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Analysis of Environmentally Acceptable Lubricants (EALs) for U.S. Army Corps of Engineers (USACE) Dams

Victor F. Medina, Michelle T. Wynter, Timothy M. Paulus, and Joseph R. Wilson

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Abstract

This report explores the use of environmentally acceptable lubricants (EALs) for U.S. Army Corps of Engineers (USACE) dams. This report also identifies above-water and in-water structures where these lubricants would be useful. The U.S. Environmental Protection Agency (USEPA) defines EALs in document 800-R-11-002 (*Environmentally Acceptable Lubricants)*. However, this definition has a range of ambiguity. Therefore, this report proposes a tiered definition, suggesting that Tier 1 EALs undergo testing to demonstrate that they meet requirements of toxicity, biodegradability, and bioaccumulation. Tier 2 EALs lack some test data, but are made of materials that the USEPA considers to be consistent with an EAL. The authors assessed 21 lubricants that met either Tier 1 or Tier 2 EALs. The authors found EALs met performance requirements comparable to the mineral oils currently used in USACE dams. In fact, there are already EALs being used effectively in USACE dams and other dams operated by various organizations. The authors also discovered that the costs of EALs is competitive with that of mineral oil lubricants, and that EALs can be readily used in USACE dams.

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Preface

The work reported herein was conducted for Headquarters, U.S. Army Corps of Engineers (HQUSACE) at the U.S. Army Engineer Research and Development Center (ERDC), Environmental Laboratory (EL) in Vicksburg, MS. The project work was funded primarily through the Navigation Systems Research Program (NAVSYS), Mr. Charles "Eddie" Wiggins, Program Manager, and Water Operations Technical Support (WOTS), Dr. Pat Deliman, Program Manager. Mr. Jeffrey A McKee was the HQUSACE Navigation Business Line Manager. Mr. W. Jeff Lillycrop, ERDC Coastal and Hydraulics Laboratory (CHL), was the ERDC Technical Director for Civil Works, and Navigation Research, Development, and Technology Transfer (RD&T) portfolio. The report preparation was funded by Dredging Operations Technical Support (DOTS), Ms. Cynthia J. Banks and Dr. Burton C. Suedel, Program Managers. At the time of publication, Dr. Andy Martin was the Engineering Branch Chief, Dr. Warren P. Lorentz was the Environmental Processes Division Chief, and Dr. Ilker R. Adiguzel was the Director of EL.

Generous in-kind support was received from USACE’s Northwest Division (NWD), Portland District (NWP), and Walla Walla District (NWW). The multiple programmatic/organizational support is a testament to the importance of this study.

COL Ivan P. Beckman was Commander of ERDC, and Dr. David W. Pittman was the ERDC Director.

Acronyms and Abbreviations

ASTM	American Society for Testing and Materials
CHL	Coastal and Hydraulics Laboratory
DoD	Department of Defense
DOTS	Dredging Operations Technical Support
EAL	Environmentally Acceptable Lubricants
EL	Environmental Laboratory
ERDC	Engineer Research Development Center
FT	Feet/foot
HDR	Henningson, Durham, and Richardson, Inc
HQUSACE	Headquarters U.S. Army Corps of Engineers
LRD	USACE Great Lakes and Ohio River Division
LRH	USACE Huntington District
m	Meters
MW	Megawatts
MVD	USACE Mississippi Valley Division
MVP	USACE St. Paul District
MVR	Rock Island District
NAVSYS	Navigation Systems Research Program
NGLI	National Lubricating Grease Institute
NWD	USACE Northwest Division
NWP	USACE Portland District
NWW	USACE Walla Walla District
OSPAR	Oil Spill Prevention, Administration, and Response
PAGs	Polyalkyl Glycols
PAOs	Polyalphaolefins
RCRA	Resource Conservation and Recovery Act
RD&T	Research, Development, and Technology Transfer
SAD	USACE South Atlantic Division

SWD	USACE Southwestern Division
TVA	Tennessee Valley Authority
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USEPA	U.S. Environmental Protection Agency
VGP	Vessel General Permit
VSG	Vane Spindle Grease
WOTS	Water Operations Technical Support

1 Introduction

1.1 Background

Medina (2015) reviewed the state of the science of environmentally acceptable lubricants (EALs) and determined that they could potentially be applied to U.S. Army Corps of Engineers (USACE) dams. However, the study was fairly limited and was not able to evaluate several products that were available. It was determined a more in depth study of EALs was required. This report provides the detailed analysis.

1.2 Objectives

This report focuses on four questions:

1. What equipment or processes at USACE hydropower or navigation projects require in-water or above-water lubrication, making them potential sources of lubricating oil/grease in the water?
2. Are EAL greases available for use at multipurpose facilities (dams)?
3. Do these EALs meet performance needs?
4. What are the economic implications of transitioning to EALs?

1.3 Approach

The approach used in the study is given in detail in section 3 of this report. The report used data collected from dams from the USACE Portland (NWP) and Walla Walla districts (NWW), but is applicable to all USACE entities.

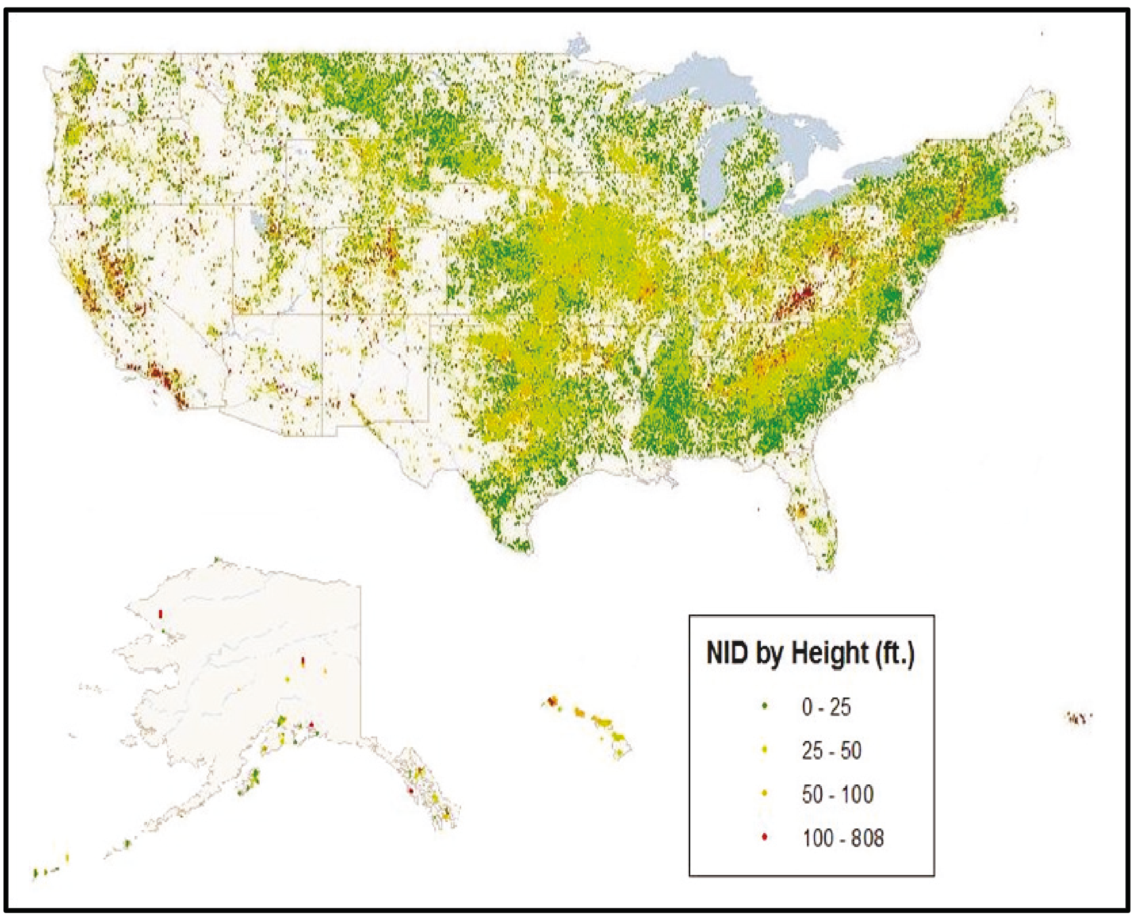
2 Dams and Lubrication

This section discusses dams and lubrication in the United States and the critical role the USACE plays in operating important dam projects throughout the country.

2.1 Dams in the United States

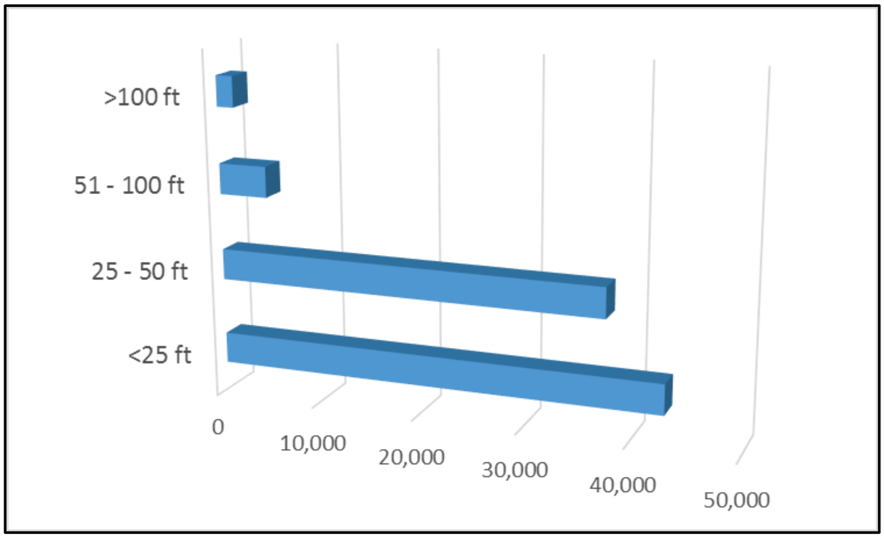
There are more than 87,000 dams in the United States (Figure 1), and local governments and private entities (i.e., irrigation districts, farming coops, etc.) (Figure 2) locally operate most of them. However, the majority of these dams are very small, on the order of 10 feet (ft) (3.05 meters (m)) high, or less (Figure 3). The Federal government owns and operates over 3,800 dams (Figure 2), including most of the large dams in the country.

Figure 1. Dams in the United States.



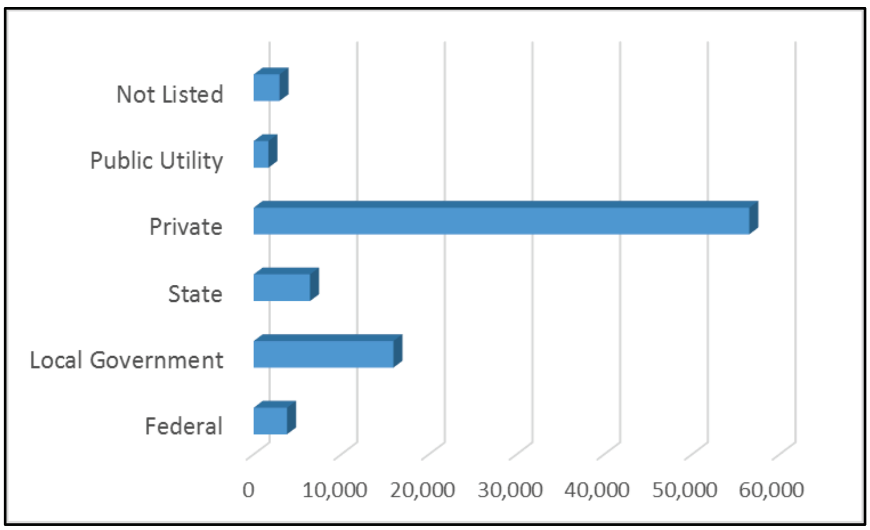
(Source: USACE National Inventory of Dams, http://nid.usace.army.mil/cm_apex/f?p=838:5:0::NO).

