APPENDIX B

Grease and Oil Selection for Machinery

INDEX

Part 1 - Grease Selection - General Information Required. .....Page B-1
Part 2 – Grease Selection for Wide Applications. .....Page B-2
Part 3 Grease Selection for Bearings. .....Page B-6
Part 4 Grease Selection for Open Gearing.....Page B-8
Part 5 Grease for Wire Rope Applications .....Page B-10
Part 6 - Hydraulic Oil Selection. .....Page B-12
Part 7 - Gear Reducer Oil Selection.....Page B-15
Part 8 Turbine Oil Selection .....Page B-19

B-1. Part 1 - Grease Selection - General Information Required.

a. Selecting greases for:

- Open Gears (see Chapters 11 and 14).
- Couplings (see Chapter 16, Para. 16-4 for discussion).
- Anti friction bearings (see Chapter 15) see bearing lubricant selection process summary below.
- Journal bearings (see Chapter 15).
- Tainter gate trunnion bearings (see Appendix C and Chapter 16).
- Pump bearings (see Chapter 16).
- Wire Ropes (see Chapter 16).

b. **Step 1 - What Is the Application?** Base Oils will be mineral based (petroleum), bio-based, or synthetic. Environmentally Acceptable greases will use either bio-based or synthetic base oil. Table 11-2 provides a summary and listing of all the common soap types. Lithium and Calcium soaps can be used for a majority of applications in USACE. Higher temperature applications can use complex soaps.

(1) List all potential requirements and provide to and work with the grease manufacturer and equipment supplier.

(2) What is grease to be used for?

- Grease for general applications includes:
- Bearings?
- Wire Ropes?
- Couplings?

- Open Gears?
- Low Temperature Grease?
- High Temperature Grease?
- Environmentally Acceptable Grease?

c. **Step 2 – Determine Test Requirements.** Some common requirements and tests for greases (see Table 11-3 for a complete list and description) include:

- Prevention of Rust – ASTM D1743.
- Water Washout – ASTM D1264.
- Pumpability – ASTM D217 and ASTM D1092.
- Base Oil Viscosity – ASTM D445.
- Anti-Wear and Scuffing – ASTM 2596 and G99.
- Shelf life and Storage – ASTM D1742.
- Oxidation Stability – ASTM D942 and D2893.

B-2. Part 2 – Grease Selection for Wide Applications.

a. **Step 1 - Determine the performance properties of the grease.** Grease performance properties include many of the same properties used for lubricating oils, as well as others exclusive to grease. Properties exclusive to grease include dropping point (temperature where grease becomes liquefied), mechanical stability, water washout, bleed characteristics, and pumpability. The most important performance properties are determined by the application. If an application operates continuously at room temperature, properties like dropping and upper operating temperature limits are not as important. If an application operates under heavy loads at low speeds, load carrying tests such as four-ball EP or Timken OK load should be considered.

b. **Step 2 - Determine the required consistency of the grease.** The consistency of grease is controlled by the thickener concentration, thickener type, and the viscosity of the base oil. The NLGI has established a scale to indicate grease consistency that ranges from grades 000 (semifluid – like ketchup) to 6 (block grease – like cheddar cheese spread). The most common NLGI grade is 2 (like peanut butter) and is recommended for most applications.

c. **Step 3 - Determine the dropping point and low temperature operation of the grease.**

(1) The operating condition should be at least 100 °F (38 °C) below dropping point. The pour point of the base oil should be considered low temperature limit of the grease.

- Dropping point is an indicator of the heat resistance of grease, i.e., the temperature at which a grease becomes fluid enough to drip. The dropping point indicates the upper temperature limit at which a grease retains its structure, not the maximum temperature at which a grease may be used.

- Oxidation stability is the ability of a grease to resist a chemical union with oxygen. The reaction of grease with oxygen produces insoluble gum, sludges, and lacquer-like deposits that cause sluggish operation, increased wear, and reduction of clearances. Prolonged exposure to high temperatures accelerates oxidation in greases.
- Low-temperature effects. If the temperature of a grease is lowered enough, it will become so viscous that it can be classified as a hard grease. Pumpability suffers and machinery operation may become impossible due to torque limitations and power requirements. As noted above, the base oil's pour point is considered the low-temperature limit of a grease. This is critical to consider in cold weather applications and the base oil pour point should always be determined.

(2) For in-water lubrication several factors are critical. These include oxidation stability (aging), evaporative loss (volatility), hydrolytic stability (reactions with water), water wash off, and corrosion protection properties. In-water structures in locks and dams and hydro turbines may be subjected to strong water currents and possible cavitation. In particular, violent water currents can occur in the draft tubes that house the wicket gate bearings. Appendices H, I, and J, provide several technical reports for recommendation of in-water greases in hydro turbine applications.

d. **Step 4 - Determine the base oil selection.**

(1) There are three options available: mineral oil, synthetics, and bio-based oils.

(2) Mineral Oils**.** Most common grease lubricants are composed of petroleum fractions called mineral oils. These are medium to heavy weight refined fractions with viscosities ranging from 103 to over 140. NLGI 2, lithium based grease will work for a majority of USACE applications and is probably the most common. It is considered to be a true multipurpose grease and is a mineral oil based, lithium soap, or lithium complex thickened grease with excellent thermal stability within its operating temperature range. Lithium complex grease has a higher dropping point and should be selected when higher operating temperatures are required. Additives can be provided depending on specific requirements. This type of grease, which can work on open gearing, couplings, and bearings, has the following characteristics:

- Excellent oxidation stability.
- Good mechanical stability.
- Excellent water resistance and rust inhibiting properties.

NLGI 3 (semi-hard like vegetable shortening) mineral oil based, lithium soap thickened grease is an option for applications requiring stiff grease. Lithium complex soap, which can be used for higher temperature applications, has the following characteristics:

- Excellent rust inhibiting properties.
- High oxidation stability within its recommended temperature range.
- Bearings >100 mm (3.9 in.) shaft size.
- Outer bearing ring rotation.

- Vertical shaft applications.
- Continuous high ambient temperatures > 95 °F (35 °C).
- Suitability for use in such applications as propeller shafts and large electric motors.

