rotating Pressure Vessel Oxidation Test [RPVOT])	ASTM D2272
Oil compatibility testing (if adding or replacing oil) (See Figure 7-5)	ASTM D7155
Diesel Engines	
Spectrochemical by ICP	ASTM D5185
Infrared Spectrometry	ASTM E2412
Viscosity	ASTM D445
Total Base Number	ASTM D974
Gasoline Engines	
Spectrochemical by ICP	ASTM D5185
Infrared Spectrometry	ASTM E2412

Requirement	**Standard**
Viscosity	ASTM D445
Total Base Number	ASTM D974
Transmissions	
Spectrochemical by ICP	ASTM D5185
Water by Karl Fischer	ASTM D6304
Total Acid Number	ASTM D664
Viscosity	ASTM D445
Particle Count	ISO D4406

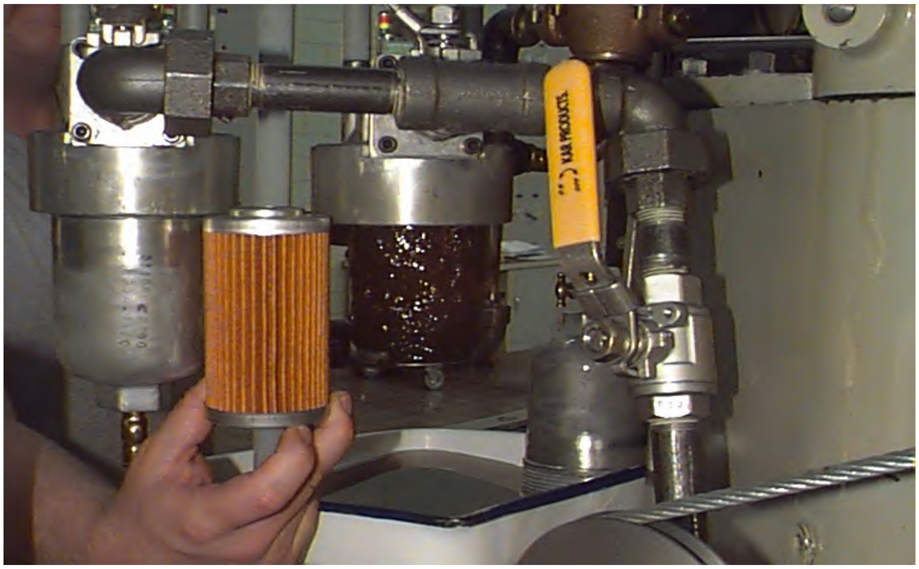


Figure 7-5. Varnish in a System That Resulted When ASTM D7155, "Oil Compatibility Testing," Was Not Performed.

7-6. Test Warning Limits.

a. Viscosity Measurement. It is common for viscosity to increase as the oil ages due to the addition of oxidation products. However, some oils can experience viscosity decreases. A significant change from baseline values is a red flag to look at other properties closely for degradation. Ways viscosity might decrease include, mixing of fuel with oil, electrostatic removal of oxides, shear thinning of VI enhancers, and cracking of lubricant. Ways viscosity can increase include addition of more viscous makeup oil, boiling off of light hydrocarbon fractions (solvents), oxidation, and polymerization. For industrial oils, a + 5% change in viscosity is at the caution level, and a +10% change is at the critical level. For engine oils, a +20% change is critical, +10% change is caution, - 5% is caution, and -10% is critical. For industrial oils, the viscosity should be measured at 104 °F (40 °C). For engine oils, the viscosity should be measured at 212 °F (100 °C).

b. Total Acid Number An acid number greater than 0.2 mg KOH /g is typically at warning level indicating that oil is degraded. An acid number of 0.4 mg KOH/g is considered at the critical limit. Acid number is an indicator of oil health. It is useful in monitoring acid buildup in oils due to depletion of antioxidants. Oil oxidation causes acidic byproducts to form. High acid levels can indicate excessive oil oxidation or depletion of the oil additives and can lead to corrosion of the internal components. By monitoring the acid level, the oil can be changed before any damage occurs. Acid number is measured by titration using ASTM D664 or D974.

c. Particle Count ISO 4406 Achieving better cleanliness will increase equipment life. Warning levels can vary somewhat depending on criticality of the system and expectations of equipment life and reliability. Figure 7-6 shows the general method of how ISO code is determined with particle counts >4µ, >6µ, and >14µ. In the example below, >4µ is 22, >6µ is 18 and >14µ is 13. ISO code is 22/18/13. Table 7-2 lists ISO target cleanliness codes for various equipment. These should be considered warning levels.