Figure 2. Sizes of dams in the United States.



(Source: USACE National Inventory of Dams, http://nid.usace.army.mil/cm_apex/f?p=838:5:0::NO)

Figure 3. Ownership of dams in the United States



(Source: USACE National Inventory of Dams, http://nid.usace.army.mil/cm_apex/f?p=838:5:0::NO).

2.2 USACE operated and constructed dams

The USACE is one of the most important operators of large dams, with nearly 700 dams throughout the United States and Puerto Rico. The total of federally owned dams is approximately 3,800, and USACE operates about 18% of them. However, according to Billington et al. (2005), the USACE and the U.S. Bureau of Reclamation (USBR) have constructed and operated the vast majority of large dams (100 ft and higher) in the United States.

The USACE has also constructed many dams that are now operated by other organizations, such as the USBR. One example is the Folsom Dam in Folsom, CA, which the USACE constructed and then turned over to the USBR for flood control and irrigation operation.

The Federal government divided responsibility of dams to different Federal entities based on their use. For example, the USBR operates dams largely to provide irrigation, and the USACE operates dams primarily for navigation and flood control, although there are other key roles as well.

2.3 Navigation

The primary role of USACE structures is to promote navigation. Dams increase the depth of rivers while decreasing current flow, this promotes increased use of these waterways for commerce. Waterborne commerce is a very effective means of transporting goods. It is generally more economical than trucking or rail transport, and has lower environmental emissions and fewer deaths and injuries (Table 1).

Table 1. Comparison of river barge transport to rail and trucking, Tennessee-Tombigbee Waterway http://business.tenntom.org/why-use-the-waterway/shipping comparisons.

	Fuel economy	Environmental		Safety	
	Miles/gal fuel per ton of cargo	Hydrocarbons emitted (lb/ton/mi)	Nitrous Oxides emitted (lb/ton/mi)	Deaths per billion tons per mile	Injuries per billion tons per mile
River Barge	514	0.0009	0.0053	0.01	0.09
Rail	202	0.0046	0.0183	0.84	No data
Semi-truck	59	0.0063	0.1017	1.15	21.77

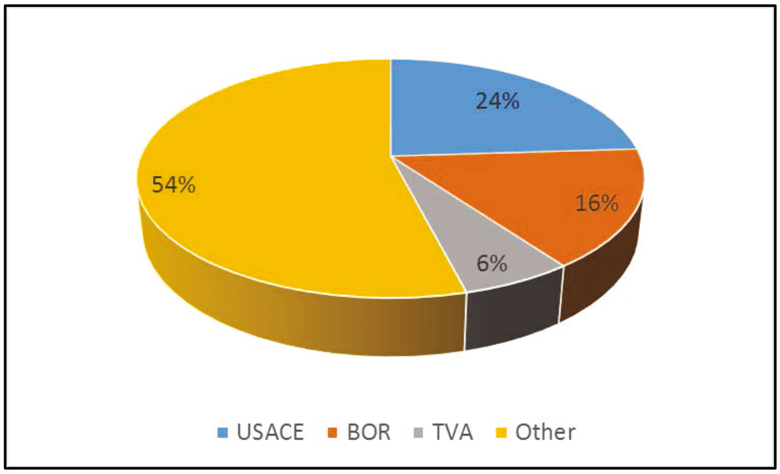
Flood control. The USACE has a critical flood control mission and operates several dams and structures with the purpose of flood control. For example, the Morganza Spillway is a massive flood control structure that can be used to divert water from the Mississippi River to the Atchafalaya river basin (Figure 4). In the USACE Northwest Division (NWD), Lookout Point, Lost Creek, and Dworshak Dams were constructed primarily for flood control.

Figure 4. USACE opened the Morganza Spillway on 14 May 2011 (Wikimedia 2011).

Recreation. Many of the dams the USACE operate have significant recreational areas associated with them, including boating, fishing, wind surfing, camping, hiking, and wildlife protection.

Hydropower. Although the USACE does not specifically operate dams for hydropower production, many dams have hydropower turbines and generate electricity. Figure 5 shows hydropower production in the United States by entity. The USACE is the largest single entity producing hydropower in the United States, accounting for 24% of national production (Figure 5). The USBR, and then the Tennessee Valley Authority (TVA) follow. Interestingly, a combination of other entities, grouped as "Other," account for more than half of the country's hydropower production. However, each Other entity individually produces less than the 6% the TVA produces. That said, many of these smaller producers actually produce their energy in partnerships with the USACE (or USBR, or TVA). For example, Eagle Creek Renewable Energy constructed, and recently started, two small (2.2 and 0.9 megawatt [MW]) hydroelectric turbines at Ball Mountain and Townshend Dams, which the USACE operates in Vermont.

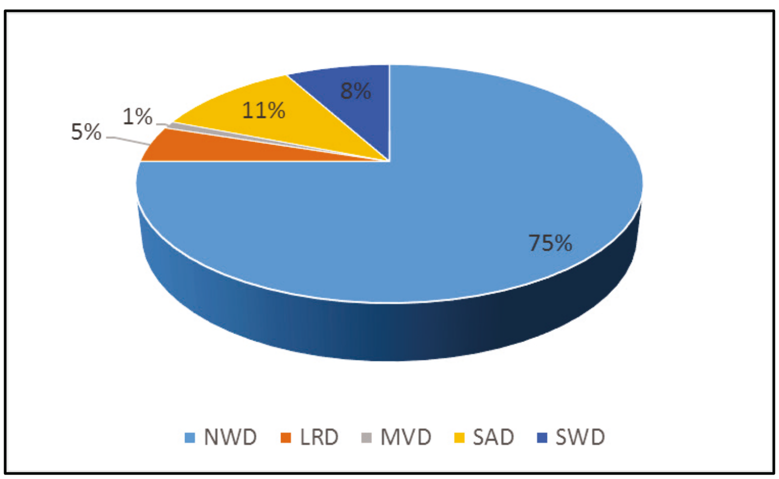
Figure 5. Hydropower producing entities in the United States.



(Source: http://www.nwd-wc.usace.army.mil/PB/NewPWR/Corps_Hydro.htm).

Figure 6 shows the breakdown of hydropower production according to USACE Divisions. Seventy-five percent of this production is from the NWD due to a series of large hydropower projects on the Columbia and Snake Rivers. The South Atlantic Division (SAD) accounts for 11%, followed by the Southwestern Division (SWD) at 8%. The Great Lakes and Ohio River Division (LRD) and the Mississippi Valley Division (MVD) account for about 6% of the USACE hydropower production combined.

Figure 6. Hydropower production by USACE Divisions



(Source: http://www.nwd-wc.usace.army.mil/PB/NewPWR/Corps_Hydro.htm).

2.4 Lubrication

Dams require lubrication for navigational features, hydropower, and other operations. This section discusses lubrication, and introduces the concept of environmentally acceptable lubricants (EALs).

2.4.1 Engineer Manual (EM) 1110-2-1424

Updated in 2016, Engineer Manual (EM) 1110-2-1424 is the official USACE lubrication manual (USACE 2016a). The manual provides extensive discussion and requirements for lubrication oils, turbine oils, grease, and EALs. In addition, this manual was created for designers and operators of navigation structures and hydropower facilities.

2.4.2 Purpose

The primary role of lubrication is to reduce friction between moving parts. Lubrication allows for easier movement and protection against material degradation. However, lubrication has several secondary purposes that can rival friction reduction in some cases. These include:

- Heat dissipation between moving parts
- Protection from sediments and grit
- Protection against oxidation and rust.

2.4.3 Oils and grease

Lubricants come in two general states, oils, and grease. Oils are generally in a pourable state at room temperature. In addition, oils are useful for engine lubrication, enclosed gear systems, and hydraulic systems. Greases are created by adding thickening agents and are semi-solids at room temperature. Greases are useful for lubricating joints, wire ropes, and gears that are open to the atmosphere as well as those that are submerged. Greases include heavy oils, asphaltic materials, and soft greases. This report will largely focus on greases.

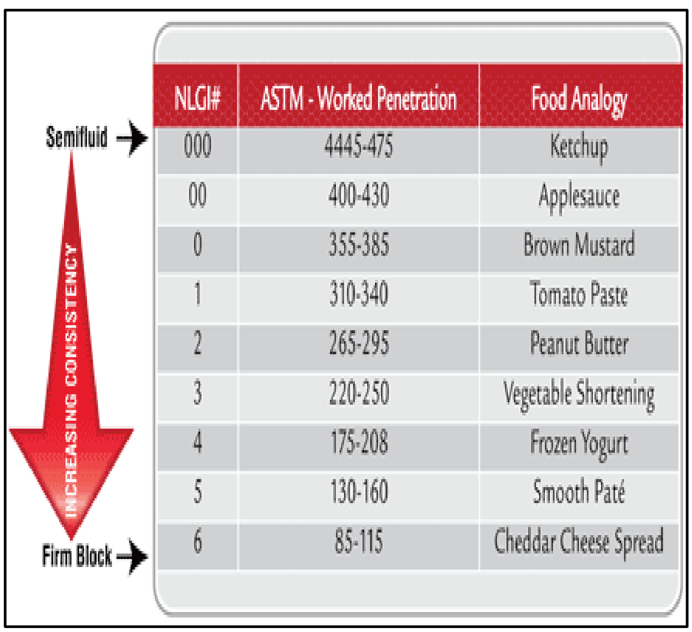
Grease consists of three parts, base oil, thickeners (i.e., soap), and additives. The base oil is the lubricating portion of the grease composition and can be composed of mineral oil (i.e., petroleum source), vegetable oil, synthetic esters, or other materials (see below for more discussion). The thickener combines with the oil to make a solid-to-semi-solid substance.

Metallic soaps like lithium, aluminum, polyurea, sodium, and calcium are most common. Additives are materials added in (usually) small quantities to improve performance, such as resistance to oxidation and rust, extreme pressure, and reduction in wear and friction.

2.4.4 Grease consistency

Consistency is one of the most important parameters of a given grease. The American Society for Testing and Materials (ASTM) Test Method D217, "*Standard Test Methods for Cone Penetration of Lubricating Grease*", and Test Method D1403, "*Standard Test Methods for Cone Penetration of Lubricating Grease Using One-quarter and One-half Scale Cone Equipment*", measuring penetration, are typically used to determine grease consistency. Rigidity, depends on the type and amount of thickener and the viscosity of its base oil. These are commonly related to the National Lubricating Grease Institute (NLGI) consistency numbers ranging from 000 to 6. Figure 7 gives the relationship of NGLI numbers to the consistency of common food items. NGLI 2 is the most common for greases used at dams. Typically, lubricating vendors can offer similar greases with different rigidities by altering the amount of thickener.

Figure 7. Relation of consistency (NGLI number) versus common food items.



NLGI#	ASTM - Worked Penetration	Food Analogy
000	4445-475	Ketchup
00	400-430	Applesauce
0	355-385	Brown Mustard
1	310-340	Tomato Paste
2	265-295	Peanut Butter
3	220-250	Vegetable Shortening
4	175-208	Frozen Yogurt
5	130-160	Smooth Paté
6	85-115	Cheddar Cheese Spread

2.4.5 Low temperature performance

Many unit operations in dams are conducted at atmospheric temperature or even in water. Many dams are located in cold climates, those in located in warm or hot areas often hold water that originated from much colder places. Therefore, many dam operate in low-temperature regimes.

