ERDC WQTN-MS-9
August 2015

Evaluation of Environmentally Acceptable Lubricants (EALS) for Dams Managed by the U.S. Army Corps of Engineers

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PURPOSE: The purpose of this study is to provide a preliminary assessment of Environmentally Acceptable Lubricants (EALs) for application in dams that are managed by the U.S. Army Corps of Engineers (USACE). The assessment will explore the environmental aspects of these lubricants and will also discuss their operational characteristics. This assessment is primarily through the literature available on this topic, and includes interviews with various experts.

BACKGROUND

Affected Dams. This project will focus on eight (8) dams in Washington State and Oregon:

- Bonneville
- John Day
- McNary
- The Dalles (Figure 1)
- Ice Harbor
- Lower Monumental
- Little Goose
- Lower Granite

Of these dams, three are reported to already have used EALs: Bonneville, John Day and The Dalles.

Structures. The settlement focuses on the application of EALs on "in-water" structures. These include wicket gates for hydropower turbines, navigation locks, and fishway equipment. The purpose of the assessment is to determine whether EALs could be safely used without compromising the target equipment. By in-water nature, the focus is primarily on greases, but other in-water lubricants could be affected.

Figure 1. The Dalles Dam, spanning the Columbia River between Washington state and Oregon.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 2015**	2. REPORT TYPE	3. DATES COVERED **00-00-2015 to 00-00-2015**

4. TITLE AND SUBTITLE **Evaluation of Environmentally Acceptable Lubricants (EALS) for Dams Managed by the U.S. Army Corps of Engineers**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Engineer Research and Development Center,,Vicksburg,,MS**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**21**	

LUBRICANTS

Purpose. Lubricants are used on moving surfaces and have several purposes, which are summarized by USACE (1999), EM 1424, and the USACE lubrication manual, which is currently being revised. Lubricants serve to reduce friction, making movement operations easier and less energy intensive, and they reduce wear on affected surfaces and dissipate heat. They also provide a protective barrier to oxidation, thereby reducing corrosion. Additionally, they can provide insulation, transmit chemical power, and seal against dirt, dust, and water.

Lubricants work by serving as a lower viscosity material between moving surfaces. The wearing surfaces are replaced by a material with a lower coefficient of friction. Any material that accomplishes this can serve as a lubricant, but the most common substances are oil and grease.

Types of Lubricating Oils/Greases

Mineral Oils. Typical lubricants are composed of petroleum fractions called mineral oils (Haus et al. 2001, Nagendramma and Kaul 2012). Mineral oil derivations are generally effective for most lubricating applications, and their performance is usually considered as a baseline for comparison in most studies. Mineral oils are also the least expensive of the lubricating materials, even lower cost than vegetable oils. Mineral oil lubricants can biodegrade, but the process is generally slow, and the toxicity of mineral oils tends to be problematic. However, used mineral oil lubricants can be recycled in certain applications.

Bio-based lubricants (Vegetable Oils). Biobased lubricants, often referred to as vegetable or plant oils or biolubricants, are lubricants derived from natural sources with minimal modification (Salimon et al. 2012). Vegetable oils are the most common and include canola oil, castor oil, palm oil, sunflower seed oil, sesame seed oil, rapeseed oil, soybean oil and coconut oil (Durak 2004, Jaydas and Prabhakaran Nair 2006, Miller et al. 2007, Nagendramma and Kaul 2012, Salimon et al. 2012). Tall oil is derived from trees and typically recovered during paper milling. Technically, animal oils also can be used, and historically, whale oil was a very effective lubricant. However, there are no animal oil lubricants on the market at this time. All of these sources generally have their lubricating properties derived from triglyceride esters (Nagendramma and Kaul 2012, Figure 2). Biobased lubricants have some limitations, particularly at low temperatures, but in the right application, their performance can actually match or even exceed that of mineral oils (Anand and Chhibber 2006). Furthermore, biobased lubricants can be modified thermally or chemically to improve certain performance characteristics. Biobased lubricants generally biodegrade quickly and are usually far less toxic than mineral oils. In fact, in most cases, biobased lubricants are the most environmentally friendly option.