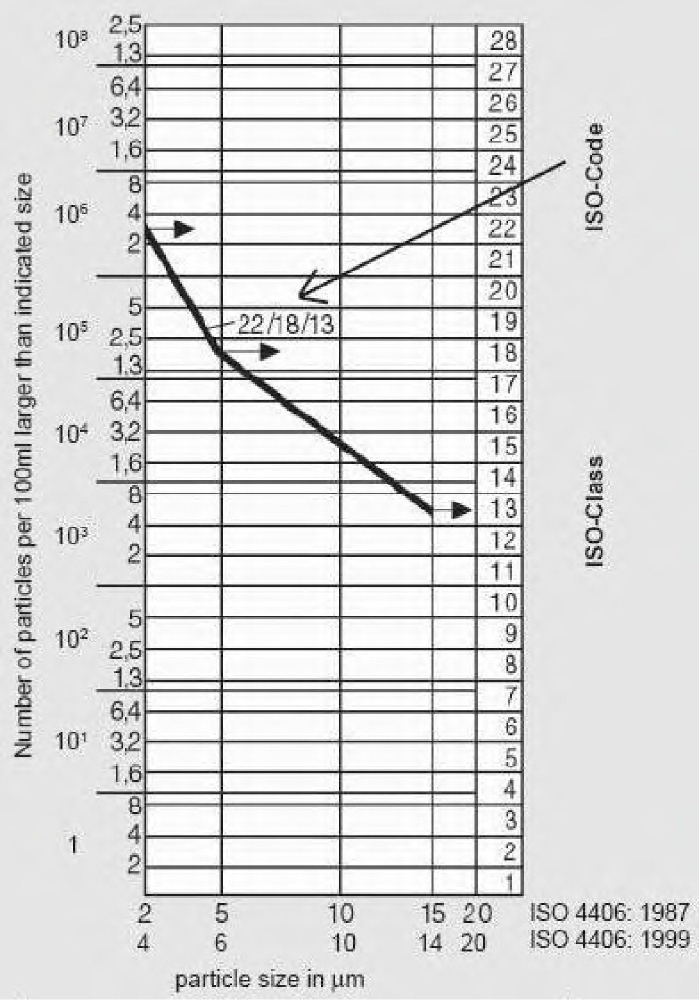


Figure 7-6. ISO Cleanliness Code.

Table 7-2. Recommended ISO 4406 Cleanliness Codes for Equipment and Components.

Pressure	**< 2000 PSI**	**< 3000 PSI**	**> 3000 PSI**
	< 140 Bar	**<210 Bar**	**> 210 Bar**
Pumps			
Fixed Gear	20/18/15	19/17/15	18/16/13
Fixed Vane	20/18/15	19/17/14	18/16/13
Fixed Piston	19/17/15	18/16/14	17/15/13
Variable Vane	19/17/15	18/16/14	17/15/13
Variable Piston	18/16/14	17/15/13	16/14/12
Valves			
Directional (solenoid)	20/18/15	19/17/14	
Pressure (modulating)	19/17/14	19/17/14	
Flow Controls (standard)	19/17/14	19/17/14	
Check Valves	20/18/15	20/18/15	
Cartridge Valves	20/18/15	19/17/14	
Screw-in Valves	18/16/13	17/15/12	
Prefill Valves	20/18/15	19/17/14	
Load-sensing Directional Valves	18/16/14	17/15/13	
Hydraulic Remote Controls	18/16/13	17/15/12	
Proportional Directional (throttle) Valves	18/16/13	17/15/12*	
Proportional Pressure Controls	18/16/13	17/15/12*	
Proportional Cartridge Valves	18/16/13	17/15/12*	
Proportional Screw-in Valves	18/16/13	17/15/12	
Servo Valves	16/14/11*	15/13/10*	
Actuators			
Cylinders	20/18/15	20/18/15	20/18/15
Vane Motors	20/18/15	19/17/14	18/16/13
Axial Piston Motors	19/17/14	18/16/13	17/15/12
Gear Motors	21/19/17	20/18/15	19/17/14
Radial Piston Motors	20/18/14	19/17/15	18/16/13
Swashplate Design Motors	18/16/14	17/15/13	16/14/12

Pressure	**< 2000 PSI**	**< 3000 PSI**	**> 3000 PSI**
	< 140 Bar	**<210 Bar**	**> 210 Bar**
Bearings			
Ball Bearing Systems	15/13/11*		
Roller Bearing Systems	16/14/12*		
Journal Bearings (high speed)	17/15/13	>400 RPM	
Journal Bearings (low speed)	18/16/14	<400 RPM	
General Industrial Gearboxes	17/15/13		
Turbines			
Hydro Turbines digital governor	15/13/10		
Hydro Turbines mechanical governor (recommended to minimize problems with current oils)	17/15/12		
Hydro Turbine bearing sumps	17/15/12		

a. Table 7-3 lists requirements for new turbine oil properties and the corresponding test standard.

b. Water in Petroleum Products ASTM D6304. Generally speaking, water content below 100 ppm is considered good. Vacuum dehydration systems can achieve much better results, but most systems use these only when oil is added into the machine. Water levels beyond 250 ppm are at a warning level. Water levels beyond 400 ppm to 500 ppm are critical. A simple crackle test can be used to determine if water is present in oil. A small volume of the lubricant is dropped onto a hot plate and, if bubbles or crackles occur, water is present. If a crackle test is positive, further testing is needed to quantify the amount of water by using Karl Fischer titration by ASTM D6304. A measured amount of oil is introduced into a titration chamber. This solution is titrated with Karl Fischer reagent to a specific endpoint. The amount of reagent used and the sample volume are calculated and converted to ppm or percent by mass.

c. Viscosity Index (Calculated) ASTM D2270. It is common for viscosity index to decrease with age and oil shear. A significant decrease from baseline values is a red flag. Look at other properties closely for degradation.

Table 7-3. New Turbine Oil Properties.