Low-temperature can affect grease performance. If the temperature of a grease becomes too low, it can become so viscous that it affects performance. Pumpability of the grease suffers and machinery operation may become impossible due to torque limitations and power requirements. As a guideline, the base oil's pour point (i.e., the temperature in which a liquid becomes a semi-solid) is considered the low-temperature limit of a grease. Greases with low pour points are needed for application in low temperature climates.

2.4.6 Other grease properties

- **Dropping point.** The dropping point is an indicator of the heat resistance of grease and is the temperature at which a grease becomes fluid enough to drip. The dropping point indicates the upper temperature limit at which a grease retains its structure, not the maximum temperature at which a grease may be used.
- **Oxidation stability**. The 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.
- **High-temperatures.** High temperatures harm greases more than they harm oils. Grease cannot dissipate heat by convection like a circulating oil. Consequently, excessive temperatures result in accelerated oxidation or even carbonization where grease hardens or forms a crust.

2.4.7 Lubrication regimes

There are several basic regimes of lubrication. The ideal regime is the hydrodynamic regime, in which the two surfaces are fully separated by a fluid film. In this case, the parts do not touch so protection is maximum. In mixed lubrication, two surfaces are partly separated and partly in contact. In elastohydrodynamic lubrication, the surfaces are separated by a very thin film. This is typical of rolling contact, similar to roller bearings. In boundary lubrication, the two surfaces are mostly in contact, although lubricating fluid is present. This is the least protective of the regimes.

Boundary lubrication conditions generally occur at start-up and shutdown, low speeds, and when a thin film is present. Many lock and hydroelectric components operate within this boundary lubrication regime, as they are large, slow moving, and are intermittently used (Figure 8). Furthermore, these parts can be submerged (in water) and be subjected to exposure by contaminants like sediment and grit. Lubricants used for these applications must resist being thrown off or scraped off. Therefore, in this capacity, greases predominate.

Figure 8. Large gear wheel, showing demanding boundary lubrication operating conditions.

2.4.8 Composition of lubricants

Lubricants can be made of a number of different base materials.

Mineral oil. Mineral oil indicates that the lubricant is derived from petroleum. Mineral oils are the most established lubricants, however, they are not considered environmentally friendly, and they rarely meet any of the standards for EALs.

Vegetable oils. Vegetable oils can be outstanding lubricants. These include canola oil, coconut oil, sunflower oil, and many others. Vegetable based oil is usually considered the most benign base oil material.

Synthetic esters. Synthetic esters are derived from hydrocarbon source materials, but are modified to form ester compounds. Although synthetic esters tend to degrade more readily and are typically lower in toxicity than mineral oils, they can be combined to form the highest performing lubricants. However, synthetic esters can be significantly more expensive than other lubricants.

Others. Although uncommon, polyalkyl glycols (PAGs) and polyalphaolefins (PAOs) are lubricants that are generally considered relatively environmentally friendly. Powders like graphite can also be used as lubricants in some situations.

2.4.9 Environmentally acceptable lubricants (EALs)

As discussed in Medina (2015), the definition of an EAL is outlined by the USEPA (2011). All EALs are based on the three following properties: toxicity, biodegradability (persistence), and accumulation. Tests are provided to demonstrate each of these properties. However, the report also discusses the lubricant based oil composition as a basis of categorizing lubricants as EALs and gives other testing, such as octanol water coefficient as a surrogate for accumulation. This has led to the need for a working definition for EALs, and this report proposes a tiered approach.

Food grade lubricants are a different class of lubricants entirely. Food grade lubricants allow for contact with food. As such, they are usually considered relatively better for the environment compared to other mineral oil products. However, food grade lubricants do not necessarily meet EAL requirements.

2.4.10 Self-lubrication

Self-lubricating materials are an established technology that is being increasing exploited by USACE in dam projects. These materials use low friction components and/or water itself as a lubricant (Sukhov et al.1986). The new USACE EM 1110-2-1424 discusses this topic extensively. Self-lubricating materials can eliminate the need to apply lubricants of any kind (USACE 2016a). However, in some cases, these fittings have had excessive wear issues, particularly in high demand areas. In other cases, even when self-lubricating materials are used, grease is sometimes applied to reduce exposure to grit that can wear the fittings.

3 Methods

3.1 Assessment of above-water and in-water operations requiring lubrication

An ERDC engineer visited three USACE dams 10–11 February 2015: The Dalles (NWP), John Day (NWP), and McNary (NWW) Dams. Engineers and operators of each facility escorted the ERDC engineer through the dams. These visits allowed for a thorough assessment of processes requiring lubrication, with an emphasis on above-water and in-water sources. Discussions with experts and operators from these facilities suggest that the operations at these three dams encompass virtually all of the primary processes expected at USACE dams. However, there are differences in the actual equipment used for many of the operations, this variability could have some effect on lubrication needs.

3.2 Assessment of EAL definition

The EAL definition was assessed by first conducting a thorough evaluation of EPA 800-R-11-002 (USEPA 2011). It also included two teleconferences with leadership from NWD, NWP, and NWW, as well as a USACE legal team representative involved with the assessment of EALs.

3.3 Performance of greases

The ASTM tests and measurements provided well defined, quantifiable results of grease performance. However, correspondence and interviews with NWP and NWW engineers and operators suggest that choosing an appropriate grease is as much an art as a science. Therefore, a final answer on performance is not really feasible until the new grease is actually used. That said, ERDC used a three-phased approach for assessing performance:

1. Comparison of EAL performance specifications to grease already being used by the NWP and NWW.
2. Comparison of EAL performance specifications to any published performance requirements.
3. Interviews of engineers, mechanics, and operators who have already used EAL greases.

3.4 Cost evaluation

Costs for mineral oil and EAL greases were obtained from vendors and from USACE entities. These were compared directly by using a simple life cycle approach. The cost difference was also contrasted to that of the total cost of dam operation.

4 Operational Definition of Environmentally Acceptable Lubricant (EAL)

The definition of an EAL is specified in Section 4 of EPA 800-R-11-002. The lubricant has to be biodegradable, minimally toxic, and non-bioaccumulative (USEPA 2011).

There are three ways that a grease could pass each criteria:

1. Testing - EPA 800-R-11-002 has defined several tests for each criteria. By presenting test results as a report or in a specifications sheet, a grease can conclusively prove that it passes the criteria.
2. Vendor's statements - Although a vendor's statement is not as conclusive as actual test results, it does indicate that vendors stand behind their product, providing a strong endorsement for meeting a given criteria.
3. Base oil composition - The USEPA indicates that greases of specific compositions generally meet the criteria (Tables 3, 5, 6, and 7 in EPA 800-R-11-002 [USEPA 2011]). For example, vegetable oil grease would generally be considered readily biodegradable, have no potential for bioaccumulation, and have low toxicity, even without supporting testing. The USEPA also indicated that synthetic ester and PAG based greases also generally meet EAL criteria. Although this is the weakest of the supporting data, it is acceptable based on EPA 800 R11-002.

4.1 Labeling

The definition also indicates that specific labeled products are considered as EALs. Several are cited including Blue Angel, Swedish Standard(s), Nordic Swan, European Eco-label, and Oil Spill Prevention Administration and Response (OSPAR). Section 5 of EPA 800-R11-002 (USEPA 2011) also identifies these labeling programs. In addition, some greases are certified as Vessel General Permit (VGP) compliant (USEPA 2013). The ERDC has determined this to be an equivalent label and all greases defined as VGP compliant are determined to be EALs.

4.2 Tiered definition

Acknowledging that some of the candidate greases have more complete data than others, and that the EPA definition can be interpreted either tightly or more broadly, the ERDC has developed a tiered definition. This might be helpful for dam owners to make more environmentally friendly grease choices (as outlined in EM 1110-2-1424 [USACE 2016a]).

A Tier 1 USACE EAL is one that conforms to a strict interpretation of the EPA definition and will either

1. Be a product labeled by European Eco-label, and/or OSPAR. Other product labeling could be considered by an Environmental Officer.
2. Be a product classified as Vane Spindle Grease (VSG) Appendix A compliant (Canola Canada Ltd., http://canolacanadaltd.com/wp-content/uploads/2016/VSG-brochure.pdf), or
3. Have test data as specified in USEPA 800-R-2-001 or in the USEPA VGP 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.

A Tier 2 USACE EAL is a product that does not meet the criteria of a Tier 1 EAL, however,

1. Is labeled by one or more of the following: Blue Angel, Nordic Swan, or Swedish Standard and/or,
2. Contains a manufacturer's statement that it meets one or more of the test criteria (bioaccumulation, toxicity, and biodegradability) as discussed in part C of the Confirmed USACE EAL definition, with appropriate test data to confirm the other criteria and/or,
3. Its base oil indicates that it meets one or more of the test criteria (see USEPA 800-R-2-011, Section 4, Table 3 for biodegradability, Table 5 for toxicity, and Table 6 for bioaccumulation), with test data to support the other criteria. USACE would prefer products with data on lubricant composition, including toxic or Resource Conservation and Recovery Act (RCRA) metals, and certification that additives do not affect toxicity or accumulation.

The preference would be to use Tier 1 EALs, but Tier 2 EALs can be used if deemed a safer choice for equipment. Recently, the architect-engineer firm Henningson, Durham, and Richardson, Inc (HDR) conducted an analysis for the USACE Hydropower Design Center (HDR 2015) using a strict interpretation of EALs that is similar to the Tier 1 definition used in this report. As a result, the HDR evaluation plan focused solely on one grease product (USACE 2016b). However, there are many excellent candidate greases that do not, as of now, have complete test data, including many of those that are currently being used by USACE and by other organizations that operate hydropower dams. Allowing a broader set of greases (i.e., Tier 2 greases) allows a much easier transition to EAL greases with a much higher degree of confidence. Since Tier 2 greases have base oil compositions that are more environmentally benign, they represent a better alternative, from an environmental perspective, than mineral oil lubricants.

5 Lubrication Needs in Dams

The results of the survey of lubrication needs in dams is presented below. The following definitions are used:

- In-water – The process is lubricated while submerged at least occasionally.
- Above-water – The process is not submerged, but is (at least sometimes) suspended above water sources.
- Encased – The process is encased and not exposed to the environment.

5.1 Hydropower

5.1.1 Wicket gate lubrication

Wicket gates are structures that control water flow through hydropower turbines (Figures 9 and 10). Wicket gates have two or three journal bearings and one thrust bearing or collar per gate. The journal bearings resist the hydrostatic and hydrodynamic loads involved in regulating the flow of water into the turbine. The water force on these gates is extreme, and this is one of the more demanding in-water lubricant uses in a hydropower dam. Even when shaft seals are provided, the grease can encounter water. In the worst cases, water can wash the lubricant out of the bearings. Wicket gate bearings are commonly lubricated with a mineral oil, lithium-based, extreme pressure National Lubrication Grease Institute grade 2 (EP NLGI-2) grease (Hanna and Pugh 1998). Self-lubricating bearings or bushings can also be installed.

5.1.2 Fish screens

Fish screens are devices to keep fish (particularly juveniles) from the turbines (Figure 11). Spray lubricants are used during periodic maintenance. A review of the spray lubricant indicates that it is a hydrocarbon based product that is approved for food contact uses (CRC Industries Inc. 2004).

Figure 9. Left- Schematic of hydropower dam turbines and wicket gates. Right- Wicket gates at Parker Dam (CA).