For extreme pressure applications, NLGI 2 with EP additives, mineral oil based, lithium soap thickened grease can be used. This grease provides good lubrication in general applications subjected to harsh conditions and vibrations. For extreme pressure applications and wide temperature variations, NLGI 2 with EP additives and lithium complex soap can be used. For low temperature and extreme pressure, an option is to use NLGI 1 mineral oil based grease with a lithium soap and extreme pressure additives.

(3) Synthetic Base Oil Grease.

Synthetic greases should be considered for high temperature and low temperature applications. There are generally three options available for synthetic grease, including PAOs, esters, and silicones. All these are discussed in Chapters 4 and 11. For in-water applications, these greases also work better since they have better hydrolytic stability. Synthetic grease generally performs better than mineral oil based grease in the following respects:

- Better oxidation stability or resistance.
- Better viscosity index.
- Better high temperature stability and protection against breakdown.
- Better low temperature viscosity.
- Better hydrolytic stability (in-water applications).

(4) Environmentally Acceptable Grease Selection.

There are several options available for environmentally acceptable greases. The first consideration is the base oil type, of which there are three base oil types to consider:

- Synthetic ester base oil with a lithium/calcium soap thickener.
- PAO base oil with a lithium or lithium complex soap thickener.
- Bio-based base oil (canola oil, rapeseed oil, etc.).

USACE has established some basic guidelines and criteria for Environmentally Acceptable Lubricants (EALs). For a grease to be considered an EAL, the grease can meet any of the following three criteria (note that hydraulic oil will have same criteria):

1. Be a product labeled by Blue Angel, Swedish Standard, Nordic Swan, European Eco-label, and/or Ospar. Other product labeling could be considered by an Environmental Officer.

2. Be a product classified as USEPA Vessel General Permit (VSG) Appendix A compliant.

3. Have test data as specified in USEPA 800-R-2-001 or in USEPA Vessel General Permit document Appendix A indicating that it meets requirements for bioaccumulation, toxicity, and biodegradability. Such data may be presented as test reports or reported on product specification sheets.

ERDC has recently evaluated EALs for several hydro sites in Northwest Division and provided the results in a technical paper. This is provided in Appendix H. A summary of this discussion is provided here. "Huskey Specialty Lubricants produces two green lubricants that might be appropriate for use for in-water dam use, Ecolube EP2 and Hydrolube.[*] Ecolube EP2 is a vegetable oil fortified by anti-oxidant, pressure, and anti-wear and anti-corrosion additives, and can be used in high and low temperature conditions.[†] It is classified as readily biodegradable and contains no ozone depleting chemicals, no SARA Title 313 chemicals, no heavy metals, no greenhouse gases, no chlorine, no phenols, no volatile organic compounds, and no Proposition 65 chemicals. Water washout data is not provided for Ecolube EP 2. Hydrolube[‡] is particularly designed for high pressure, underwater environments found in hydroelectric dams. Like Ecolube, it does not contain any problematic chemicals or metals and is rated for incidental food and potable water contact. It comes in four grades, and has ASTM D1264 water washout values ranging from 0 to 1% depending on the grade.

VSG Wicket Gate Grease is an EAL that is used at Dworshak Dam, which is a Walla Walla District managed dam. General information on VSG is provided on the ECO Fluid website.[§] VSG is a canola oil based lubricant with a benign calcium sulfanate thickener that is readily biodegradable, and is designed for hydroelectric dam applications. It reportedly meets all performance standards. VSG reportedly offers excellent corrosion protection and is resistant to grease line plugging. It has excellent low temperature pumpability, yet stiffens on water contact, allowing it to stay in bearing. VSG grease has an ASTM D-1264 washout loss (at 175 °F [79.4 °C]) of 1.21%. VSG is reportedly compatible with more lithium based mineral oil greases.

Mobil Oil EALs. Mobil SHC 100 EAL series[**] consists of two products, 101 and 102. The SHC 100 series are designed to be high performance greases to be used in environmentally sensitive applications, and both the 101 and 102 products are registered EALs. The SHC 100 series are synthetic ester formulations and are reportedly readily biodegradable. Both were tested using the OECD 203 aquatic toxicity test (OECD 2013b), and were found to be "virtually non-toxic." Furthermore, both are specifically designed for in-water use for marine equipment, water treatment plants, and dams, locks, and waterways. As such, they have good adhesion and water resistance properties and offer excellent rust and corrosion protection."

---

[*] http://huskey.com/PRODUCTS/IndustrialGreases/igrl/1/app/igrl

[†] A specifications sheet is available through: http://huskey.com/Product/item/12/Ecolube-EP2

[‡] A specifications sheet is available through: http://huskey.com/Product/item/66/Hydrolube

[§] http://fluidcenter.com/vsg.html; the technical sheet is available for download theough: http://fluidcenter.com/pdf/vsgtechdata.pdf

[**] http://www.mobil.com/USA-English/Lubes/PDS/GLXXENGRSMOMobil_SHC_Grease_100_EAL_Series.aspx

B-3. Part 3 Grease Selection for Bearings.

a. **Step 1- Determine proper base oil viscosity.** Base oil viscosity is important because too high a viscosity will overheat the bearing. Too low of a viscosity will result in improper lubrication of bearing and could result in bearing damage. There are several common methods for determining minimum and optimum viscosity requirements for rolling element bearings, most of which use speed factors, commonly denoted as DN. See Chapter 15 for further discussion on different types of bearings and calculation procedures. The bearing manufacturer can also help determine proper base oil viscosity.

b. **Step 2 – Additives and Base Oil Type.** Once the viscosity has been determined, additives need to be evaluated and the base oil type determined. Most performance-enhancing additives found in lubricating oils are also used in grease formulation and should be chosen according to the demands of the application. Table B-1 lists some common additive requirements by application. Most grease applications in USACE can be formulated using mineral oil base stocks, which are appropriate for most applications. However, some applications might benefit from the use of a synthetic base oil. Such applications include high or low operating temperatures, a wide ambient temperature range, or any application where extended relubrication intervals are desired.

Table B-1. Common Additive Requirements by Application.