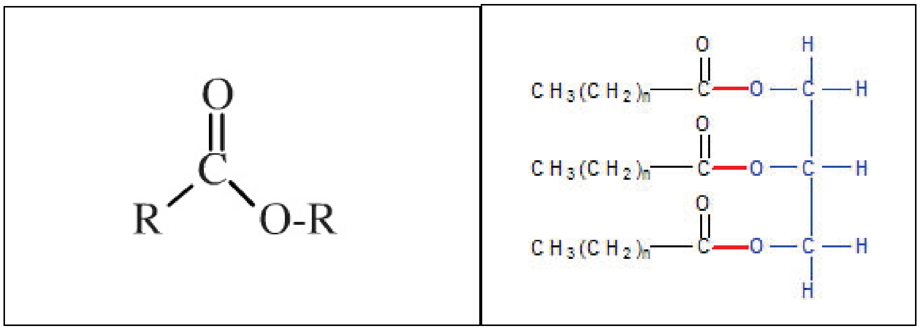

Figure 2. A generalized ester bond and a triglyceride ester (the common structure in biolubricants).

Synthetic Lubricants. Synthetic lubricants are formulated via chemical synthesis to create materials with desirable properties for lubrication (Nagendramma and Kaul 2012, USACE 1999). Chemicals used in synthetic lubricants can be derived from petroleum or from plant sources. Synthetic lubricants can be formulated to have properties far superior to mineral oil lubricants, and they can be synthesized precisely, so as to have unparalleled consistency of properties. Furthermore, it is possible to include labile structures that facilitate biodegradation while reducing toxic exposures compared to mineral oil lubricants. However, synthetic lubricants are significantly more expensive than either mineral-oil- or vegetable-oil-derived lubricants (Nagendramma and Kaul 2012, USACE 1999).

Synthetic Esters. Synthetic esters are lubricants generally derived from biological or petroleum sources, which are chemically modified to form a wider range of synthetic esters (Nagendramma and Kaul 2012, Figure 2 shows a basic ester structure). Synthetic ester-based lubricants are often derived for very high performance applications, such as racing and jet engines. They are also widely used for military applications, because they can be formulated to last far longer than mineral oil or biolubricants. They can be very expensive, however.

Polyalkaline Glycols (PAGs). PAGs are derived from petroleum sources, but are modified to form glycols (Beran 2003, Nagendramma and Kaul 2012, Figure 3). Overall, PAGs make up the smallest category of lubricants.

Polyalphaolefin (PAO) lubricants. PAO lubricants are synthetic oils that have been widely developed for a variety of uses, and have been used for many years. However, recent formulations have been developed to meet environmental performance criteria.

Additives. Lubricating oils typically include additives that can improve performance (Herdan 1997). These include oxidation inhibitors (anti-oxidants), rust inhibitors, extreme pressure agents, antiwear agents, and friction-reducing materials (Duzcukoglu and Acaroglu 2010, USACE 1999, Wright 2008). However, these additives can also affect the environmental effects of the lubricants, most commonly making them worse (particularly by increasing their toxicity). However, sometimes environmentally acceptable materials can be used as additives, improving the overall environmental friendliness of the product (Durak 2004).

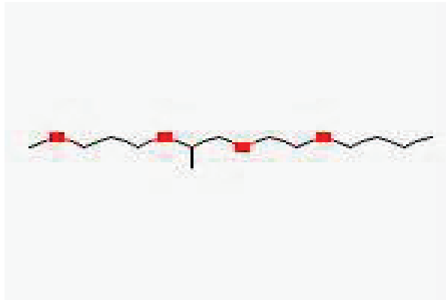

Figure 3. An idealized polyalkaline glycol (PAG) structure.

Blends. Different lubricating materials can be blended together to create new lubricant combinations that combine the strengths of the different materials. Blending can be effective, but it is also a complex process. Not all lubricating materials are miscible in others; thus when creating blends, one must consider compatibilities of the different stock materials.

Grease. Grease is a semi-fluid to a solid mixture designed for lubrication, and consists of a base oil, thickener(s), and additives (USACE 1999). The base oil (discussed in the sections above) actually provides the lubricating properties. Grease also contains thickeners, which are often referred to as soaps that act like a sponge that holds the lubricant together (USACE 1999, Wright 2008). These are generally solids or semi-solids to make the lubricant more thick, like a paste material. Metal soaps based on lithium, aluminum, clay, polyurea, sodium, and calcium are most common. Complex thickeners can be composed of metal soaps mixed with low-molecular-weight organic acids. Non-soap thickeners are sometimes used for high-temperature applications, and include bentonite and silica aerogels. Additives are generally added to customize performance.