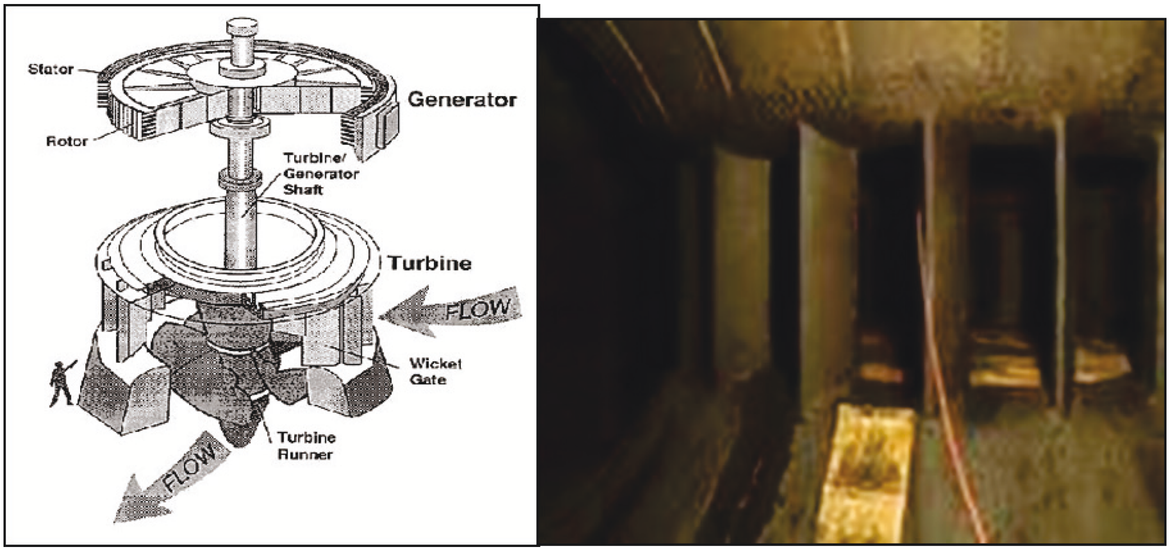


Figure 10. Wicket gate arms at The Dalles Dam, OR.

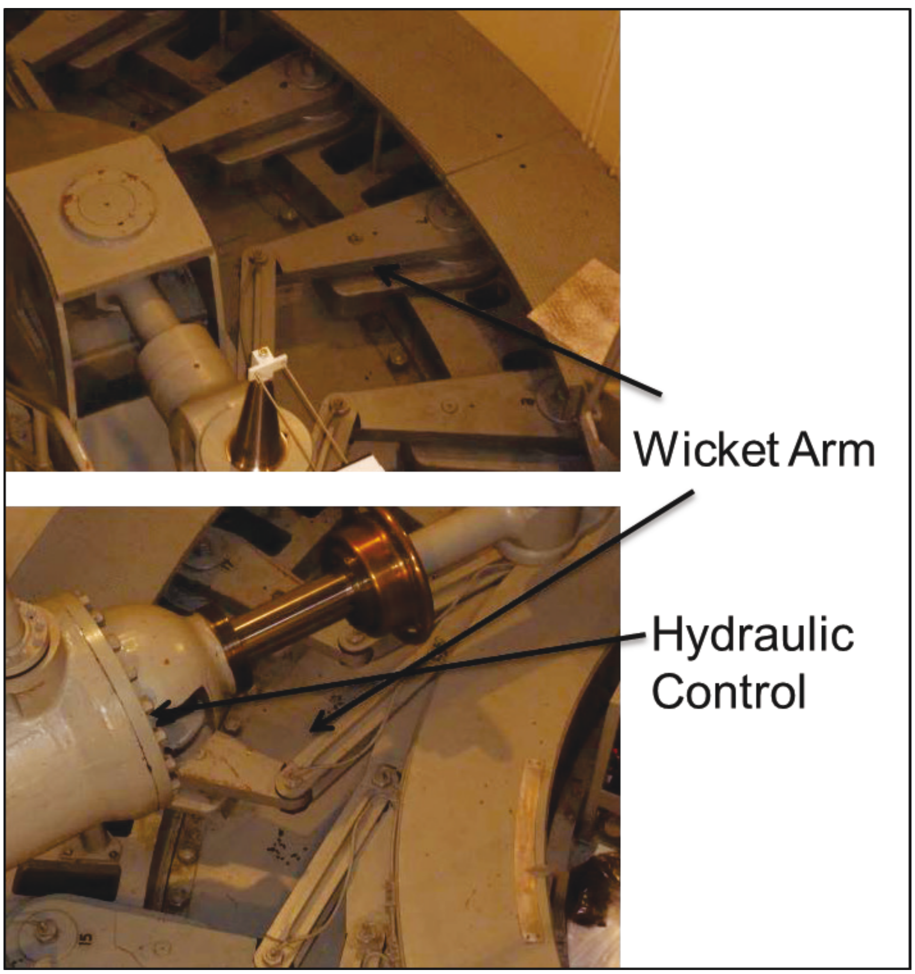


Figure 11. Left- Fish screen undergoing maintenance at John Day Dam, OR. Right- Spray-on chain lubricant.

5.2 Navigation locks

Navigation locks are massive structures that allow watercraft to pass dams. Their general design has an upstream and downstream gate that work together to allow vessel movement in the lock (Figure 12). The size of the structures (Figure 13), and the water forces put massive stresses on the structures. In addition, open gears that move these structures are generally, very slow moving, very large, and exposed to the elements. The components are prone to contamination from dirt and debris brought from boats and barges into the locks. Any lubricants in navigation locks must perform in adverse conditions. Downstream gates typically have more forces associated with them and are generally more heavy-duty structures.

5.3 Gate structures

Miter gates. The Dalles and McNary Dams both use dual, door swing gate structures called miter gates (Figures 14, 15, and 16). These gates have pintle bearings (Figures 14 and 15) that support the weight of the gate. Pintle bearing construction material has typically been bronze with grease lubrication required. However, greaseless bearing technologies are now available. For example, at The Dalles Dam the pintle bearings are designed for greaseless operation. The upper bearings (above-water) are greased to protect against corrosion, and grease lines are maintained to the lower bearings (in-water) in case they are needed in the future.

Figure 12. Schematic showing upstream and downstream miter gates in a navigation lock.

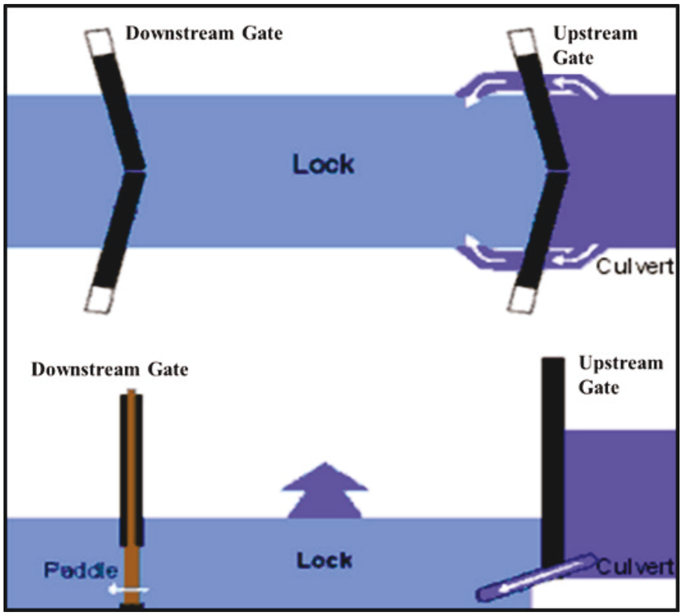


Figure 13. Picture of repairs at The Dalles Dam downstream miter gate in 2010, which also shows the massive size of the structure.

Figure 14. A self-lubricating pintle bearing.

Figure 15. Downstream miter gate structure at The Dalles Dam.

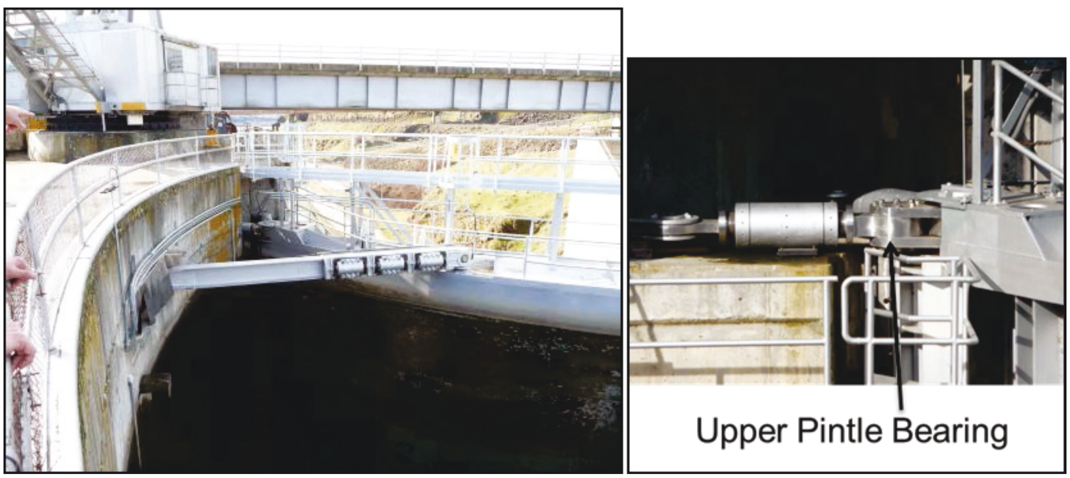
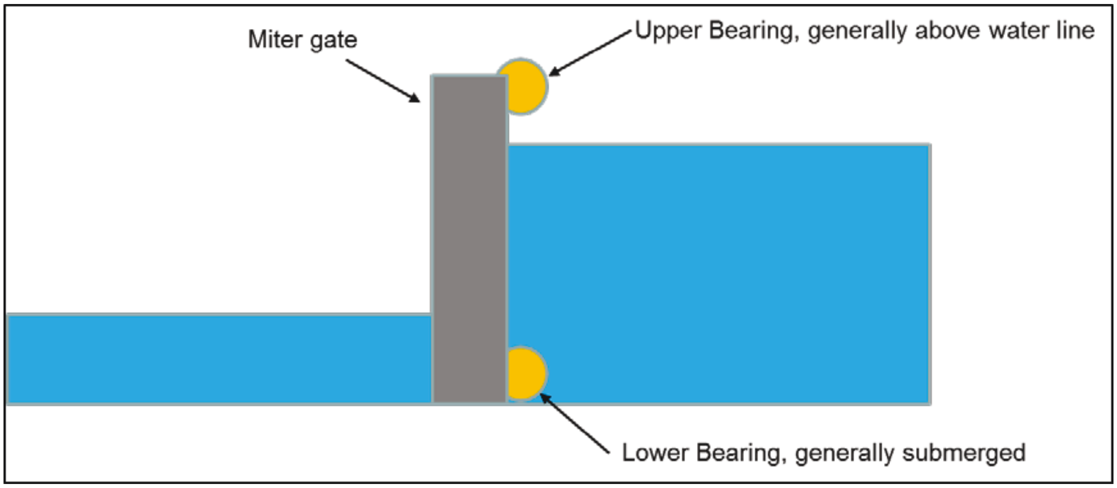


Figure 16. Schematic of a miter gate. Upper bearings are typically above water, but lower bearings are generally submerged.