Chemical and Physical Characteristics	**Requirements ISO 68 Oil**	**Requirements ISO 100 Oil**	**Test Method**
Viscosity at 40 °C, centistokes (cSt)	64 – 70	95 – 102	ASTM D445
Viscosity Index, minimum	98	95	ASTM D2270
Flash Point, minimum, °C (°F)	204 (400)	210 (410)	ASTM D92

Chemical and Physical Characteristics	**Requirements ISO 68 Oil**	**Requirements ISO 100 Oil**	**Test Method**
Pour Point, maximum, °C (°F)	-9 (16)	-9 (16)	ASTM D97
Acid Number (AN) mg KOH/g, maximum	0.1	0.1	ASTM D664
Oxidation Stability by Rotating Pressure Vessel Oxidation Test (RPVOT), minutes, minimum	750	750	ASTM D2272
Rust Preventive Characteristics, Procedures “A” and “B”	Pass	Pass	ASTM D665
Water Content, parts per million (ppm), max	250	250	ASTM D6304
Water Separability of Petroleum Oil	40-40-0 (30)	40-40-0 (60)	ASTM D1401
Corrosion from Oil by Copper Strip Tarnish Test	Classification 1	Classification 1	ASTM D130
Foaming characteristics <u>After 5 minutes blowing period</u>:			ASTM D892 (Option “A” excluded)
Sequence 1, foam volume in ml, maximum	50	50	
Sequence 2, foam volume in ml, maximum	10	10	
Sequence 3, foam volume in ml, maximum	50	50	
Foaming characteristics <u>After 10 minutes settling period</u>:			
Sequence 1, foam volume in ml, maximum	0	0	
Sequence 2, foam volume in ml, maximum	0	0	
Sequence 3, foam volume in ml, maximum	0	0	
Air Release Properties, minutes, max.	30	60	ASTM D3427
Cleanliness, ISO Code Particle Count, particle sizes of greater than 4, 6, and 14 m (c)	17/15/12©	17/15/12©	ISO 4406 (ISO 11171)
Appearance	Clear and Bright	Clear and Bright	Visual Observation
Note: This table is for reference to show the typical new properties for hydro turbine oils.			

d. Foaming Characteristics ASTM D892. For a blowing period, a value greater than 50 ml, after 10 minutes settling is at the warning limit. Foaming will not result in short term failures, but if levels are higher, problems with oil degradation and operation will occur (Figure 7-7). It is generally not practical to keep adding antifoam additive. The critical level will be at a level greater than 50 ml and system operation is severely compromised and oil replacement would be needed. Some issues to check and address to mitigate foaming are: Leaking Pump Suction, Improper Returns to Reservoir, and Pump Cycle Time. It is important to note that water, oxidation, and contamination can all damage the antifoaming properties.

e. Water Separability of Oils @ 129 °F (54 °C) ASTM D1401. The warning level is 40-40-0 (30) Oil, Water, Emulsion (minutes). The first number is the thickness of the oil layer, the second is thickness of water layer, the third is thickness of emulsion layer, and the fourth is the time in minutes. The criticality of the numbers depends on the measured water content of the oil. In general, it is desirable to procure oil that readily separates and leaves no emulsion. Otherwise, it will become difficult to remove water completely from the system and there will be effects on other additives such as foaming characteristics.

Figure 7-7. Extreme Foaming in the Sump of a System in which ASTM D892 Antifoaming Properties Were Not Adequate.

f. Rust Preventive Characteristics ASTM D665. Using Procedure A with distilled water, and Procedure B with sea water, if any rust spot or rust streak is visible, confirmed by pits or roughness, the result is “fail.” This would be considered the warning limit as well.

g. Copper Corrosion by Copper Strip ASTM D130. This is a measure of copper corrosion in the presence of the oil due to sulfur compounds. A level of 2 or higher would be a warning limit.

- Level 1: slight tarnish or discoloration - a. Light orange b. Dark orange.
- Level 2: moderate tarnish - a. Claret red b. Lavender c. Multicolored with lavender blue or silver, or both, overlaid on claret red d. Silvery e. Brassy or gold.
- Level 3: dark tarnish - a. Magenta overcast b. Multicolored with red and green but no gray.
- Level 4: corrosion - a. Transparent black, dark gray or brown with peacock green barely showing b. Graphite or lusterless black c. Glossy or jet black.

h. Oxidation Stability (RPVOT) ASTM D2272. New oil should have a specified RPVOT of at least 750 minutes. It would be very valuable to know the baseline value of RPVOT for the specific oil in use. When the value drops to 25% of the original value, it is considered critical. The oil needs to be replaced. Due to the nature of how oxidation progresses, there is almost no usable life remaining in the oil. Anything approaching 25% of the original value is considered a warning limit.

i. Spectrochemical by ICP ASTM D5185. The test determines the concentration in ppm of elements in the oil including wear metals, contaminants, and additive metals. Wear metals include iron, aluminum, chromium, copper, lead, tin, nickel, silver, and vanadium. Contaminants contain silicon, sodium, and boron. Additive metals include zinc, phosphorous, calcium, barium, magnesium, cadmium, manganese, and titanium. For this test, trending is typically essential to track developing problems. If a baseline for the particular fluid is unknown, it is suggested that a sample of new oil be tested as well to establish what is "normal." In most cases, there will also be some guidance from the lab when concentrations exceed normal or acceptable levels. Spectrochemical analysis detects concentration of small particles. It is most accurate for particles less than 1 micron. For particles greater than 7 microns, accuracy decreases substantially.

j. Infrared Spectrometry (also Fourier Transform Infrared [FTIR] Spectrometry) ASTM E2412. This test is used to determine % fuel dilution, soot, oxidation, sulfination, nitration, and glycol. Fuel dilution can help diagnose problems such as leaking injectors, fittings, seals, or combustion characteristics. Testing for soot is helpful in determining if there is excessive blow by. Oxidation measures the amount of infrared light absorbed by oxidation products; this measure helps to determine usable life left in the oil. Sulfination measures the amount of infrared light absorbed by harmful sulfur compounds. Nitration measures the amount of infrared light absorbed by harmful nitrogen compounds. Glycol indicates coolant leaks into the oil such as those that would occur with a head gasket leak.