Additive*	**Journal Bearings**	**Ball Bearings**	**Thrust Bearings**	**Roller Bearings**	**Needle Bearings**
Antioxidants	●	●	●	●	●
Antifoam Agents	●	●	●	●	●
Antiwear/EP		●	●	●	●
Rust Inhibitors	●	●	●	●	-
Extreme Pressure			–	–	
Demulsibility	●	●	●	●	–
VI Improvers	–	–	–	–	●
Corrosion Inhibitors	●	●	●	●	●

*Source: *Noria Practical Handbook of Machinery Lubrication* (Noria 2011).
● Required, – Depends on application

(1) For bearings, speed factor and operating temperature can be used to determine the best consistency or NLGI grade for a given application. Table B-2 below provides a general guide to selecting NLGI grade based on speed factor and operating temperature.

Table B-2. General Guide to Selecting NLGI Grade Based on Speed Factor and Operating Temperature.

Operating Temperature*	**DN (Speed Factor)**	**NLGI No.****
-30 to 100 °F (-34 to 38 °C)	0 - 75,000 75,00 - 150,000 150,000 - 300,000	1 2 2
0 to 150 °F (-18 to 66 °C)	0 - 75,000 75,00 - 150,000 150,000 - 300,000	2 2 3
100 to 275 °F (38 to 135 °C)	0 - 75,000 75,00 - 150,000 150,000 - 300,000	2 3 3

*Source: *Noria Practical Handbook of Machinery Lubrication* (Noria 2011).
**Depends on other factors as well, including bearing type, thickener type, base oil viscosity and base oil type

c. **Step 3 – Tainter Gate Trunnion Bearings.** Appendix C provides the complete Engineering Construction Bulletin 2006-11, which provides lubrication requirements for tainter gate bearings. Many of the requirements listed in ECB 2006-11 were based on tests conducted by the Bureau of Reclamation at Folsom Dam. A summary of ECB 2006-11 is provided below:

- Rust prevention: ASTM D-1743 Pass.
- Resist water washout: ASTM D-1264 Max 1.9%.
- Ease to pump and distribute: ASTM D-217 Worked Penetration NLG 1.
- High viscosity mineral and/or synthetic oil base: ASTM D 445 Minimum 700 cSt at 104 °F (40 °C). NOTE: the viscosity selected here was based on a single Huskey product. The viscosity selected in the ECB 2006-11 is too high and near the top of the viscosity chart. It is too high for most applications within USACE. The viscosity selection for trunnion bearings should be based on the specific location and application and temperature range necessary. A viscocity selection in the middle of the scale (320 cSt - 40 °C) will be more appropriate for most applications.
- Anti wear and anti scuffing: ASTM D-2596.
- Measurement of Extreme-Pressure Properties of Lubricating Grease (Four-Ball Method); recommend that the criteria be set as follows: minimum Wear Load Index of 40 kgf, and minimum Weld Point of 140 kgf. Trunnion application is typical boundary condition, and it is appropriate to set these parameters to make sure excessive wear and/or welding does not occur at the exhibited loads and speeds.
- Good adhesion to bearing surfaces: No test.
- Corrosion of bronze prevention: ASTM D-4048 Classification 1b.

- Non-separation in storage: ASTM D-1742.
- Maximum separation allowed should be limited to 0.5 or 1.0%. This characteristic is not only important during storage of grease, but to grease in lube lines (where an automatic greasing system is in place and used) because of long pauses between actual greasing. It is important that oil not separate from thickeners and additives while in the grease lines.

B-4. Part 4 Grease Selection for Open Gearing

Mineral based, multi-purpose, lithium soap, NLGI 2 can be used for a majority of these applications. The need for extreme pressure (EP) additives should be evaluated. Environmentally Acceptable grease can also be evaluated.

a. **Step 1 - Open Gear Lubricant Requirements and Industry Standards.** Open gearing applications are considered some of the most difficult applications a lubricant can encounter. Open gear lubricants must possess the following characteristics and properties:

1. Tackiness (adhesive/cohesive properties) – excellent adhesion to the gears.
2. Resistance to water washout and spray-off.
3. Load-carrying capability to protect against friction and wear.
4. Protection of the gears against wear and corrosion.
5. Cushioning ability (vibration reduction).
6. Sprayability and/or ease of dispensability.
7. Alleviation of housekeeping and maintenance problem.
8. Resistance to fling-off.
9. No buildup in the roots of the gear teeth.
10. Properly selected dropping point and low temperature pumpability.

b. **Step 2 - Some Key Test Requirements with Suggested Ratings.** Note – these are suggested ratings and guidelines only. It is imperative to work with the gear manufacturer and the lubricant supplier to provide the correct lubricant for the specific application.

- Water washout @ 174 °F (79 °C), wt% per ASTM D1264 <2 (for applications frequently submerged suggest Rating <1).
- ASTM D4049 Standard Test Method for Determining the Resistance of Lubricating Grease to Water Spray Recommended Value <2.
- Timken OK Load pounds (EP lubricants), ASTM D2782: 45 minimum.

- Timken OK Load pounds, ASTM D2509: 75 minimum.
- Four Ball EP Weld Point, kgf, ASTM D2596: 500.
- Four Ball EP Load Wear Index, kgf, ASTM D2596: 100.
- Oxidation Stability, ASTM D2893**.**
- Prevention of Rust, ASTM D1743: Pass.
- Pour Point, °F, ASTM D97.
- Pumpability, ASTM D217 and ASTM D1092.
- Anti-Wear and Scuffing, ASTM 2596 and G99.
- Shelf life and Storage, ASTM D1742.
- Oxidation Stability, ASTM D942 and D2893.

c. **Step 3 – Selecting the Types of Open Gear Lubricants.** The types of open gear lubricants generally fall into the following categories:

- Asphaltic type (also referred to as residual compounds).
- Semifluid greases (also known as paste type).
- Semifluid grease cutbacks.
- Gel/polymer-thickened types.
- High-viscosity synthetics oils.

(1) **Asphaltic Type.** Asphaltic-type open gear lubricants are known as residual compounds or black oils. They are formulated from high-viscosity mineral oils or residual compounds that contain a high level of asphalt or bitumen and a volatile solvent diluent, which is used in the application of the product. Typically the residual black oils used in the formulation have viscosities of 643 cSt (643 mm^2/s) or higher at 212 °F (100 °C).