Vertical gates. Another common dam gate is a wire rope operated vertical gate. One example is at the John Day Dam where a single door, vertical lift gate is in operation (Figure 17). Lifting is performed using massive, above-water wire ropes that are heavily lubricated. Wire rope lubrication can be applied manually to the surface of the wire rope, sprayed on the wire rope, or applied with a pressurized lubricator (Figure 18). Wire rope lubrication serves the following two purposes: 1) wire ropes are lubricated primarily to prevent corrosion of carbon steel wire ropes, and 2) it helps to prevent abrasion damage of the ropes as they pass through sheaves or wrap on drums. Because of this, stainless steel wire rope is typically lubricated on a regular basis, similar to galvanized wire rope. The new EM 1110-2-1424 also requires lubricating the stainless steel wire rope (USACE 2016a). The side runners at John Day Dam are greaseless, but should be evaluated in other dams.

EM 1110-2-2610 gives an alternative to wire rope, this option is the use of roller chain with aluminum bronze sidebars and stainless steel pins (USACE 2004) (Figure 19). These chains have been successfully used without using grease lubricants.

Figure 17. The downstream gate at John Day Dam. A rotating drum raises and lowers the gate via heavily greased wire ropes.

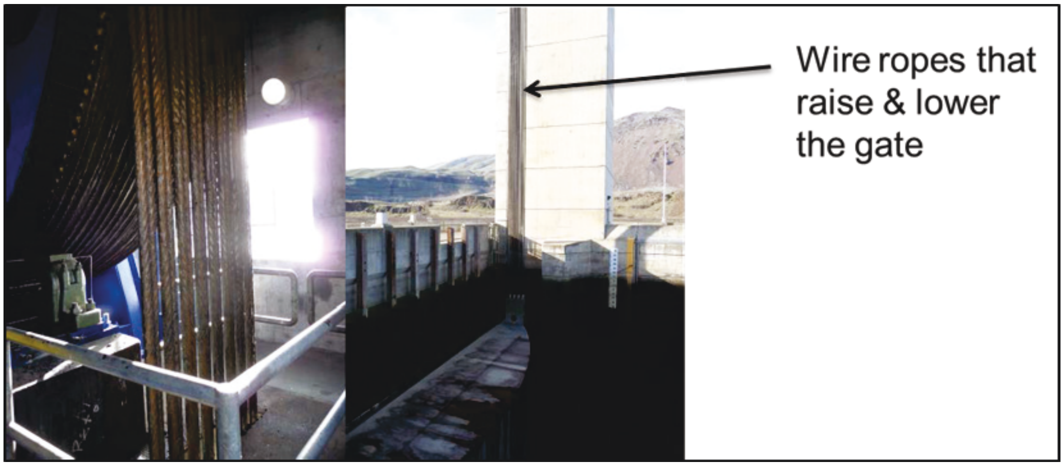


Figure 18. A wire rope spool with a pressurized lubricating device (the yellow device).

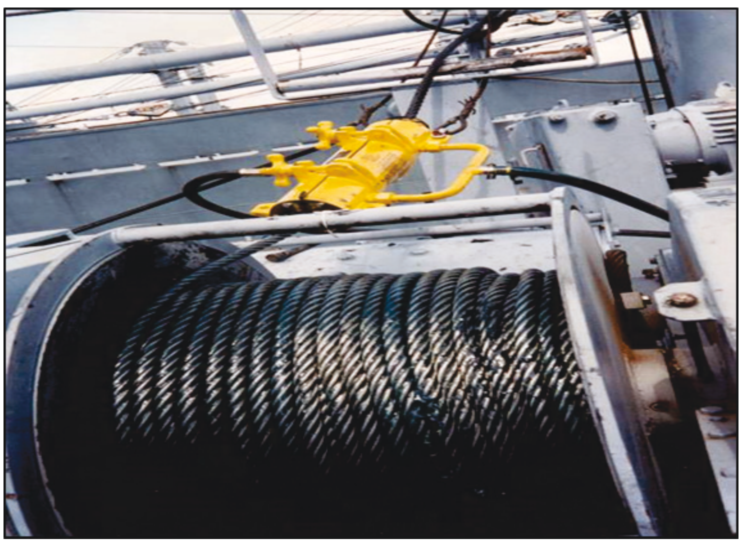
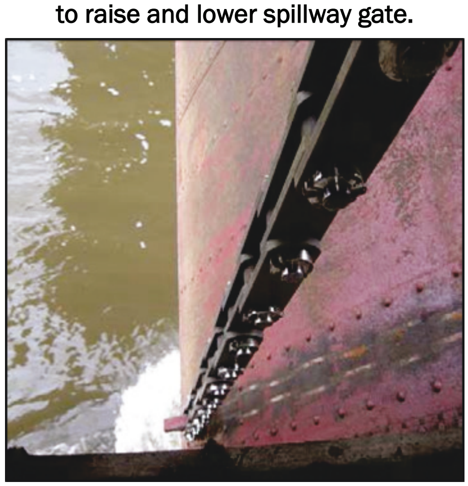


Figure 19. Greaseless roller chain used to raise and lower spillway gate.



Tainter gates. Tainter gates use a semi-circular motion to move a gate (a portion of a cylinder) up and down. This design allows for a lot of strength in an efficient design. A Tainter gate is used as a top gate at The Dalles Dam (Figure 20). However, Tainter gates are far more common on spillways.

Figure 20. Upper Tainter gate at The Dalles Dam.

5.4 Floating mooring bits

Floating mooring bits that allow boats to tie off while in the structure are found in navigation locks. Identical mooring bit structures are in use at The Dalles, John Day, and McNary Dams (Figure 21). The runners for these particular bits are not designed to require lubrication. However, it is possible that older structures might require lubrication.

Figure 21. A mooring bit at the The Dalles Dam.

5.5 Submerged valves

Grease lubricated submerged valves are used to fill and drain the locks. Tainter valves are commonly used based on Tainter gate designs. Figure 22 shows a design schematic of a Tainter valve design.

5.6 Spillways

Spillways are used to control water levels in dams. Spillway gates open and close to control reservoir water levels upstream of the dam. Like navigation gates, the actual design of spillway gates can vary from dam to dam, however, Tainter and lift gates are common (Figure 23 shows a lift gate). Depending on the design, such gates can have in-water lubrication points or above-water lubricated wire ropes or gearing.

Figure 22. Tainter valve design of a filling valve from EM 1110-2-1610 (USACE 1989).

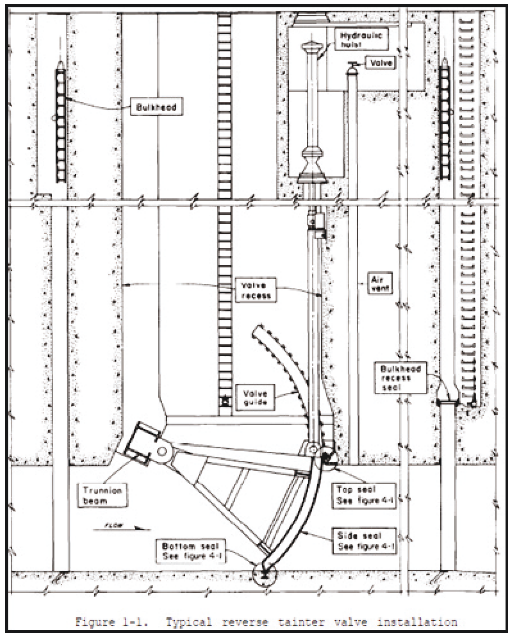


Figure 23. Left - Lift gate style spillway gate at McNary Dam. Gates are moved using greased wire ropes, which are above water. Right - Open spillways at John Day Dam.

Spillway gate motors are typically suspended above the gates (Figure 24). At The Dalles, leakage of oil lubricant was found associated with spillway gate motors. Sorbent pads were used to contain the leakage (Figure 24). These motors use lubrication oils as opposed to greases, which is not within the scope of this study. Still, this can be a consideration for future lubrication projects.

Figure 24. Suspended gate motor showing lubricant leakage at The Dalles. Sorbent pads controlled dripping below.

5.7 Fishways

Many dams contain special structures called fishways or fish ladders that allow fish to swim upstream, climbing up the height of the dam safely for reproduction. These structures contain many above-water lubricated devices, including gates and adjustable weirs (Figure 25).

Figure 25. Left - Heavily greased above-water gearing for movement of adjustable fishway weirs at McNary Dam. Right - Greased above water cable system movement of adjustable fishway entrance gates, McNary Dam.

To attract fish to the structure, a heavy current is often provided, called fish attraction water. This can come from redirecting some of the outflow from the hydropower system. In some cases, powerful pumps are used to create a strong current to attract fish to the fish ladders (Figure 26). The turbines of the pumps are grease lubricated, and the lubricant eventually is discharged into the water.

Figure 26. Left- Fish pump at John Day Dam. Right- Grease metering system.

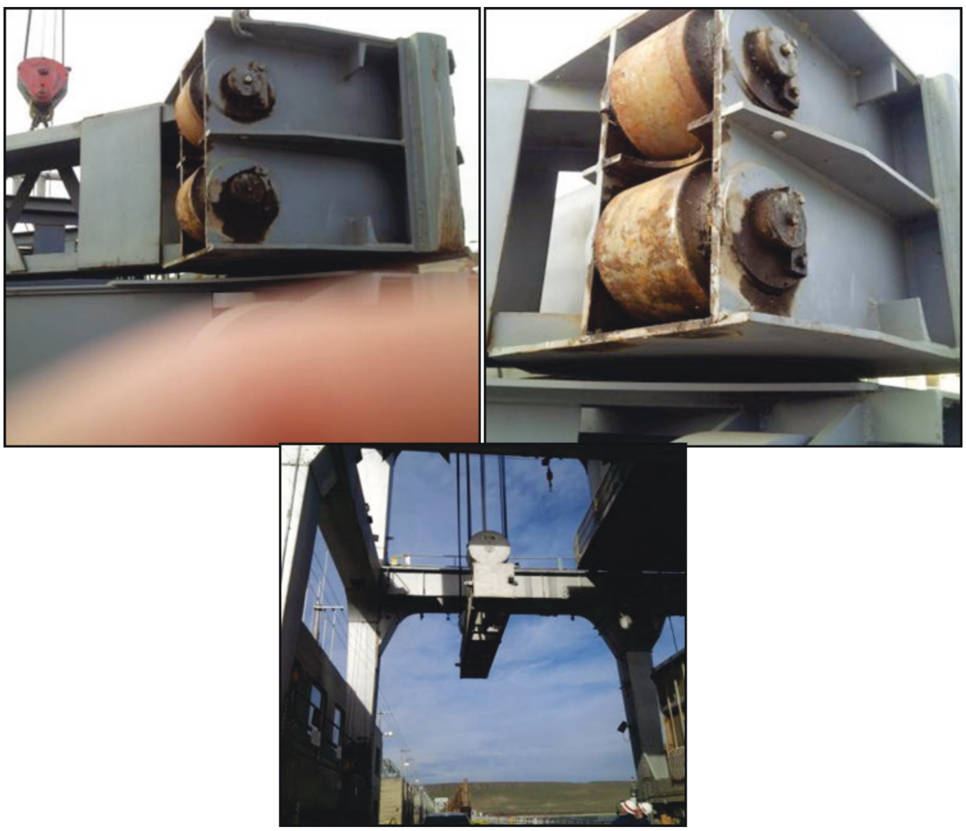
5.8 Cranes and lifting beams

Cranes are used for numerous operations at dams (Figure 27). Depending on the exact use, cranes may contain hoists and wire ropes that actually submerge into the water.