k. Total Base Number ASTM D974. This is a measure of the total reserve alkalinity in the oils additive package. Since combustion products are acidic, the reserve alkalinity is needed to accommodate for the acidity. Base numbers for new oil may range from about 5 to 12. Typically, when the base number has reached 50% of the original value, it is time to replace the oil. The rate of change increases as base number drops so at 50%, there is very little life left in the oil. If the original base number is not known, a sample of new oil should be tested to establish the baseline.

l. Oxidation Stability ASTM D942. This test is for oxidation stability of greases. The test apparatus is different from RPVOT used for oil, but interpretation of the results is similar. The original value of oxidation stability should be known. If it is unknown, a sample of new grease and used grease can be tested. When the value of oxidation stability, in hours, drops below 25% of the original value the grease has expended its useful life.

m. Apparent Viscosity ASTM D1092. Greases are non-Newtonian fluids, in which viscosity increases with load so typical viscosity measurements will not work with them. This test measures the apparent thickness of the grease and helps determine whether it has broken down. It is necessary to know the original value of this property for the grease, but if this is not available, perform the test on both an old and new sample.

n. Extreme Pressure Properties (four-ball method) ASTM D2596. This test measures the scar diameter versus applied load. It is useful for determining the extreme pressure properties of EP greases. It is important to know the original properties of the grease. If this is not available, perform the test on both an old and new sample.

7-7. Oil Monitoring Program.

a. The oil monitoring program should evaluate, track, and trend oil test data. The program should establish baseline data, especially on the following tests:

- Viscosity.
- Sufficiency of additives.
- Water content.
- Acidity.
- Oxidation stability.
- Trace metals content.

b. The program should set “warning” and “critical” limits. Test reporting and tracking software is available for assistance in managing the information. Some oil laboratories offer web-accessible programs and commercially designed web-based fee-for-service software is also available. More detailed guidance for oil monitoring for a variety of equipment, pumps, compressors, gears, diesel engines, electrohydraulic controls, and others is shown in ASTM D6224, “Standard Practice for In-Service Monitoring of Lubricating Oil for Auxiliary Power Plant Equipment.”

7-8. Laboratories.

a. Use of reputable laboratories is critical to success. This can be a challenge in the contracting environment. Many tests are inexpensive enough that a contract is not required. Once the trusted lab is found, it is highly preferred that the same lab be used for ongoing testing. It is still acceptable to use multiple laboratories as long as results are verified. One verification method is to send identical samples to two or more laboratories for testing. Other individuals or organizations with applicable experience may provide references to qualified laboratories.

b. It is possible to require the lab to prove proficiency through ASTM’s Hydraulic Fluids and Oils Proficiency Testing Program. For spectroscopy, it is possible to require the lab to calibrate according to ASTM D7578, “Standard Guide for Calibration Requirements for Elemental Analysis of Petroleum Products and Lubricants.” The ASTM D7155 Compatibility Test can present difficulties for laboratories that do not regularly perform the test. Since it is most commonly used for hydro turbines, it is not widely used by industry. Check with other references to help determine qualified laboratories for this test.

c. Test Reports and Interpretation. Competent laboratories issue a written test report with each laboratory test. Although formats may vary, a typical lab report includes acceptable limits and interpretation of results.

CHAPTER 8

Oil Storage, Handling, Disposal, and Safety

8-1. Lubricant Storage. 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 8-1 lists some causes of lubricant deterioration and prevention during storage. Additional information may be found in MIL-STD-3004C w/Change 1, Department of Defense (DoD) Standard Practice, "Quality Assurance/Surveillance for Fuels, Lubricants and Related Products" available from https://assist.dla.mil. MIL-STD-3004C details DoD recommendations on storage, shelf life, stock rotation, sampling, and storage stability of lubricants and packaged petroleum products. Chapter 16 also provides information regarding storage of lubricated mechanical equipment. All storage and handling of lubricants shall follow EM 385-1-1, *USACE Safety and Health Requirements*, 30 November 2014.

8-2. Storage and Degradation of Lubricants. Several considerations for lubricant storage to reduce degradation and contamination are discussed below, including temperature, moisture, and the storage environment. Lubricants need to be kept clean and dry to reduce contamination. All lubricants should be properly labeled and stored to prevent cross contamination and to ensure that the proper lubricant is used on the correct machinery.

a. Temperature. Lubricants should be stored at a constant, moderate temperature that is within the manufacturer designated range for the particular lubricant type. Generally speaking, lubricants should be stored between 32 and 68 °F (0 and 20 °C). Widely varying temperatures can expand and contract container seams causing leakage. Storage at extreme temperatures can cause separation of chemical elements and change the nature of the lubricant. Lubricants should be stored away from extreme heat sources that could cause fire or explosion. It is important to document the manufacturer specified storage temperature for each lubricant. Water-based lubricants and some fire resistant hydraulic oils cannot be allowed to freeze.

b. Moisture. Lubricants should be stored such that moisture cannot enter the storage container. Moisture causes oxidation of the lubricant's base oil and chemically degrades additives. Water contamination changes viscosity and reduces lubricant effectiveness, which leads to equipment wear, corrosion, and eventual failure.

c. Storage Environment. Lubricant should be stored indoors if possible where humidity can be kept to a minimum. Oils will naturally absorb moisture when exposed to humid air. If lubricant drums must be stored outdoors, they should be under shelter and covered with tarpaulin or a convex lid. Ensure that bungs are tight when drum is not being poured or filled. Drums should be stored on their side such that the bungs are at 3 o'clock and 9 o'clock positions to prevent water accumulation around the bungs. Wipe and dry drums before removing bungs. Drums should be stored off the ground. Ideally, storage racks should be used.