Greases can differ in consistency based on their formulation, and these differences can be used in customizing their applications. The National Lubricating Grease Institute (NGLI) has a rating system that is called the NGLI consistency number or the NGLI grade. These range from 000 to 6, with a range from cooking oil to cheddar cheese. The most common greases used in the dam projects are from 0 to 3, which range from brown mustard to vegetable shortening. NGLI 2 is the most common consistency, and is termed “normal grease,” and has a consistency of peanut butter.

Greases are particularly useful for applications that run intermittently and for external applications. The thickener helps the lubricant stay in place without a containment system. The in-water applications specified by the Riverkeepers’ settlement are best served by greases.

Lubrication Needs of Dams. Dams use a very wide range of equipment that requires lubrication; as a result, dams use large amounts of lubricants and commonly have large quantities of lubricants on site. Turbines and electrical generating equipment use large quantities of lubricating oils. In-water structures, like wicket gates and lock gates, use greases. There are boats and maintenance equipment as well. Environmental releases of the lubricants are, apparently, common. These can be intentional, as in the case of in-water use of a lubricant, or unintentional, as in the case of a spill.

Environmental Effects of Lubricant Releases. It has been estimated that 40 kilotons of lubricating oils of all kinds are released into the environment annually (Bartz 1998). Betton (2010) estimated that 15% of lubricants used in the European Union are either unaccounted for or even intentionally released into the environment. Etkin (2010) estimated that a combination of leaks and operational releases of lubricating oils into marine waters reach a level of 36.9 to 61 million liters annually — about 1.5 times the size of the Exxon-Valdez oil spill — moreover, the cost of the environmental damage was estimated at $322 million (Etkin 2010).

Brunner and Salmon (1997) documented that oil and lubricant leaks from hydroelectric dams are a significant environmental risk, and they developed a model to assess risk for dams in Canada. Similarly, Verlind et al. (2004) reported that concerns over lubricating oil releases in Sweden led to research to develop new Kaplan runners for their turbines that reduced and even — in some cases — eliminated lubricating oil use. The Riverkeepers reported significant releases of oils of all kinds from dams on the Columbia and Snake Rivers (Johnson 2014). Reported leaks of up to 1,680 gallons are mentioned, and some of the leaks were reported to contain polychlorinated biphenyls (PCBs), which are highly regulated and very resistant to biodegradation (Johnson 2014).

ENVIRONMENTALLY ACCEPTABLE LUBRICANTS

Definition. "Environmentally friendly lubricants" is a loose term that defines a lubricant that would be expected to have a neutral-to-slightly-negative (within an acceptable level) impact on the environment if released. The term "Environmentally Acceptable Lubricant" (EAL) is a restrictive term that implies that the product has met certain requirements. The USEPA (2011) defines EALs as meeting specific, albeit broad, criteria for biodegradation, aquatic toxicity, and bioaccumulation (these are discussed in more detail in subsequent sections). Furthermore, the USEPA definition is particularly targeted for marine usages of lubricants, although its definitions could be applied to other usages. USACE (1999) discusses EALs in Chapter 8.

The EPA also defines EALs in its requirements of vessel general permit requirements (VGP) (USEPA 2013, see Appendix A). The definition is essentially identical to that found in 800-R-2-002, although some additional details are provided concerning testing. Therefore, we can determine that any grease certified to meet VGP requirements is an EAL.

Generally, it is assumed that mineral oil lubricants do not meet EAL requirements and that biolubricants are essentially EALs. However, the general definition of an EAL does not specify the composition of the lubricant; although some of the labeling programs do consider this (see Other Factors and Labeling sections).

Biodegradability. Biodegradability measures the breakdown of the chemical structure of the lubricant by microorganisms (USEPA 2011). Two types of biodegradation are identified in evaluating lubricants. Primary biodegradation is the loss of one or more active groups that reduces or eliminates the toxicity of the lubricants. Ultimate biodegradation is the mineralization of the compounds to carbon dioxide and water. Compounds that are inherently biodegradable are those that can degrade in any test, and those that are readily biodegradable show a fraction of removal within a specified time frame. Table 1 summarizes tests commonly used to determine the biodegradability of chemicals, and which are or can be used to assess lubricants.