Lifting beams are structures that snap onto overhead crane systems (Figure 28) and are used for a wide range of applications throughout dams. Lifting beams have rollers and other fittings that are commonly greased and can be submerged.

Figure 27. Large crane and hoist at the John Day Dam.

Figure 28. Lifting beams. Close up on rollers show grease application.



5.9 Other

Other lubricant needs include motor vehicles and cable ratchets that operate on the dam. Cable ratchets with lubricated gearing are used at John Day Dam (Figure 29). Although the gearing is housed, leakage can be observed at the fill points. Keysar et al. (2016) discusses environmentally acceptable hydraulic oils that can address issues of leaks and accidental spillage of these materials.

Figure 29. Cable ratchets at John Day Dam.

6 Assessment of Products

The literature contains numerous studies comparing mineral oil lubricants to lubricants that are marketed as environmentally friendly. Various survey reports indicate that although each formulation of lubricants has its respective advantages and disadvantages, there is no inherent advantage to mineral oil lubricants, and that bio-based lubricants and synthetic esters can perform as well, and in some cases far superior (Bartz 1998; Pai and Hargreaves 2002). Pearson and Spagnoli (2000) documented the order of a dozen applications ranging from pump applications, hydraulic oil applications, sewage outfall applications, maintenance of golf course equipment, and construction equipment maintenance, all with successful long term performance.

Regarding application to a dam, the USBR (Hanna and Pugh 1998) conducted a comparison study of various lubricants. Hanna and Pugh (1998) defined a lithium based mineral oil grease lubricant as providing 100% lubrication and the friction torque was measured at 401 in.-lb. A synthetic ester grease reached 93% lubrication (437 in.-lb), this was deemed acceptable performance. Better still, a canola based lubricant (which has been revealed to be VSG, a Tier 1 EAL) outperformed all of the greases, providing 105% percent lubrication and the lowest friction torque at 377 in.-lb.

6.1 Products meeting EAL definition

Products meeting EAL definition were evaluated and the results are summarized in Table 2. Twenty-one greases were evaluated with eleven of them being determined as Tier 1 EALs based on testing, VGP compliance (no other labels were identified), or both. The remaining ten greases met the Tier 2 standard. Of the Tier 2 greases, it should be noted that there were also variations in the quality of data available. Five of these greases contained test data for two of the criteria, but passed the third criteria due to composition or vendor statement. However, the remaining five greases had weaker data sets, with more than one of the criteria based on either composition or vendor statement.

Table 2. Tiered assessment of EALs.

Lubricant	Composition	Label	Bioaccumulation	Toxicity	Biodegradability	EAL
Bioblend BioGrease HD	Canola oil	VGP compliant	Yes, test results	Yes, test Results	Yes, test results	Tier 1
BioBlend BioGrease GP	Canola oil	VGP compliant	Yes, tTest results	Yes, test Results	Yes, test results	Tier 1
Dynagard Blue	Solvent refined mineral oil	None	Yes, vendor's statement	Yes, test results	Yes, test results	Tier 2
Dynagard E	Seed oil	None	Yes, vendor's statement	Yes, test results	Yes, test results	Tier 2
Huskey Lube O Seal	Synthetic ester	None	Yes, composition	Yes, composition	Yes, vendor's statement	Tier 2
Huskey Ecolube EP2	Vegetable oil	None	Yes, composition	Yes, composition	Yes, vendor's statement	Tier 2
Huskey Hydrolube	Synthetic ester	None	Yes, composition	Yes, tendor's statement	Yes, composition	Tier 2
Huskey LVI-50	Synthetic ester	None	Yes, composition	Yes, test results	Yes, test results	Tier 2
ROCOL Biogen Wireshield	Vegetable/ synthetic ester mix	None	Yes, test results	Yes, test results	Yes, test results	Tier 1
Mobil SHC Aware Grease EP 2	Synthetic ester	VGP compliant	Yes, test results	Yes, test results	Yes, test results	Tier 1
Mobil SHC Grease 100 EAL Series	Synthetic ester	None	Yes, composition	Yes, test results	Yes, test results	Tier 2
Renewable Lubricants Bio- EP Wire Rope Lubricant	Vegetable oil	None	Yes, composition	Yes, test results	Yes, test results	Tier 2
Vickers Oil Product Biogrease EP 2	Synthetic ester	VGP compliant	Yes, composition	Yes, test results	Yes, test results	Tier 1
Lubriplate ATB Biobased EP-2 Grease	Vegetable oil	VGP compliant	Yes, test results	Yes, test results	Yes, test results	Tier 1
VSG Wicket Gate Grease	Canola oil	None	Yes, octanol/water coefficient testing	Yes, test results	Yes, test results	Tier 1

The USACE currently reported using six products that were included in the assessment. The VSG Wicket Grease and BioBlend BioGrease are Tier 1 EALs. The Mobil SHC EAL 100 Series, Huskey LVI-50, and Dynagard Blue and Dynagard E all had test results available for two of the criteria (biodegradability and toxicity) and one criteria filled based on base oil composition or vendor's statement (bioaccumulation). Huskey Hydrolube, had a weaker data set, with all three criteria lacking actual test data, being based on either vendor statement or on base oil composition. Panolin BioGrease EP 2 is a Tier 1 EAL that is undergoing testing with the NWD (USACE 2016b).

6.2 Comparison of EALs to greases already in use

The ERDC identified nine test specifications based on review of various literature and reports. These specifications are identified in the first column of Table 3 (EAL candidate greases reported as being used or tested by USACE) and Table 4 (other EAL candidate greases). The ERDC then examined a grease survey conducted by NWP and NWW. While reviewing the survey, the ERDC focused on non-hydropower uses and identified seven greases that were widely used and/or used in high quantities. These were

- Chevron EP NGLI 0
- Chevron EP NGLI 1
- Chevron EP NGLI 2
- Omega 65
- Purplex with Omnistal
- Super GL6 High Core
- Mobil SHC 100 EAL Series.

The first six of these greases are conventional greases, while Mobil SHC 100 is a Tier 2 EAL. The range of performance of these greases was recorded (as shown in the last column of Table 2). The performance range of USACE Engineering and Construction Bulletin (ECB) ECB 2006-11 was also incorporated into this range (USACE 2006). Data for the existing greases were limited to the first six tests, some of the products had incomplete data sets for these tests.

Table 3 compares data for EAL greases that have been reportedly used at USACE dams. VSG Wicket Gate Grease, Panolin Biogrease EP 2, and Bioblend HD1 were Tier 1 EALs. Huskey Hydrolube (D NLGI grade) was a Tier 2 EAL that had data for all of the six tests to compare to the existing greases. For these greases, all of the performance requirements were within or exceeded the range of the existing greases. For the cumulative data available for the Table 3 greases, only one was below the range of the existing greases (the lubricating viscosity for the Huskey Ecolube EP 2). In addition to the data provided in Table 3, Panolin Biogrease EP 2 was tested as part of the HDR (2015) study and found to be suitable for hydropower applications and compatible with most of existing greases currently being used (HDR 2015).

Table 3. Comparison of EAL candidate greases reportedly in use or testing in at least one USACE dam to greases already used by the NWD (last column). Blue greases are Tier 1 EALs, and orange greases are Tier 2. Light green parameters are within ranges of existing greases and ECB 2006- 11 requirements, dark green exceeds those ranges, and yellow is below range. Purple indicates no data found in reviewed sources.

	VSG Wicket Gate Grease	Huskey: Ecolube EP 2	Huskey: Hydrolube (0 NLGI Grade)	Huskey LVI-50	Mobil SHC™ Grease 100 EAL Series	Panolin Biogrease EP2	BioBlend Biogrease M 3	Bioblent Biogrease HD1	Bioblend Biogrease HD2	Range: ECB 2006-11 and existing greases
D217 Penetration of Lubricating Grease (mm)	325	265-295	355-385	280	280	280	220-250	310-340	265-295	267-430
D566 Dropping Point of Lubricating Grease (°C)	260	----	+500	----	265	192	176 D-2265	176	176 D-2265	172-286
D1092 Viscosity of Lubricating Greases (cSt) @ 40°C	429	*35.8 D-445	*7800 D-445	*781 D-445	100	161	*220 D-445	*220 D-445	*220 D-445	*100-460
D1264 Water Washout Characteristic of Lubricating Greases (wt %)	5	----	0.5	1.9	6	4.17	5.4	6	6	0.2-15
D2596 Extreme-Pressure Properties of Lubricating Greases, Four Ball Method [weld point] (kgf)	400	----	160	----	250	315	----	315	315	140-500
D2509 Extreme-Pressure Properties of Lubricating Greases, Timken Method (lb)	55	----	60	35	----	55	----	55	55	25-70
D4048 Corrosion Preventive Properties of Lubricating Greases	1B	----	----	----	1A	1B	----	1A	1A	----
D942 Oxidation Stability of Lubricating Greases by the Oxygen Bomb Method (psi)	10 (100 hours)	----	----	----	----	7.9	----	----	----	----
Rust prevention D1743	----	----	PASS	PASS	PASS	PASS	----	PASS	PASS	----

Table 4 covers EAL candidate greases that apparently have not been used (at the time of this report) at USACE dams. Many of these greases did not contain complete data sets for the six parameters to compare. However, the Vickers Biogrease EP 2 and the Lubriplate Biobased EP-2 contained complete data sets to compare. In addition, the available parameters met or exceeded the performance range of existing greases.

Table 4. Comparison of EAL candidate greases that have not been used to date at a USACE dam (to the best of our knowledge) to greases already used by the NWD (last column). Blue greases are Tier 1 EALs, and orange greases are Tier 2. Light green parameters are within ranges of existing greases and ECB 2006-11 requirements, dark green exceeds those ranges, and yellow is below range. Purple indicates no data found in reviewed sources.

	MOBIL SHC Grease 100 EAL Series	MOBIL SHC Aware Grease EP-2 (VGP)	Huskey Lube O Seal Grease	Huskey Ecolube EP 2	Huskey Hydrolube (0 NLGI Grade)	Dynaguard Blue	Dynaguard E	Renewable Lubricants Bio-EP Wire Rope	Vickers Oil Product (Biogrease EP 2) (VGP)	VSG Wicket Gate Grease	Lanopro EP Grease 53	Envirologic 803 Grease (VGP)	Shell Naturelle Grease S5 V120P 2	Shell Naturelle S2 Wire Rope Grease A (VGP)	Lubriplate Biobased	Omega	Ranges found in greases currently used by NWD	Ranges given in ECB 2006-11
D217 Penetration of Lubricating Grease (mm)	280	280	280	265-285	355-385	305	301	--	--	325	265-295	265-295	--	--	265-295	400-430	267-430	--
D566 Dropping Point of Lubricating Grease (deg. C)	265	>160	--	--	500	177	Over 200	--	178	260	>140	550	180	120	385	--	172-286	--
D1092 Viscosity of Lubricating Greases (cSt at 40 C)	100	150	200	35.8 (D445)	200 (D445)	--	--	212	--	429	--	--	--	120	100	350 (D88 @100F)	220-460	--
D1264 Water Washout Characteristic of Lubricating Greases (wt %)	6	7	0.01	--	0.5	--	--	--	1.8 @ 38C 6.1 @79C	5	<5	4	--	--	1	--	0.2-15	1.9% max.
D2596 Extreme Pressure Properties of Lubricating Greases Four Ball Method [weld point] (kgf)	250	400	--	--	160	250	--	450	>480	400	--	400	--	--	250 (D2783)	--	250-500	140 min.