Table 8-1. Causes of Lubricant Deterioration and Their Prevention.

Cause	**Components Affected**	**Effect**	**Prevention**
		ATMOSPHERIC	
Oxygen	• Lubricants.	• Forms gums, resins, and acidic products with viscosity increase.	• Use lubricant containing anti-oxidation 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
	• Seals.	• Promotes slow cracking of natural rubber and some similar materials. • Negligible normally at ambient temperatures.	• Use of different polymer. • Do not store in hot place.
		Pollutants	
(e.g., sulfur dioxide, hydrogen sulfide)	• Engines and components. • Cables and wires. • 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 wear between bearing surfaces.	• Keep covered or in containers.
	• Engines and components. • Cables and wires. • Brakes and clutches.	• Increased rate of wear between bearing surfaces. • Promote corrosion in the presence of moisture.	• Keep covered or in containers.

Cause	**Components Affected**	**Effect**	**Prevention**
		TEMPERATURE	
Heat	• Lubricants.	• Increases rate of deterioration as under "Oxygen." • Will increase oil separation from greases.	• Keep stored temperature no higher than 68 °F (20 °C).
	• 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. • 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. • Belts, ropes, 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. • Belts and ropes, seals.	• Surface covered and attacked by mold growth.	• Store in dry location. Treat with biocide and fungicide.

Cause	**Components Affected**	**Effect**	**Prevention**
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. 1995. *A Tribology Handbook*. Butterworth-Heinemann Ltd., Oxford, England.			

d. Storage Vessel. Lubricant storage vessels need to be dry and airtight to prevent moisture contamination. Seals should be inspected for age, wear, and leakage. Partially filled containers can accumulate moisture in the headspace, which may require the use of a headspace dehumidifier or other means to reduce water infiltration.

e. Desiccant Breathers. The use of a desiccant breather on equipment sumps and reservoirs is recommended in cases of excessive or persistent water contamination. A desiccant breather provides ventilation of the storage vessel without allowing moisture and particulates to enter. Goose neck vents, breather caps, and vent plugs should be replaced with desiccant breathers.

f. Debris and Settlement. Lubricants should be protected against dust and dirt contamination. Particulate contamination can cause significant damage to equipment. Additionally, settlement of oil can affect performance if not properly accounted for. The following should be considered regarding debris and settlement:

(1) Storage environment. It is recommended that lubricant storage vessels be stored in a clean environment, preferably indoors. If they are located in a dusty area, a filter should be installed in the vent line.

(2) Storage vessel. Lubricant should remain in a sealed environment at all times. Ensure that reservoir lids are securely fastened and that seals do not have significant wear, aging, or leakage. If possible, keep drums elevated off the ground to prevent rusting and dust accumulation. Oil should be filtered before entering bulk storage tanks as well as when it is transferred into equipment. Ensure that vessel inlets and outlets are wiped clean to prevent dust accumulation. Lubricant containers should be inspected every 3 months for internal cleanliness, corrosion, and sediment buildup. At least annually, lubricant containers should be checked for damages. Filtered oil tanks should be periodically drained and thoroughly cleaned. Containers should be thoroughly cleaned before reuse.

g. Storage Stability. Some oil formulations will degrade over time. This can be due to settlement of additives. If stored for a long time frame, some formulations may require mixing and retesting before use to determine if the lubricant still meets intended performance levels.

h. Shelf Life. Over prolonged periods of storage, lubricants can break down and lose their performance. The shelf life of lubricants varies widely. The lubricant label or manufacturer should be consulted for recommended shelf life. As a general rule, oil storage should not exceed 5 yrs; a year or less is preferable. If lubricants are stored for long periods of time, testing should be done on an annual basis. This should include testing for water content. Grease should be stored for no more than 1 year as it may bleed or change consistency over longer storage periods. Stored lubricant stock should be rotated such that the oldest stock is used first. Most lubricants have supplier recommended shelf lives based largely on the lubricant's additive package. For example, lubricants containing rust inhibitors may lose performance after as little as 6 months in storage. Conversely, some turbine fluids with a light additive dose may be shelved for up to 3 yrs. Shelf life information is available from the lubricant supplier and/or manufacturer for each product used. Shelf life is typically based on ideal storage conditions. Most manufacturers provide a recommended storage procedure to maximize lubricant shelf life.

i. Used Oil Storage. Lubricants should be stored according to regulations set by Governmental agencies such as the USEPA, and the Department of Environmental Quality (DEQ). Local laws and regulations can vary and should also be consulted regarding the storage of used oils. As a general rule, used oil should be stored in double-walled containers with water-based, glycol-based, and synthetic oils stored separately from mineral-based oils. Containers should be properly labeled.

8-3. <u>Categories and Applications of Lubrication Storage</u>. The majority of hydroelectric plants use onsite storage facilities for lubricants in particular turbine oils. Lock and dam sites typically store lubricants in drums and containers. For hydroelectric plants, oil is stored in active oil reservoirs, where it is drawn as needed, and in oil drums for replenishing used stock. Each has its own storage requirements. Cleanliness levels and water contamination limits should be established for all oils and lubricants. All new oil should be filtered. At hydroelectric plants, all bulk truckloads of new turbine oil shall be tested for cleanliness and water contamination, and then filtered.

a. 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 (Figure 8-1). 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.

b. Oil Drums. If possible, oil drums should be stored indoors. If stored outdoors, oil drums should either be covered or provided with a covered shelter. Oil drums should be stored away from sparks, flames, and extreme heat. The storage location must ensure that the proper temperature, ventilation, and fire protection requirements are maintained. Maintain moderate and constant temperatures when storing indoors. 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. Ideally, bungs should be at 9 and 3 o'clock positions to minimize moisture migration and drying out seals. 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. Long term storage should not exceed 5 yrs and desiccant breathers should be installed as the sole source of storage vessel ventilation if used. Storage racks should be used to store drums when possible (Figure 8-2). Storage racks should be designed to fully support drums.