(2) **Semifluid Greases and Semifluid Solvent Cutbacks (Paste Type).** These types of open gear lubricants typically contain medium- to high-viscosity petroleum base oil, which may contain some asphalt or bitumen. They may also contain a synthetic oil; gelling agent; or thickener system such as aluminum complex or lithium complex; solid lubricants such as molybdenum disulfide and graphite; rust inhibitors; and extreme pressure (EP) agents. Because these types of open gear lubricants contain a thickener system, they are commonly referred to as paste-type open gear lubes. Their consistency typically ranges from an NLGI grade 0 to 2. The cutback versions contain a volatile solvent to enhance the product's ability to be applied with spraying and automatic lubrication systems, especially when low temperatures are encountered.

(3) **Gel/Polymer-Thickened Type.** These types of lubricants are similar to paste-type open gear lubricants because they contain medium- to high-viscosity petroleum or synthetic base oils that are thickened with a polymeric thickener, EP agents and solid lubricants to enhance their thin film and boundary film performance. These types of open gear lubricants are typically NLGI 00 to 0 in consistency or are semifluid in consistency.

(4) **High-Viscosity Synthetic Oils.** Oils are typically not used on open gearing within USACE and their use is generally not recommended. AGMA 9005 provides more discussion and details on oil lubricated open gearing. These are typically formulated from medium- to very high-synthetic base fluids, such as PAO and polyol esters, or a combination of both, and contain EP agents and rust and corrosion additive systems. Some products may also contain solid lubricants such as molybdenum disulfide that is dispersed into the lubricant in a colloidal suspension, or contain viscosity index improvers.

B-5. Part 5 Grease for Wire Rope Applications.

USACE has thousands of applications of wire rope on locks, dams, and hydro sites. Wire rope lubricants have the following principal functions:

- To reduce friction as the individual wires move over each other.
- To reduce abrasion as wire rope goes over sheaves or drums.
- To provide corrosion protection and lubrication in the core and inside wires and on the exterior surfaces.

a. **Step 1 – Determine the type of wire rope lubricant.** There are two types of wire rope lubricants, penetrating and coating. Penetrating lubricants contain a petroleum solvent that carries the lubricant into the core of the wire rope then evaporates, leaving behind a heavy lubricating film to protect and lubricate each strand. Coating lubricants penetrate slightly, sealing the outside of the cable from moisture and reducing wear and fretting corrosion from contact with external bodies. But because most wire ropes fail from the inside, it is important to make sure that the center core receives sufficient lubricant. A combination approach in which a penetrating lubricant is used to saturate the core, followed with a coating to seal and protect the outer surface, is recommended. It is also recommended to use pressurized lubricators when possible. This is discussed further in Chapter 16, which also provides a photo of a wire rope lubricator (Figure 16-5). Wire rope lubricants can be petrolatum, asphaltic, grease, petroleum oils or vegetable oil-based. Products from Lubrication Engineers: (http://www.lelubricants.com/wire-rope-lubricants.html) have proven to be successful in multiple wire rope applications in USACE. They also manufacture pressurized lubrication applicators. The Kirkpatrick Group also manufactures pressurized wire rope lubrication systems and provides a full line of wire rope lubricants (http://www.thekirkpatrickgroup.com/index.html).

Mineral based lubricants, with the proper additives, provide excellent corrosion and water resistance and are recommended for most applications.

Asphaltic compounds generally dry to a very dark hardened surface, which makes inspection difficult. They adhere well for extended long-term storage but will crack and become brittle in cold climates. Asphaltics are the coating type.

Various types of greases are used for wire rope lubrication. These are the coating types that penetrate partially but usually do not saturate the rope core. Common grease thickeners include sodium, lithium, lithium complex, and aluminum complex soaps. Greases used for this application generally have a soft semifluid consistency. They coat and achieve partial penetration if applied with pressure lubricators.

Petroleum and vegetable oils penetrate best and are the easiest to apply because proper additive design of these penetrating types gives them excellent wear and corrosion resistance. The fluid property of oil type lubricants helps to wash the rope to remove abrasive external contaminants.

Figure B-1. Wire Rope Lubricant – Penetrating Type.

Wire ropes should be lubricated during the manufacturing process. If the rope has a fiber core center, the fiber will be lubricated with a mineral oil or petrolatum type lubricant. The core will absorb the lubricant and function as a reservoir for prolonged lubrication while in service. If the rope has a steel core, the lubricant (both oil and grease type) is pumped in a stream just ahead of the die that twists the wires into a strand. This allows complete coverage of all wires.

Once in service, wire ropes should cleaned before applying new lubricant. If a cable is dirty or has accumulated layers of hardened lubricant or other contaminants, it must be cleaned with a wire brush and petroleum solvent, compressed air or steam cleaner before re-lubrication. The wire rope must then be dried and lubricated immediately to prevent rusting. Field lubricants can be applied by spray, brush, dip, drip, or pressure boot. Lubricants are best applied at a drum or sheave where the rope strands have a tendency to separate slightly due to bending to facilitate maximum penetration to the core. If a pressure boot application is used, the lubricant is applied to the rope under slight tension in a straight condition. Excessive lubricant application should be avoided to prevent safety hazards.

b. **Step 2 - Determine Lubricant Performance Measures.** Some key performance attributes to look for in a wire rope lubricant are wear resistance and corrosion prevention. Some useful performance benchmarks include high four-ball EP test values, such as a weld point (ASTM D2783) of above 350 kg and a load wear index of above 50. For corrosion protection, look for wire rope lubricants with salt spray (ASTM B117) resistance values above 60 hours and humidity cabinet (ASTM D1748) values of more than 60 days.