Table 1. Commonly used test methods for measuring biodegradability (adapted from Willing 2001 and USEPA 2011).

Test Type	Test Name[a]	Measured Parameter[b]	Pass Level (degradation greater or equal)	Method[c]
Readily biodegradable[d,e]	DDAT	DOC	70%	OECD 301A
	Strum test	CO_2	60%	OECD 301B
	MITI test	DOC	70%	OECD 301C
	Closed bottle	BOD/COD	70%	OECD 301D
	MOST	DOC	70%	OECD 301E
	Sapromat	BOD/COD	60%	OECD 301F (OECD 2012 for all OECD tests)
	Shake flask test	CO_2	60%	EPA 560/6-82-003 (USEPA 1982b)
	Strum test	CO_2	60%	ASTM D-5864-11 (ASTM 2011)
	BODIS test	BOD/COD	60%	ISO 10708 (ISO 1997)
Hydrocarbon degradability	CEC test	Infrared Spectrum	80%	CEC L-33-A-934
Screening	CO_2 headspace	CO_2	60%	ISO 14593 (ISO 1999)

a DDAT = DOC Die away test, MITI – Ministry of Trade & Industry, Japan, MOST = Modified OECD Screening Test, BODIS = BOD of insoluble substances
b DOC = dissolved organic carbon, BOD = biochemical oxygen demand, COD = chemical oxygen demand
c OECD = Organization of Economic Cooperation and Development, EPA = U.S. Environmental Protection Agency, ASTM = ASTM International, ISO = International Organization for Standardization, CEC = Coordinating European Council.
d Tests that show a specific target degradation (implies mineralization) within a specific time period.
e Each of these tests also can be used to determine inherent biodegradability – if 20% biodegradation is observed during the test period.

Mineral oils typically biodegrade, but the processes are slow and may be incomplete. EALs tend to biodegrade faster and more completely, with vegetable oils in particular showing rapid rates (Aluyor et al. 2009). Battersby (2000) studied the degradation of various lubricating oils using the CEC L-33-A-93 test, and found that vegetable oils were >95% degraded in 21 days, while mineral oils range from 4 to 57% in the same time period. In general, the following pattern is found for biodegradability:

Mineral oil < Polyalkaline glycols < Synthetic esters < Biolubricants (Vegetable Oils)

Aquatic Toxicity. The second criterion that an EAL must meet is low aquatic toxicity. Like biodegradability, there are a number of toxicity tests that can be applied (Table 2).

Table 2. Aquatic toxicity tests applicable for EAL evaluation (Adapted from USEPA 2011).

Test & Species	OECD Number[a]	EPA Equivalent[b]
72 hour growth inhibition test, alga	201	EG-8
Acute immobilization test, Daphnia sp.	202	EG-1
Acute toxicity test, fish	203	EG-9
Prolonged toxicity test: 14 day study, fish	204	
Respiration inhibition test, bacteria	209	
Early-life stage toxicity, fish	210	
Reproduction test, Daphnia magna	211	
Short-term toxicity on embryo & sac-fry states, fish	212	

a OECD 2013
b Source: USEPA 1982a (EPA 560/6-82-002)

In general, mineral oil lubricants have relatively high toxic effects, while PAGs, synthetic esters, and biolubricants have low toxic effects. PAGs, however, can have higher levels of toxicity in some cases, due to their increased solubility resulting from the glycol groups.

Bioaccumulation. The third criterion that an EPA-defined EAL must meet is that it must be below certain thresholds for bioaccumulation. Bioaccumulation can be directly measured by exposing organisms to the contaminant, then measuring uptake. However, this type of measurement is complicated by the wide variety of environmental factors that can affect uptake. Furthermore, in the case of organic constituents, these can be transformed and degraded in the target organism, making measurements difficult. Finally, tests with organisms can be expensive. Because of these reasons, surrogate measurements have become more common when it comes to measuring bioaccumulation. In particular, the octanol-/water-partitioning coefficient (K_{ow}) is the common basis for assessing bioaccumulation. In a K_{ow} test, a chemical of interest is placed in a container containing both water and octanol, and the solution is vigorously mixed. The ratio of the contaminant in the octanol and in the water is then measured. Since differences frequently span orders of magnitude, K_{ow} is typically presented as a logarithmic scale (log K_{ow}).