Figure 8-1. Hydroelectric Plant Turbine Oil Storage Tanks.

Figure 8-2. Typical Oil Storage Rack.

c. Tank Trucks. At some facilities and especially hydroelectric plants, these vehicles are used to transfer large quantities of lubricants to remote or isolated equipment. Because of the mobile nature of tank trucks and the variable environmental conditions that they may be exposed to, it is recommended that lubricants not be stored in these vehicles for any length of time longer than needed to execute transfer activities. This will mitigate the risks of contamination due to environmental conditions or faulty equipment such as failed seals or breathers. Additionally, it is during the transfer of fluids that most spills occur and contaminate the surrounding area. Preventive measures consist of protective curbing, spill cleanup kits, and drip pans. Minimizing the time that lubricants are in tank trucks also reduces the risk of oil spills due to failed valves or collisions.

d. Small Containers (Hand Held). Storage of small containers can present challenges. Because they are portable, there is a potential for storage in areas that are not ideal for oil storage due to variable environmental conditions. Small containers should be stored in a designated area with protected from the elements and other contaminants and located within independent containment curbing or equivalent. Small containers should have clear labeling indicating material data, compatibility, and flammability. Small containers should be sorted and stored using these labels.

e. Built-in Piping Systems. Some facilities require transporting oil or hazardous fluids from one location to another location. These systems should be treated like a storage vessel. Annual inspections should be performed to ensure that leaks are detected and that any hazardous material is remediated. Facility piping systems can be complex and can extend over large areas so it may also be necessary to protect features that would allow hazardous materials to enter the environment if a leak occurred. Frequency of use should also be considered. Oil that sits in a piping system for a prolonged period of time is at higher risk of contamination due to environmental conditions. If the oil transfer system is not needed for an extended period, then the oil should be drained back into the oil storage tanks and then flushed again before use.

f. Grease Storage. Because grease fundamentally differs from oil in composition and uses, it also has its own special considerations for storage:

(1) Grease drums and cartridges. 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 amount of grease in storage should not exceed a 1-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

(2) Grease delivery systems. Grease systems, such as automatic delivery systems (Figure 8-3), must also be considered as a type of storage system. Depending on the frequency of grease application, long grease lines may have grease in them for months or even years. These systems can often be exposed to the elements, as is the case for radial spillway gate trunnion bushings, and are subjected to many thermal cycles and periods of high and low humidity. Thus, by the time that the grease is applied to the bushings, it may be heavily degraded. Improvements to grease lines may be

made such as insulation. Another method for preventing negative impacts is, when feasible, to remove the automatic grease system and shorten the grease line. The equipment can then be manually greased via a shorter line guaranteeing that fresh grease is always applied to the equipment.

g. Table 8-1 lists some typical causes of lubrication deterioration and their prevention. The table addresses a number of causes of deterioration from dust and debris, to temperature, humidity, etc.

Figure 8-3. Automatic Grease-Dispensing System for Lock Machinery and Miter Gate Pintle

8-4. Lubricant Handling. When possible, lubricants should be handled in areas that are clean and dry. If this is not possible, measures should be taken to mitigate the exposure of the lubricant to the elements. This can be done by minimizing the amount of time that a lubricant container is open to the amount of time needed for transfer. Another method is to use oil or grease applicators such as grease guns and oil cans with positive locking connections to prevent intrusion by contaminants. Ensure that the connection points are clean before applying the lubricant. A filter cart (Figure 8-4) should always be used to transfer lubricating fluids and oils from barrel to equipment to remove any contaminants that may have entered the barrel while in storage or that came from the oil supply source.

Figure 8-4. Typical Filter Cart.

a. Labeling. Two common consequences of lubricant mismanagement are cross contamination and lubricant confusion. All drums must be clearly labeled and stenciled to ensure proper product identification. Avoid using labeling methods that are not legible or may wear out over time. Take extra care in the labeling of containers that must be stored outdoors since the elements may damage the label. Labeling shall follow 29 CFR 1910.1200 (the revised hazard ommunication standard, 2012). The standard requires workplace labeling in accordance with 1910.1200(f)(6). Each container of lubricant in the workplace shall be labeled, tagged or marked with either the labels provided by the distributor on the shipped containers or product identifier with words, pictures, symbols, or a combination thereof, which provide general information regarding the hazards of the lubricant. Color coding labels simplifies the process and reduces the risk of misapplication. If a color coding system is employed, be sure alpha or numeric information is also present.

b. Dispensing. Lubricant dispensing equipment often lies at the root of cross contamination problems. By dispensing oil through equipment that was previously used with a different lubricant, the two fluids mix, potentially causing lubrication impairment. Equipment such as transport containers, hand pumps, transfer carts, and filter carts should be labeled to match the lubricant to the equipment with which it will be used. Where mixing is unavoidable, verify compatibility in advance with the lubricant supplier. Extend the identification process to the machine’s lubricant fill ports. Using identification tags or color-codes helps to ensure that the proper lubricant is added to the reservoir fitted with the proper dispensing tools. If dispensing equipment must be used for a variety of lubricants, employ a proper cleaning or flushing procedure that emphasizes the removal of the previous lubricant and other contamination to minimize risk.