B-6. Part 6 - Hydraulic Oil Selection. The required application should be the most critical attribute when selecting a hydraulic fluid to ensure the system's ability to function properly and attain long life. Many hydraulic systems in USACE applications are near water and are subject to a variety of environmental conditions. This includes possible submersion, heat, cold, rain, and snow. When selecting a hydraulic fluid, it is very critical to determine the system's needs: viscosity, additives, operation, etc. There are three primary types of hydraulic oils:

- Fire-resistant applications – hydraulic oils.
- Hydraulic systems for mobile and industrial systems. (These are typically either mineral based or synthetic hydraulic oils.)
- Environmentally Acceptable Hydraulic Oils.

Fire resistant applications are not common within USACE especially for civil works applications and will not be discussed further in this appendix. Most applications in USACE civil works fall under the industrial system category. Environmentally Acceptable hydraulic oils are becoming more common and their use is encouraged. In addition, hydraulic oils can be synthetic based, mineral oil based, or bio-based. With hydraulic systems, there are two primary considerations, the viscosity grade and the hydraulic oil type. These specifications are typically determined by the type of hydraulic pump employed in the system, operating temperature, and the system's operating pressure.

a. **Step 1 – Determine Pump Requirements.** There are three major design types of pumps used in hydraulic systems: vane, piston, and gear (internal and external):

- *Vane*. Vane pumps typically require a viscosity range of 14 to 160 cSt (14 to 160 mm^2/s) at operating temperatures.
- *Piston*. They can produce much higher operating pressures - up to 6,000 psi (413.70 bar). The typical viscosity range for piston pumps is 10 to 160 cSt (10 to 160 mm^2/s) at operating temperatures.
- *Gear*. Gear pumps are typically the most inefficient of the three pump types, but are more agreeable with larger amounts of contamination. Gear pumps operate by pressurizing the fluid between the trapped air volume of the meshing teeth of a gear set and the inside wall of the gear housing, then expelling that fluid. The two main types of gear pumps are internal and external.

Internal gear pumps offer a wide range of viscosity choices, the highest of which can be up to 2,200 cSt (2,200 mm^2/s). This pump type offers good efficiency and quiet operation, and can produce pressures from 3,000 to 3,500 psi (206.8 to 241.3 kPa). External gear pumps are less efficient than their counterpart, but have some advantages. They offer ease of maintenance, steady flow, and are less expensive to buy and repair. As with the internal gear pump, these pumps can produce pressures ranging from 3,000 to 3,500 psi (206.8 to 241.3 kPa), but their viscosity range is limited to 300 cSt (300 mm^2/s).

b. **Step 2 – Determine Viscosity Requirements.** Viscosity should be determined by the pump type. Not having the correct viscosity for the application will dramatically reduce the average life of the pump and system, thereby directly reducing its reliability and production. When selecting the

appropriate viscosity grade, look for the optimum viscosity required by the pump. This can be determined by collecting data from the pump OEM, actual operating temperature of the pump, and the lubricant properties referenced to the ISO grading system at 104 and 212 °F (40 and 100 °C).

Viscosity is the single most important factor when selecting a hydraulic fluid. Defining the correct fluid viscosity grade for a particular hydraulic system involves consideration of several interdependent variables. These include:

- starting viscosity at minimum ambient temperature.
- maximum expected operating temperature, which is influenced by maximum ambient temperature.
- permissible and optimum viscosity range for the system's components.

If the hydraulic system is required to operate in freezing temperatures in winter and tropical conditions in summer, then it is likely that multigrade oil will be required to maintain viscosity within permissible limits across a wide operating temperature range. If fluid viscosity can be maintained in the optimum range, typically 25 to 36 cSt (25 to 36 mm^2/s), the overall efficiency of the hydraulic system is maximized (less input power is given up to heat). This means that under certain conditions, the use of a multigrade can reduce the power consumption of the hydraulic system.

Table B-3. Typical Minimum Viscosity Values for Hydraulic Components.

Component Type*	**Minimum Permissible Viscosity**		**Minimum Optimum Viscosity (cSt)**	
	cSt	**mm^2/s**	**cSt**	**mm^2/s**
Vane	25	25	25	25
External gear	10	10	25	25
Internal gear	20	20	25	25
Radial piston	18	18	30	30
Axial piston	10	10	16	16
*Source: Noria Practical Handbook of Machinery Lubrication (Noria 2011).				

c. Step 3 - Hydraulic Fluid Selection.

(1) Mineral Oil Based – These types of hydraulic fluids are the most common within USACE and will work for a majority of applications. They are refined with supplemental additive s, which range from anti-wear (AW), R&O inhibitors, and viscosity index (VI) improvers. These fluids offer a lower cost alternative to synthetics and can be very comparable in performance when certain additive packages are included. Chapter 10 provides additional discussion. Some variations of mineral based hydraulic oils include:

- Straight oils: same as petroleum-based oil but without the additives.

- Automatic transmission fluids (ATF): excellent low temp viscosity and very high VI.
- Military hydraulic fluids (i.e., MIL-H-5606 and MIL-H-83282): also called "red oil" because of the color.

(2) Synthetic Based. Synthetic hydraulic fluids are discussed in Chapter 4 and Chapter 10. They have better hydrolytic stability when exposed to water. They can operate at higher and lower temperatures than mineral oil based hydraulic fluids. Many synthetic based hydraulic fluids can also be considered as EALs. The primary categories of synthetic base hydraulic fluid include:

- PAOs - polyalphaolefins.
- PAGs - polyalkylene glycols.
- Esters.

PAOs are generally compatible with existing seal materials where PAGs are not.

(3) Environmentally Acceptable Hydraulic Fluid. ISO 15380 identifies four categories of biodegradable hydraulic oil: (1) HETG, or tri-glyceride, which are biobased or vegetable oils such as rapeseed, (2) HEES, synthetic ester, (3) HEPG, poly glycol or PAG, and (4) HEPR, hydrocarbon and ester mix (typically PAOs). To be considered an EAL, it should follow the same three criteria as listed above for grease. Some considerations include:

(4) Trident PAG from Dow Chemical is an option when considering a polyalkylene glycol.[*] The product is being used at the new Folsom Dam tainter gates. However, at the time of the writing of this manual, a performance evaluation has not been done. PAGs can hold much more water in solution than other synthetics which is their primary advantage.