	MOBIL SHC Grease 100 EAL Series	MOBIL SHC Aware Grease EP-2 (VGP)	Huskey Lube O Seal Grease	Huskey Ecolube EP 2	Huskey Hydrolube (0 NLGI Grade)	Dynaguard Blue	Dynaguard E	Renewable Lubricants Bio-EP Wire Rope	Vickers Oil Product (Biogrease EP 2) (VGP)	VSG Wicket Gate Grease	Lanopro EP Grease 53	Envirologic 803 Grease (VGP)	Shell Naturelle Grease S5 V120P 2	Shell Naturelle S2 Wire Rope Grease A (VGP)	Lubriplate Biobased	Omega	Ranges found in greases currently used by NWD	Ranges given in ECB 2006-11
D2509 Extreme-Pressure Properties of Lubricating Greases, Timken Method (lb)	--	--	40	--	60	--	--	70	40	55	--	60	--	--	40	--	25-70	--
D4048 Corrosion Preventive Properties of Lubricating Greases	--	18	--	--	--	--	--	1B	--	1B	--	1A	--	--	1A	--	--	--
D942 Oxidation Stability of Lubricating Greases by the Oxygen Bomb Method	--	--	--	--	--	--	--	--	--	10 (100 hrs)	--	0 psi at 100 hrs -2 psi typical @ 500 hrs	--	--	3 psi/100 hrs	5.0 max	--	--
D1743 Rust Prevention	PASS	PASS	PASS	PASS	PASS	PASS	PASS	PASS	--	--	--	--	--	--	--	PASS	--	--
D1742 Non-Separation in Storage (%)	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0.5 to 1.0%

6.3 Comparison of EAL performance specifications to published performance requirements

The ERDC pursued several venues to find published performance requirements for greases in non-hydropower roles. One document was found, USACE ECB 2006-11 (USACE 2006), this focused on Tainter gate trunnion lubrication. The tests and criteria are presented in Table 5, this compares how the EALs performed. Although the data is spotty, at least one EAL grease met each requirement (although separation was not evaluated). Only two of the EAL greases met the viscosity requirement (Huskey Hydrolube and Huskey LVI-50, both Tier 2 EALs), but none of the existing non-EAL greases met the target value. Huskey Hydrolube has an unusually large viscosity. To ensure accuracy, the value was reassessed using specification sheets provided by Huskey. EM 1110-2-1424 was used to investigate this issue and indicated that the viscosity in ECB 2006-11 was too high for most applications (USACE 2016a).

Table 5. Comparison of EAL performance to target performance values given in ECB 2006-11.

Test	Purpose	Requirement	EAL performance
ASTM D-1743	Rust Prevention	Pass	13 of the EAL greases had this data and all passed
ASTM D-1264	Water washout	Max. 1.9%	15 of the EAL greases had this data, 6 met the criteria. Most of the mineral oil greases evaluated did not meet this criteria.
ASTM D-217	Worked Penetration	NGLI 1	The EAL greases had a range of NGLI numbers. In particular, VSG and Mobil EAL 101 are NGLI 1
ASTM D-445	Viscosity	Minimum 700 cSt at 40C	Only two of the EALs met this. However, none of the existing mineral oil greases had this level either. EM 1110-2-1424: Viscosity too [illegible]
ASTM D-2596	Antiwear/scuffing	Wear load index 40 kgf Weld point 140 kgf	All the EAL greases exceeded the weld point.
ASTM D-4048	Prevention of Copper Corrosion	1B	5 of the greases are listed as 1B
ASTM D-1742	Non-separation in storage	0.5 to 1%	Not evaluated

6.4 Interviews with engineers and operators who are already using EALs

The ERDC interviewed (via phone, e-mail, or face-to-face discussion) the following people who have used EALs at dams. The following testimonials discuss the implementation and use of EALs in numerous environments.

Bob McKeown, Orillia Power District, Canada. Orillia Power is located in Canada, and is subject to subzero weather. They use VSG grease (a Tier 1 EAL) for wicket gates and for other purposes.

> *"We have not had any operating difficulties with the (VSG) grease at our plants that I am aware of. We use it to lubricate our wicket gates, and it was adopted to mitigate concerns about its contact with water (i.e., pollution). Our staff also used it on the vertical screw arrangement on our two sluice gates at our Matthias plant in Bracebridge. I have not heard of any issues in regards to the screw application, and this application is outdoors in severe weather (-30^{o} C in the winter, +30^{o} C max in the summer)."*
>
> In terms of a new application:
>
> *"I was not with the company when the changeover was carried out, but I think they would have just started to pump in the new grease without removing the old. The manufacturer would likely have some input on this. I don't have any idea of what was used previous to this product. We do use the grease on some sluice gate screws - these stand about 20 feet (ft) in the air on top of a dam with no wind break or shade, and we have found that it seems to adhere to the steel fairly well, and have not heard of any issues with the grease itself."*

Kelly LaCoste, USBR. Reliability Program Analyst. Power Resources Office, Parker Dam.

> *"Yes, we used VSG wicket gate grease (http://vsggrease.com/) at Parker Dam (you will see a picture of Parker Dam when you open up their website). It performed well at Parker. We*

had approximately 80 ft of hydraulic head and ~28 pounds per square inch (psi) at the gate.

I would recommend this as a 'Green Grease', the only draw back is if you use it outside of water (i.e., on the fixed wheel gates), it would separate (oil/wax) in the heat for those wheels above the waterline (Parker sees in excess of 120° F in the summer), but performs well on the Wicket Gates."

Parker Dam has a long history of use of VSG, as documented in USEPA (2002).

Frank Salber, USACE. The Dalles Dam. Mobil EAL 101 and Huskey LVI 50 are both Tier 2 EALs.

"The trunnion bearings on the NL upstream gate and spillway all use Mobil SHC EAL 101 and it works. For fish weirs, we use Huskey LVI 50. All wire ropes use Omega#65."

In a meeting at The Dalles Dam on 10 February 2015, engineers and operators discussed implementing the Mobil SHC EAL 101 grease. Unfortunately, no one on staff remembered the process of implementation of the grease. However, the engineers and operators confirmed that they had not undertaken any significant grease removal or overhaul, or it is doubtful the grease change would have been implemented.

William Lewis, TVA, stated that VSG actually performed better than mineral oil greases.

"TVA started using the VSG product about 14–15 years ago on one of the units at Fontana Dam. This was just following a discovery of some problems with greaseless wicket gate bushings. Fontana was chosen because it had three units, one with greaseless bushings, one using grease from mineral oil, and one where the VSG was used. All three units had a differential pressure transmitter across the servo motors.

The trends over the first 5 years showed the VSG was better than the mineral oil grease by a consistent 10 psi.

The greaseless bushings also performed just as well, but due to greaseless bushing issues at other TVA dams, a decision was made to continue using the greased bushings.

Over the following years, almost all of our units have been changed to the VSG grease for greasing wicket gate bushings. The grease has what appears to be an infinite shelf life (over 5 years), while the mineral oil grease would separate after 2–3 years."

Isaac Allen, a Mechanical Engineer at TVA.

"Mobil - EAL 101 and 102 is used on Spillway gate wheels, radial gate chains, and Howell-Bunger Valve drive screws. Approved for TVA use in submerged service. This is a mineral oil (it is actually a synthetic ester) lubricant that is bound very well to the thickeners. Release of oil into water is nearly insignificant."

Eric Jones, Maintenance Mechanic at Bluestone Dam (USACE Huntington District, [LRH]) shared his experiences with BioBlend products, all of which are Tier 1 EALs, as well as some Mobil products.

"We have been using Bioblend products for roughly the last year with no issues. We have been happy with their performance.

Cost of the Bioblend is significantly lower than the Mobil brand EAL."

Regarding implementation, compatibility.

"We have yet to encounter any issues. The compatibility of Bioblends products with the previously used Mobil products is seamless. As for transitioning to Bioblend from traditional greases and lubricants, it is just a matter of clearing the traditional grease and applying. No issues noted."

In one case, a wire rope application, the BioBlend product did not work as well as the previous grease.

> *"We did a side-by-side comparison of the BIOGrease and the Kirkpatrick Group Dynagard Blue Environmental Wire rope Lubricant because our crane had side by side wire rope spools and we could compare them accurately. The Dynagard Blue outperformed the BIOGrease in this application. In BioBlend's defense, the product was new, and they had not designed it to work with the applicator that we used."*

However, for other applications, the BioBlend worked as well or better than previous greases used.

> *"We have used Bioblend tube grease and their penetrating oil. Both have seemed to perform well."*

Mr. Jones indicated that BioBlend is willing to work with them and modify formulations for better performance

> *"Overall, we are happy with the Bioblend products in both price and performance. They are also a good company to work with because they are interested in making both products that we need and finding ways to adapt their products to our uses."*

The ERDC team contacted Dr. Alex Qiang of Exxon/Mobil regarding Mobil SHC Environmental Aware EP2 grease, which is a Tier 1 grease with promising characteristics.

> *"I don't have any experience of applying Aware Grease EP 2 into any hydropower dams, so I can't guarantee it would work properly. The base oil of Mobil SHC Aware Grease EP 2 is only 150 centi-Stokes (cSt) and I guess it might be a little bit lower in terms of dams."*

This should not rule out the use of this grease, but it does suggest that its application should be conducted cautiously.

HDR (2015) also sought user information primarily by using questionnaires. One of their results indicated that a user of Shell Naturelle grease found its performance was not satisfactory, and they returned to the previously used mineral oil grease.

These testimonials suggest that several types of Tier 1 and Tier 2 EALs, particularly VSG, BioBlend, and Mobil EAL 100 series, have been used in dam projects with no adverse effect on performance, and their implementation should not be an insurmountable obstacle. However, the HDR report found an unfavorable review of the Shell Naturelle product.

7 Costs

Costs are a key factor in EAL implementation. It is generally accepted that EAL products will be of higher costs. However, there are other factors that might ultimately make using EALs more cost-effective.

7.1 EAL costs in the literature

Medina (2015) reviewed literature on costs and found that base costs of EALs in comparison with mineral oil-based lubricants are 1.2 to 3 times higher on average (Table 6). Some high performance synthetic ester formulations can cost 20 times more than their mineral oil equivalents, although their performance characteristics are generally much superior (Nagendramma and Kaul 2012).

Table 6. Cost comparison of greases suitable for wicket gate application.

Grease	Cost Source	Base cost ($)	Quantity	USACE Project Experience
EAL				
Panolin Biogrease EP 2	Panolin USA	$2,261.32	Drum (55 gallon)	Being tested by NWD on 8 dams (USACE 2016b)
VSG Wicket Gate Grease	From Via Canoil Canada LTD	$2,723.66	Drum (55 gallon)	Dworshak
BioBlend	BioBlend	~$1,500.00 (based on price per pound)	Drum (55 gallon)	Bluestone Lake
Mobil 101 SHC EAL	From John Day Dam	$2,549.81	Drum (55 gallon)	John Day
Other Greases				
Chevron EP NLGI 1	Grainger	$2,155.68	Drum (55 gallon)	Multiple
Chevron EP NLGI 2	Grainger	$2,155.68	Drum (55 gallon)	Multiple
Chevron FM ALC EP1	Grainger	$2,644.09	Drum (55 gallon)	Multiple

7.2 A survey of EAL costs vs. existing lubricants at USACE dams

Table 6 shows costs the authors obtained from a number of sources comparing greases suitable for wicket gate application and other related uses. Interestingly, the costs do not show a substantial difference between

EAL products and mineral oil greases. Mobil EAL (Tier 2) and VSG (Tier 1) were approximately $400.00 and $500.00 per drum, respectively, more expensive than that of the Chevron EP products. The Mobil EAL product was actually a little less expensive than the Chevron FM ALC product, and the VSG was less than $100 more expensive. Panolin Biogrease EP 2 was only slightly more than the Chevron EP products, and less expensive than the Chevron FM ALC product. In addition, the BioBlend BioGrease HD, a Tier 1 EAL, was the least expensive material evaluated.