8-5. 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. Safety Data Sheets. When handled properly, most lubricants are safe, but when handled improperly, some hazards may exist. Occupational Safety and Health Administration (OSHA) Communication Standard 29 CFR 1910.1200 requires that lubricant distributors provide a Safety

Data Sheet (SDS) at the time lubricants are purchased. The SDS, which provides essential information on the potential hazards associated with a specific lubricant, shall be readily accessible to all personnel responsible for handling lubricants and stored on site. The lubricant's SDS shall provide at least the following information: identification, hazard(s) identification, composition/information on ingredients, first-aid measures, fire-fighting measures, accidental release measures, handling and storage, exposure controls/personal protection, Physical and chemical properties, Stability and reactivity, Toxicological information, Ecological information, Disposal considerations, Transport information, Regulatory information, and Other information, including date of preparation or last revision.

b. Exposure Limits. Contact with lubricants and greases should minimized and only done using the appropriate protective equipment. Lubricants and greases can contain many different hazardous chemicals at various concentrations. An Industrial Hygienist should evaluate each type of lubricant and grease and then provide an exposure limit for each lubricant or grease. Exposure limits established by OSHA or American Conference of Governmental Industrial Hygienists (ACGIH) will be used for evaluations. The most stringent limit shall be used. 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.

c. Personal Protective Equipment. Before handling grease or lubricants, gloves or barrier creams should be used to protect exposed skin. Overalls or other protective clothing should be worn to protect any areas of exposed skin. Equipment and surrounding areas should be cleaned after the work is complete. Contaminated disposable protective equipment should be processed per local regulation.

d. Hygiene. Work area cleanliness is important to reduce the risk of exposure, contamination, and injury. After oil-handling activities are complete, oil contaminated surfaces, tools, and equipment should be cleaned to remove oil or grease that could be easily transferred. Personnel should follow the procedures established by their local safety office and practice good hygiene for oil removal from skin and clothing to prevent prolonged exposure or contamination of off-duty clothing.

e. Safety Equipment for Facilities. Oil storage and handling areas should contain:

- Fire Extinguisher.
- Oil absorbent rags.
- Oil contaminated rag disposal container. (Only approved fire resistant containers should be used for oily rags.)
- Double-walled containment for used oil storage.
- Adequate Ventilation.

- Filter cart and associated oil transfer equipment.
- Adequate signage, labels, and Workplace Hazardous Information Sheets.

f. Service Contractors. Entities that are contracted for service by the Government shall be provided references deemed appropriate by the Contracting Officer. Contractors under contract shall abide by Federal regulations for workplace safety. Each project site's safety personnel should be involved with development of the contract requirements regarding oil-handling activities to ensure that the Contractor complies with project-specific requirements.

g. Fire and Explosion. 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. These conditions can be produced when oils are contained in enclosures such as crankcases, reciprocating compressors, and large gear boxes. The flash point of most lubricants is above 390 °F (200 °C). Solvents, however, can be much lower than this. Additionally, pressure relief devices, such as the ones found on electrical transformers, can increase the risk of explosion during a fire. Older style pressure relief valves are typically located on top of the transformer and vent in a 360-degree pattern. If a fire occurs at or near the transformer causing the pressure relief valve to vent, atomized oil can be sprayed directly onto the flame and cause an explosion. For this reason, directional pressure valves are recommended to be used to direct the oil down and away from the ignition source and into secondary containment. If the oil catches on fire, it will be much less dangerous as a burning pool of oil than as a cloud of explosive atomized oil.

h. 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 generally less flammable than mineral oils. Under normal circumstances, synthetic fluid will not support combustion once the ignition source has been removed. Refer to Chapter 10, which summarizes the properties of water-based and synthetic hydraulic fluids and notes special precautions that must be taken when they are used.

i. Fire Safety Requirements. Lubricant storage sites located within government facilities have specialized fire safety requirements. A fire safety engineer should annually evaluate each location to ensure the fire protection systems are adequate and safe to use with the stored materials per National Fire Protection Association (NFPA) 30 or 30A. The Unified Facilities Criteria (UFC) 3-600-01, Fire Protection Engineering for Facilities, also provides guidance. Other standards may be applicable as determined by a qualified fire protection engineer. Typical fire suppression methods are listed below however each system may vary depending on the types of lubricants stored:

- Overhead Sprinkler System.
- Dry chemical fixed extinguishing systems.
- Gaseous agent fixed extinguishing systems.

j. Fire Resistant Hydraulic Fluids. During the design of new equipment, designers should consider fire resistant hydraulic fluides when feasible. Use care when retrofitting existing systems as a new working fluid can generate additional maintenance issues. See Chapter 10 for more information on flame resistant hydraulic fluids.