(5) Panolin is an option when considering a synthetic ester. This is used extensively and throughout Europe on multiple lock sites and has worked well.[†]

---

[*] http://www.dow.com/ucon/formulated/fluids/anhy.htm

[†] http://www.panolin.com/inten/products/environmentally_considerate_lubricants/panolin_hlp_synth/hlp_synth_overview.php

Figure B-2. Panolin Hydraulic Fluid.

(6) For PAO hydraulic fluids, RSC Bio Solutions hydraulic oils are an option. No USACE research has been done on the product, however. Their product literature indicates they are compliant with the EPA Vessel General Permit requirements.*

B-7. Part 7 - Gear Reducer Oil Selection

Gear reducers are also used extensively in USACE civil works applications. Selecting the proper gear lubricant is important to the long-term efficient operation of the gear drive. There are many factors to consider when selecting an industrial gear lubricant for a particular application. Two key questions to start with include:

- What is the type of gear reducer?
- What is the application?

The appropriate viscosity and oil selection criteria for a particular type of industrial gear drive can be determined using AGMA 9005-E02 “Industrial Gear Lubrication.” The AGMA 9005-E02 standard shows suggested viscosity grades for industrial gear drives operating under normal loads over a range of speeds and ambient temperatures.

In addition, the gear lubricant selected for a particular application should match the recommendations of the original equipment manufacturer (OEM). These lubrication specifications can be found inscribed either on the industrial gear drive’s nameplate or in the published specifications found in the operator’s manual. These lubrication specifications are designed to balance the lubrication needs of the bearings, which generally require a light-viscosity lubricant. The specifications are also designed to balance the lubrication needs of the

* http://rscbio.com/products/envirologic/hydraulic-fluids

gears, which usually require the use of a medium- to high-viscosity lubricant. This balance can be achieved only through proper viscosity selection.

a. **Step 1 - Viscosity and Viscosity Selection.**

(1) Viscosity provides the proper thickness of the oil film at the operating temperature and conditions to keep the mating surfaces of the gears and bearings apart during hydrodynamic lubrication conditions. It also allows for the proper flow of the lubricant to carry frictional heat away from the stress points along with any wear debris or contaminants present. In addition, the viscosity of the industrial gear lubricant selected is important to the overall load-carrying ability of the gear lubricant. For new equipment, the manufacturer will select the proper viscosity of the gear oil and provide this as part of the project operation and maintenance manual.

(2) A general rule of thumb is that the higher the viscosity, the higher the load-carrying contribution to the gear lubricant. However, care must be taken in selecting the proper viscosity for an industrial gear application. The use of a lubricant with too heavy a viscosity can result in the generation of excessive heat, excessive power losses, decreased gearbox efficiency, and improper oil flow. The optimum selection will take into consideration ambient temperatures, the operating temperatures, drive loads and operating speeds that are most desirable in keeping wear rates at a minimum. Again, AGMA 9005-E02 should be used.

(3) As mentioned previously, the manufacturer of the industrial gear drive generally will specify the viscosity grade to use based on the ambient temperatures and operating conditions. An original equipment manufacturer (OEM) will usually specify the industrial gear lubricant's required viscosity grade in centistokes (cSt) at 104 °F (40 °C), in Saybolt Universal Seconds (SUS) at 100 °F (38 °C) or reference the required AGMA or ISO viscosity grade.

(4) If the gear reducer manufacturer does not specify a particular viscosity grade to use or if the lubrication recommendations are no longer available due to lost maintenance records, misplaced operator's manuals or painted-over nameplates, the correct viscosity grade for a particular industrial gear lubricant can still be determined. AGMA 9005-E02 can be used to determine the correct viscosity and provides calculations to determine proper viscosity based on speed and load.

b. **Step 2 - Other Considerations.** These include the type of gearing, the loads and transmitted power applied to the industrial gear drive, the speed of the gears, the operating and/or ambient temperatures, the materials used, and the condition of the gears. These factors can help with determining the type of industrial gear lubricant to use for a particular application.

(1) The pour point of the gear oil should be at least 9 °F (5 °C) below the minimum expected ambient temperature during start-up. If this cannot be achieved, use a gear lubricant that has a lower pour point, such as one that is formulated with synthetic base fluids, or use a heater to heat the oil before starting the industrial gear drive.

(2) The intermittent and infrequent use of machinery on navigation structures can also contribute to corrosion on the interior of gear reducers. Most of these gear reducers have breathers that are open to the atmosphere and rely on splash lubrication. Long periods of non-use allow any protective film of lubrication to evaporate. Moisture in the air within the gearbox can condense and

cause rust and corrosion to form. As the oil in a gear reducer heats and cools, it expands and contracts, allowing moist outside air into the gear reducer through the breather. To limit the entrance of moisture into gear reducers, the use of an appropriately sized oil bath or disposable desiccant breather is necessary. With this type of breather, not only must they be designed and installed correctly, they must also be replaced when the desiccant is saturated. Gear reducer outdoor exposure to humidity and sunlight will draw water into the gear reducer oil. Fabricated protective covers or roofs are justified to limit the direct exposure to sunlight and the elements. Closed systems can also be considered for high humidity applications.

(3) Oxidation stability of the lubricant is critical for gear reducers. Lubricants with low values of oxidation stability will oxide rapidly in the presence of water at high temperatures. When oil oxidizes, it may result in sludge accumulation in the gear reducer. The sludge may interfere with the cooling and lubrication. The oxidized oil will also cause corrosion.

c. **Step 3 – Oil Selection.** The four types of gear lubricants that could be used in the lubrication of gear reducers include rust and oxidation (R&O) inhibited oils, extreme pressure (EP) gear oils, compounded gear oils, and synthetic gear oils:

- **Rust and Oxidation Inhibited Gear Oils.** These are typically formulated with highly refined petroleum or synthetic base oils and contain additives that enhance oxidation stability, provide corrosion protection, and suppress foam. Their superior oxidation stabilities typically set them apart from other gear oil types. However, their load-carrying capabilities may be less than other gear oil types. These oils are generally associated with higher speed and lighter load applications. Rust and oxidation inhibited gear lubricants can perform well over a wide range of gear sizes and speeds and ambient temperatures ranging from -5 to 250 °F (-15 to 121°C). R&O inhibited oils are commonly used to lubricate high-speed single helical, herringbone reduction gear sets that have pitchline velocities greater than 3,500 ft/min (17.5 m/s) and are subjected to light to moderate loads. They are also used in the lubrication of spur, straight bevel, and spiral bevel gear drives that are subjected to light loads.