Dam operators estimated that a typically dam uses one to five drums of wicket gate grease per year (the grease may be used for many other uses). If the greatest cost difference (VSG grease vs. Chevron EP NGLI grease) is considered, this is a cost differential of $567.08 to $2,839.90 annually.

7.3 Cost difference vs. operating costs

Even considering the greatest cost differential (VSG grease to Chevron EP products), contrasting this cost to the costs of dam operation and maintenance is virtually insignificant. For example, a study by Kenyon College estimated the operating costs of the Bonneville Dam at $10 million per year (Kenyon College 1998). A study of structures managed by the USACE Mississippi Valley Division (MVD), Rock Island District (MVR), estimated maintenance issues for eight dams to range from $39 to $181 million (USACE 2012). Based on the Bonneville costs, the cost differential of switching to an EAL, assuming the same usage rate and the greatest cost difference found in Table 5, would be on the order of 0.03% increase in the operational costs.

7.4 Costs associated with continued mineral oil use

It is also important to assess costs associated with continued mineral oil use, particularly, if there are any legal actions taken regarding environmental protection. Johnson (2014) documents efforts by the Riverkeepers, an environmentally oriented action group, to address perceived issues with lubricants in rivers of the Pacific Northwest.

Addressing these issues required legal expertise for USACE. Estimating legal costs at $200/hour, a week's worth of legal costs by a single person could pay for two or three years of additional costs of EAL lubricants, even when considering the greatest cost differential.

7.5 Transitioning costs

There can be additional costs associated with transitioning from a mineral oil lubricant to an EAL. These costs can include (estimated costs in parentheses)

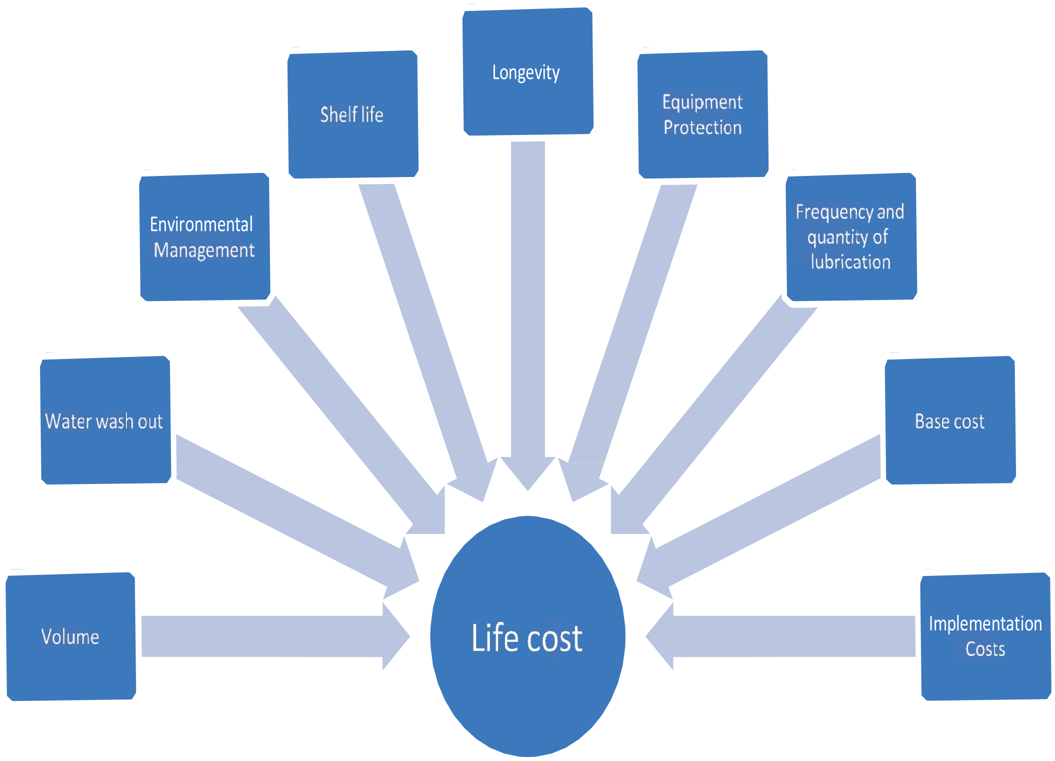
- Labor and effort to research and identify an appropriate EAL product. (50% of four weeks at $90/hour = $7,200).
- Laboratory testing to assess compatibility with existing mineral oil lubricant and/or performance characteristics. ($5,000 to $15,000).
- Costs of cleaning or removal of previous lubricant from system. (up to $20,000)
- Studies to assess performance of EALs in a controlled setting to insure effective performance. (A large range, but a study currently being conducted with a working cost just under $1.7 million).

Not all of these costs will be necessary in all cases. For products with a long history of successful application, it may simply require identification and application. However, for more risky changeovers, a thorough set of studies might make sense. As time goes on, with more experiences to share between various USACE projects, it is anticipated that transitioning costs will be steadily reduced.

7.6 Life cycle cost model

Figure 30 is a conceptual lifecycle model to fully assess the cost impacts of changing from a mineral oil to an EAL. There are several costs that are expected to increase, like base cost and implementation costs. However, there are several long term benefits that may result in lower overall life cycle costs. These are discussed below.

Figure 30. A conceptual life cycle model to compare lubricants.



7.7 Base cost

Base cost is the most fundamental cost differential. Some lubricants cost more than others, however, an investigation into lubricant costs suggests that price differences between lubricants is not excessive (Table 5).

7.8 Frequency and quantity of lubrication

Generally, the operation governs the frequency and quantity of lubrication, but this can be affected by the properties of the lubricant itself. Even if a lubricant does allow for less quantity, it is common for over-lubrication to occur, as the costs of the lubricants are generally minuscule compared to the consequences of insufficient lubrication.

7.9 Water wash out

The standard test method for determining the water washout characteristics of lubricating greases is ASTM D1264-16 (ASTM 2012). This method consists of resistance of lubricants to washout by water from a bearing when tested under various conditions.

Greases that have the capability to resist softening and emulsification will not wash out of the bearing. If wash out does occur, there can be several consequences of the particular grease. There can be a reduction in the bearing life, increased wear, increased grease consumption, rusting and corrosion of moving parts, and the inability to act as a seal against contaminants. Research conducted for this report suggests that EALs have comparable washout characteristics to standard mineral oil alternatives and are often superior (Tables 3 and 4).

7.10 Environmental management

In the case of many operations at dams, there is a release of lubricants into the environment. The quantities may be small, but this could result in unfavorable public relations and even legal action, therefore, the role of public awareness towards lubricants in dams must be considered.

Furthermore, long-term environmental damage by toxic lubricants could be assessed by studies and result in substantial costs towards USACE.

7.11 Shelf life

Shelf life represents the time period during which a stored product can continue to be used without quality-control checks to verify performance attributes. Shelf life recommendations can be provided for customers from the particular vendor. In addition, shelf life recommendations apply to lubricants that have been stored in their original, sealed containers under proper conditions. At the end of the shelf life period, laboratory testing can be done to ensure the product will continue to provide desired performance. A longer shelf life can result in purchasing in bulk, this may reduce costs.

7.12 Longevity

The longevity of lubricants varies depending on the properties associated with the lubricants. This can dictate how often the lubricant has to be added to the perspective area. The longevity and quality of the lubricants is based on a case-by-case basis.

7.13 Equipment protection

Equipment damage caused by poor lubrication is a serious problem and can occur internally and externally. This can include wear, corrosion, abrasion, and pitting (USACE 2016a). Such damage requires that the operation be discontinued and parts replaced, sometimes this can be very expensive. Even worse is catastrophic failure, this can be enormously expensive and may result in injury or death. Obviously, saving money on less expensive lubricants does not make sense if it does not properly protect the equipment or process. It is critical that an EAL provide the same level of, or greater, protection as a mineral oil lubricant in regards to this issue.

7.14 Frequency of lubrication

The frequency of lubrication differs among different greases. Temperature, friction, frequency of operation, condition of bearing surfaces (e.g., rust, pitting), and whether the equipment is submerged are factors that affect the frequency of lubrication.

7.15 Implementation costs

Implementation costs consist of any expenses associated with implantation, including research of new EAL products, laboratory testing, costs associated with removal of previous grease (if needed), and demonstration costs.

8 Conclusions

A two tiered definition was developed for EALs. Tier 1 EALs either are certified by an acceptable labeling program, or have test data for all three criteria (i.e., biodegradation, bioaccumulation, and toxicity). Tier 2 EALs are not labeled and lack data for at least one of the criteria, but are classified based on vendor statement and/or base oil composition. The following conclusions were derived from this study:

- There are numerous above-water and in-water lubrication needs at USACE dams that could use EALs.
- A strict EAL definition (i.e., products that have test results for accumulation, biodegradation, and toxicity, equivalent to Tier 1 definition) would limit EAL choices, and may actually result in less adaptation of environmentally beneficial lubricants. Therefore, a tiered EAL definition is recommended.
- ERDC found twenty-one greases that qualify as EALs, nine as Tier 1 and twelve as Tier 2. Five of these greases are already being used at USACE dams (Mobil SHC 100 series, VSG, Huskey Hydrolube, Huskey LVI 50, and Bioblend Biogrease HD). VSG and the BioBlend grease are Tier 1 greases, and the others are Tier 2 greases.
- EAL greases (both Tier 1 and 2) have similar performance requirements for non-hydropower uses of the dams compared to greases currently being used.
- At least two EAL greases meet each of the performance requirements given by ECB 2006-11.
- Testimonials from longtime users of EAL qualifying greases indicate that they are satisfied with their performance, and in some cases, indicate even better performance than previously used mineral oil greases. Although there were not a lot of details on the implementation, it appears that the process was relatively easy and did not involve complete removal of the previous grease.
- There is a need for extensive hydropower use for some of the greases. Care should be taken in applying grease without any hydropower experience, even if the specifications are in range.
- Studies documented in the literature also indicate EALs can perform as well as mineral oil greases for a wide range of applications.
- In some cases, EALs cost more than conventional mineral oil lubricants, but the additional costs are small compared to the overall costs of dam operation. Furthermore, evaluating costs that could be

associated with environmental litigation or cleanup could make EALs a cost-effective choice. However, transitional costs could be high in some cases.

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14. ABSTRACT
This report explores the use of environmentally acceptable lubricants (EALs) for U.S. Army Corps of Engineers (USACE) dams in the Pacific Northwest. This report also identifies above-water and in-water structures where these lubricants would be useful. The U.S. Environmental Protection Agency (USEPA) defines EALs in document 800-R-11-002. However, this definition has a range of ambiguity; therefore, the authors of this report propose a tiered definition in which Tier 1 EALs undergo testing to demonstrate that they meet requirements of toxicity, biodegradability, and bioaccumulation. Tier 2 lacks some test data, but it is made of materials that the EPA considers to be consistent with an EAL. The authors assessed 21 lubricants that met either Tier 1 or Tier 2 EALs. The authors found EALs met performance requirements comparable to the mineral oils currently used in USACE dams. In fact, there are already EALs being used effectively in USACE dams as well as with dams operated by other organizations. The authors also found that the costs of EALs is competitive with that of mineral oil lubricants and that EALs can be readily used in USACE dams.

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