8-6. Environmental Regulations. 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 Government such as the USEPA. 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.

a. 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 protecting the environment from contamination. 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. The Government Printing Office can be accessed online at http://www.gpo.gov/. The CFR can also be accessed at http://www.ecfr.gov.

b. 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.

c. The regulations discussed in this subchapter are current at the time (2014) 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.

d. Water Quality Regulations. The USEPA 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."

e. 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:

- Discharges that violate applicable water quality standards.
- Discharges that cause a film or sheen on or discoloration of the surface of the water or adjoining shorelines. Sheen means an iridescent appearance on the surface of the water.
- Discharges that cause a sludge or emulsion to be deposited beneath the surface of the water or adjoining shorelines.

f. Spill Prevention Control and Countermeasures (SPCC) Plan. 40 CFR 112 requires regulated facilities that have discharged or could reasonably discharge harmful oil into navigable U.S. waters or adjoining shorelines to prepare and implement an SPCC plan. The regulation applies to nontransportation related facilities provided:

> The facility's total above-ground oil storage capacity is greater than 1320 gallons (5000 L), or the above-ground storage capacity of a single container is in excess of 660 gallons (2500 L), or the total underground storage capacity of the facility is greater than 42,000 gallons (160,000 L). Only containers 55 gallons (208 L) or larger are counted toward total above-ground storage volumes.
>
> Facilities which, due to their location, could reasonably expect spilled oil to reach waters of the U.S.

g. General SPCC Plan Requirements. 40 CFR 112.7 provides guidelines for preparing and implementing a 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:

(1) 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.

(2) 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.

(3) Plans to remove and dispose of spilled oil.

h. Specific SPCC plan requirements include:

(1) Time limits. Prepare and implement the SPCC plan within 6 months from startup. Extensions may be authorized due to non-availability of qualified personnel or delay in construction or equipment delivery beyond the control of the owner or operator (40 CFR 112.3).

(2) Certification. A registered professional engineer must certify the SPCC plan and amendments (40 CFR112.3).

(3) Plan availability. Maintain a complete copy of the SPCC plan at an attended facility or at the nearest field office if the facility is not attended at least 4 hours per day (40 CFR 112.3).

(4) Training. Conduct employee training on applicable pollution control laws, rules and regulations, proper equipment operation and maintenance to prevent oil discharge. Conduct spill prevention briefings to assure adequate understanding of the contents of the SPCC plan (40 CFR 112.7).

(5) Plan review. Review the SPCC at least once every 5 yrs (40 CFR 112.5).

(6) Amendments. Certified amendments to the SPCC are required when:

> The USEPA Regional Administrator requires amendment after a facility has discharged more than 1000 gallons (3785 L) of oil into navigable waters in a single spill event or discharged oil in more than 42 gallons (159 L) quantities into navigable waters in each of two spill events within any 12-month period (40 CFR 112.4).
>
> Within 6 months if there is a change in design, construction, operation, or maintenance that affects the potential for an oil spill (40 CFR 112.5).
>
> The required 5-year review indicates more effective field proven prevention and control technology will significantly reduce the likelihood of a spill (40 CFR 112.5).

i. 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 42,000 gallons (160,000 L), or the facility’s total oil storage capacity is at least 1 million gallons (3.78 million liters) with conditions. Most Corps of Engineers civil works facilities do not fall under these categories.

j. Liability Limits. 40 CFR 113 establishes size classifications and associated liability limits for small onshore oil storage facilities with fixed capacity of 42,000 gallons (160,000 L, or 1000 barrels) or less that discharge oil into U.S. waters. 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 (Tables 8-2 and 8-3) as follows:

(1) Above-ground storage.

Table 8-2. Above-Ground Storage Classifications.

Size Class	Capacity (barrels)	Capacity (gallons)	Capacity (L)	Limit (dollars)
I	Up to 10	Up to 420	Up to 1,590 L	4,000
II	11 to 170	462 to 7,140	1,749 to 27,025 L)	60,000
III	171 to 500	7,182 to 21,000	27,184 to 79,485 L	150,000
IV	501 to 1,000	21,042 to 42,000	79,644 to 158,970 L	200,000

(2) Underground storage.

Table 8-3. Underground Storage Classifications.

Size Class	Capacity (barrels)	Capacity (gallons)	Capacity (L)	Limit (dollars)
I	Up to 10	Up to 420	1,590 L	5,200
II	11 to 170	462 to 7,140	1,749 to 27,025 L)	78,000
III	171 to 500	7,182 to 21,000	27,184 to 79,485 L	195,000
IV	501 to 1,000	21,042 to 42,000	79,644 to 158,970 L	260,000

k. 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.

l. Turbine Oil Accountability. Turbine oil accountability is a complex issue that will become increasingly important in the future. This manual will not discuss the issue in any detail or provide any specific guidance or recommendations. Turbine oil accountability at a hydroplant encompasses everything from the delivery truck to the storage tanks and into the hydroturbines themselves. A typical hydroplant utilizes thousands of gallons of turbine oil that has the potential to leak into the environment. It is anticipated that future technical reports will address this issue in more depth. Chapter 9 further discusses turbine oils.

m. Vessel General Permit. As of 28 March 2013, non-recreational vessels greater than 79 ft that are not vessels of the Armed Forces and that operate in a capacity as a means of transportation requiring National Pollutant Discharge Elimination System (NPDES) coverage for their incidental discharges will generally be subject to the Vessel General Permit (VGP). Similarly situated vessels less than 79 ft may be covered under the VGP, or may instead opt for coverage under the Small Vessel General Permit (sVGP). These permits apply to 26 specific vessel discharge categories. The use of Environmentally Acceptable Lubricants (EALs) in vessels is one of the ways to mitigate risks to the environment and gain compliance with the general permits. Operators of government vessels that are subject to the VGP and sVGP shall apply for and obtain these permits. More information is available in the USEPA publication titled "U.S. Environmental Protection Agency 2013 final issuance of its fact sheet titled *National Pollutant Discharge Elimination System (NPDES) Small Vessel General Permit for Discharges Incidental to the Normal Operation of Vessels Less than 79 Feet (sVGP).*