- **Extreme Pressure Gear Oils.** These oils provide protection against corrosion and oxidation and contain additives that provide protection against unacceptable wear and scuffing. These oils are formulated with refined petroleum or synthetic base oils. They are generally used in ISO VGs of 150 and above, and were developed to protect geared systems operating at high loads and severe impact or reversal conditions. EP gear lubricants are recommended for use with spur, straight bevel, spiral bevel, helical, herringbone, and hypoid-type gear drives that are subjected to high loading conditions, moderate to high sliding conditions, and high-transmitted power conditions.

  On worm gear drives avoid the use of EP additives when possible. When used in worm gear drives, EP lubricants must resist the thinning due to high temperatures and the wiping effect of sliding action, and they must provide adequate cooling. Mineral oils compounded with lubricity additives are recommended. EP additives usually are not required for worm gears and may actually be detrimental to a bronze worm gear. Because some types of EP gear lubricants contain chemically active additives systems, care must be taken if they are used in systems where the gears and bearings

are lubricated from the same system or if they are used in heavily loaded worm gear drives. EP gear lubricants can contain additives that are corrosive to brass or bronze components. When used in these applications, the lubricant supplier should be contacted to determine if the EP gear lubricant can be used in such applications. Some EP gear lubricants will also contain solid lubricants such as graphite or molybdenum disulfide that are held in a suspension. These solid lubricants are formulated into the industrial gear lubricant to further improve the gear lubricant's load-carrying capabilities.

EP gear lubricants perform well over a range of gear sizes and speeds and ambient temperatures ranging from -5 to 250 °F (-15 to 121 °C). Constant relubrication by the use of either splash lubrication or circulation lubrication systems of the gear teeth is preferred because EP industrial gear oils do not adhere to the surface of the gear teeth. They can be used effectively to cool the gear mesh and flush the tooth surfaces of wear particles or debris.

- **Compounded Gear Oils.** Compounded gear oils are a blend of petroleum base oils with 3 to 10% of natural or synthetic fatty oils. These lubricants are frequently used in wormgear drives where the high sliding action of the gear teeth requires a friction-reducing agent to reduce heat and improve efficiency. The surface active agent, which is a fatty or synthetic fatty oil, prevents sliding wear and provides the lubricity needed to reduce sliding wear. Their use is limited by an upper operating temperature of 180 °F (82 °C). Most worm gear drives normally require an ISO 460 or 680 compounded oil, and in some cases an ISO 1000. The viscosity grade required depends on the worm gear drive's speed and operating temperature. Generally the lower the worm's gear speed, the heavier the viscosity grade.
- **Synthetics.** Synthetic gear oils are primarily used in spur, straight bevel, spiral bevel, helical, herringbone and hypoid worm enclosed gear drive applications whenever petroleum-based industrial gear lubricants have reached their performance limits. Synthetic gear lubricants can contain R&O inhibited additive systems or contain antiwear or EP additives. They are used in enclosed gear drive applications where very low or high ambient and/or operating temperatures are encountered. Synthetic gear lubricants offer the following advantages in enclosed gear drive applications:
  - Improved thermal and oxidation stability.
  - Improved viscosity-temperature characteristics (high viscosity index).
  - Very good to excellent low temperature characteristics.
  - Lower volatility and evaporation rates.
  - Reduced flammability (dependent on the type of synthetic base used).
  - Improved lubricity at mesh temperatures above 365 °F (185 °C).
  - Resistance to the formation of residues and deposits at high temperatures.
  - Improves efficiency due to reduced tooth-related friction losses (low traction coefficients).

- Lower gearing losses due to reduced frictional losses (low traction coefficients).
- Extended oil drain intervals.
- Reduced operating temperatures especially under fully loaded conditions.
- Reduced energy consumption.

B-8. Part 8 Turbine Oil Selection

Selection of proper turbine oil is essential for several reasons. The expected life of the oil is very high, on the order of 30 years. It becomes very expensive if the wrong oil is chosen, either for a system oil replacement or for the addition of a modest amount makeup oil. The volume of these systems can exceed 100,000 gallons (378,500 L) for large plants. Poor oil selection can affect the reliability of an entire plant and correcting a problem is both time consuming and very expensive.

The turbine oil serves several functions: as a hydrodynamic lubricant for the thrust and guide bearings, as a hydraulic oil for the governor, as a boundary lubricant for a Kaplan runner hub, and as a heat transfer fluid for the bearing coolers.

a. **Step 1 – Compatibility.** The most important and critical step to defend against problems when adding or changing oil is to do oil compatibility testing per ASTM D7155. Incompatible mixtures of oil show evidence of chemical reactions between the additive packages. A common end result in incompatible mixtures is the formation of varnish. This will greatly reduce the service life and create numerous maintenance problems. Mitigation can include coalescing, electrostatic, or balanced charge agglomeration filters. Those may help reduce the symptoms, but the source of the problem will remain. It is essential that samples chosen for compatibility testing be a good representation of the oil in the system. Though it is always best practice to make oil changes only with the same oil or with very careful consideration of compatibility, it is not uncommon for plants to have a somewhat complex history of past oil changes. In certain cases, recent oil purchases may have ended up as the primary oil in some units. This must be considered when selecting samples. Multiple samples from the plant may be necessary to cover the possibility of such differences. If the system is highly contaminated, accumulations of sludge and varnish may have an effect and the system should be cleaned and flushed prior to the replacement.

Once a suitable replacement oil has been found, it is recommended that same oil be used for makeup oil as well. It is certainly not recommended to change the oil randomly whenever makeup oil is purchased, even though the makeup oil may pass the compatibility test. Doing so would create an ever changing complex blend of oils in the system, and is likely to cause significant variations of the blend from unit to unit. Over time, this can create a situation that is unrecoverable, possibly requiring complete change out of the oil in the system.

b. **Step 2 - Turbine Oil versus Circulating Oil.** For hydroelectric turbines and generators, the use of the term “turbine oil” is historical. The oils that are used for these units are no longer called “turbine oils” in today’s lubricating oil market. They are more commonly referred to as circulating oils or sometimes industrial oils. The turbine oils of today are primarily intended for the gas and steam turbine market. Those oils are exposed to much higher temperatures and require higher

oxidation stability. The additive packages in those advanced oils do not serve an identical purpose and are typically quite different than those. It is not recommended to use such oils in hydro turbines, and the compatibility tests would typically show that they are not suitable for mixing together. This recommendation is due to the difficulty and cost of complete removal of all traces of old oil from the hydro turbine units. It a turbine rehabilitation of all units in a plant is being done, such a changeover could be considered. The essential properties are high rust and oxidation resistance, antifoaming, proper viscosity selection, compatibility and resistance to emulsification.

c. **Step 3 – API Group I and II Oil.** Most of the oils purchased for turbine oil application today will be Group II oils, though there are a limited number of oils remaining that are still Group I. One method to determine group is by measuring the aniline point. The aniline point for Group I oils is 226 °F (108 °C) and below. For Group II oils it is above 226 °F (108 °C) but less than 261 °F (127 °C). Determination of Group type can also be made by FTIR. Group I oils have higher solubility than Group II oils at a given temperature. Thus they are more likely to dissolve varnish if it occurs. At the same time, Group I oils have a lower oxidation resistance than Group II oils. A properly selected Group II replacement oil will have a longer lifetime than a Group I replacement oil. A common misconception is that Group I and II oils are not compatible. This is not true, but the additive packages in some Group I and II oils are incompatible. Appendix G provides an ERDC report with further discussion of incompatibility between Group I and II turbine oils.

d. **Step 4 - Rust and Oxidation.** The rust additives help to prevent corrosion in the system in the presence of water. Though it is important to keep water levels under control, preferably well below 100 ppm and always well below 400 ppm, it is common to have problems with water at certain times and locations in the system. In those cases, the oil needs to provide protection against corrosion. ASTM D 665 is used to rust preventing characteristics. The required result of the test is "pass."

Another measure is the Corrosion from oil by Copper Strip Tarnish Test, ASTM D130. The test result must be class I or better.

Oxidation resistance is the ability of the oil to withstand oxidation in an operating environment that includes oxygen, temperature, and pressure. For the oils used in hydro turbines, the standard test is ASTM D2272, "Standard Test Method for Oxidation Stability of Steam Turbine Oils by Rotating Pressure Vessel." The minimum value for new oils is 500 minutes. Oils that drop to 25% of their original value of RPVOT are considered to be worn out and should be replaced. They have minimal (or no) remaining usable life. Total acid number, TAN, is also a useful indicator of life. For new oil, TAN should not exceed 0.5 mg KOH/g. When it reaches 0.4, the oil is typically considered to be at the end of its life.

e. **Step 5 – Viscosity.** Typical oils for hydro turbines are ISO 68, which is almost always consistent with the original turbine manufacturer's recommendations. In some cases, ISO 100 oil is used on Kaplan turbines since that can help enhance its performance in boundary lubrication for the Kaplan runner hub. That is not universally true, since that depends on the specific oil used and the details of the application.

Once an oil is added to a system, the performance in boundary lubrication can be verified by a field stick slip test. The results of such a test depend both on the oil and the turbine. In general,

the majority of both Kaplan and Francis turbines will use an ISO 68 oil. A select few, especially those may have shown a functional problem with the ability to regulate blade position, or a history of Kaplan linkage failures may require a different viscosity grade. These may necessitate a more intensive investigation to identify a more suitable oil, or other measures to reduce friction. This investigation may include an investigation of past testing or even performing new lab tests prior to selection of the new oil.

f. **Step 6 - Viscosity Index.** This is a measure of the stability of viscosity with temperature change. For ISO 68 oils, the minimum acceptable value is 98. For ISO 100 oils, the minimum acceptable value is 95. For Group I oils in both weights, the acceptable value should be adjusted slightly lower to 95. Because these oils are typically not subjected to extreme temperature, the viscosity index usually is not a critical factor. It can be important for thrust bearings, which typically run hotter, or some guide bearings with tighter clearances or higher loads. Typically, 158 to 167 °F (70 to 75 °C) is as hot as these bearings would ever be run, though some users push the limits beyond those temperatures. When the temperature is high, it is important to have an acceptable VI, since that will determine actual viscosity at operating temperature, and subsequently the oil film thickness. The film thickness is critical to preventing bearing failures.

g. **Step 7 – Emulsification.** Emulsification of water into the oil can cause a multitude of problems for turbines. Separability allows the water to be removed from oil. Water does harm in many different ways: it accelerates fatigue, reduces oxidation life of the oil, and can harm additives (one of which is the antifoamant). Water separability is measured with ASTM D1401 “Standard Test Method for Water Separability of Petroleum Oils and Synthetic Fluids.” The required results is 40-40-0 (30) meaning that after 30 minutes the sample consists of an oil layer of 40 ml, water layer of 40 ml and emulsion layer of 0 ml. That is, complete separation of the water from the oil occurs in 30 minutes under the test conditions.

h. **Step 8 – Foaming.** The obvious reason to avoid foaming is that one of the oil’s functions is as a hydraulic fluid. Hydraulic fluids do not work properly when they contain a compressible gas. The presence of foam will also be associated with entrained and free air. When air is present in the system, the oxidation in the oil will progress at a faster rate. Turbines normally do see some level of foaming, particularly in the governor and sometimes at the thrust bearing. When air that is present in the governor passes through the pumps, micro dieseling occurs and varnish forms. Minimizing the amount of air and allowing it to release from the oil is very important. This is influenced by system design, temperature, and pump cycle time. Anti foaming additives greatly facilitate the release of air. Having good initial antifoamant properties and keeping the oil dry are critical. This property is measured with two tests: ASTM D892, “Standard Test Method for Foaming Characteristics of Lubricating Oils” and ASTM D3427, “Standard Test Method for Air Release Properties of Petroleum Oils.”

THIS PAGE INTENTIONALLY LEFT BLANK