Log K_{ow}s for marine environments tend to vary between 0 and 6. Substances with Log $K_{ow} < 3$ tend not to bioaccumulate, while those with $K_{ow} > 3$ area are considered as bioaccumulating. OECD 107 and 117 are common methods used to measure K_{ow} values for EAL purposes (OECD 2013a).

Other Considerations. Other considerations include the environmental fate of the material, such as its attenuation (particularly biodegradability) and its transport characteristics. Some assessments also factor in environmental effects related to the production of the lubricant: Are greenhouse gas emissions generated? Is the material made of renewable sources? Does the product contain hazardous or dangerous materials? Still other assessments factor in circumstances such as public perception of the lubricant material and stakeholder acceptance.

Labeling. There are several labels that have been developed that are generally accepted as defining a lubricant as an EAL. These include:

- Blue Angel – A label developed by Germany, which has now been accepted internationally as an acceptable standard. (http://www.ecolabelindex.com/ecolabel/blue-angel)
- Swedish Standard – A label developed by Sweden.
- Nordic Swan (Nordic Ecolabel) – A label jointly developed by Iceland, Norway, Denmark, Sweden, and Finland. Nordic swan is meant to consider the entire product life cycle. (http://www.nordic-ecolabel.org/)
- European Eco-label – Developed by the European Union (http://ec.europa.eu/environment/ecolabel/)
- OSPAR – Developed by the OSPAR commission to protect the Northeast Atlantic Ocean and its resources. (http://www.ospar.org/)

Table 3 summarizes the criteria for these labels.

Table 3. Criteria for labeling programs for EALs.

Labeling Program	Biodegradability	Aquatic Toxicity	Bioaccumulation	Other
Blue Angel	OECD 301B-F (Ultimate biodegradation) or CEC L-33-A-934 (primary biodegradation)	OECD 201-203	OECD 305 A-E or Kow	Dangerous materials, technical performance
Swedish Standard	ISO 9439	NA	None	Renewable content
Nordic Swan	NA	OECD 201-202	None	Renewable content, technical performance
European Eco-label	OECD 301 A-F (ultimate biodegradation), OECD 302C, or ISO 14593	OECD 201 & 202 (acute) and OECD 210 or 211 (chronic)	OECD 107, 117, or 123 (Kow for organic compounds) or OECD 305	Dangerous materials, restricted substances, renewable content, technical performance
OSPAR	OECD 306 (degradation under marine conditions)	Marine toxicity to 4 species	OECD 117 or 107 (Kow)	

Other labels may be acceptable, or a testing regiment could be presented to show that a lubricant meets EAL requirements. Modified assessment tools are available (Cunningham et al. 2004).

Recycling. Lubricants of all kinds can be recovered and recycled, which is a positive environmental practice (Betton 2010), but not all uses allow for these activities. Specifically, in-water lubrication does not allow for recycling.

Performance. Table 4 summarizes performance of EALs to mineral oil (polyaklylene glycols are PAGs, polyalpaole phines are PAOs, and dicarboylic acid ester and neopental polyesters are synthetic esters). EALs generally perform well compared to mineral oil lubricants. EALs typically are more mechanically durable and have superior lubricating properties (Pai and Hargreaves 2002). Mineral oils, however, tend to have better low temperature performance and have strong corrosion resistance.

Table 4. Performance of EALs as compared to Mineral Oil lubricants (adapted from Bartz 1998).

	Min. Oil	Polyalpha	Polyalkyl	DAE	N Polyest	Rape Seed
Viscosity Temperature Behavior (VI)	4	2	2	2	2	2
Low Temperature Behavior (Pourpoint)	5	1	3	1	2	3
Liquid Range	4	2	3	1	2	3
Oxidation Stability (Aging)	4	2	3	2/3	2	5
Thermal Stability	4	4	3	3	2	4
Evaporative Loss (Volatility)	4	2	3	1	1	3
Fire Resistance, Flash Temperature	5	5	4	4	4	5
Hydrolytic Stability	1	1	3	4	4	5
Corrosion Protection Properties	1	1	3	4	4	5
Seal Material Compatibility	3	2	3	4	4	4
Paint & Lacquer Compatability	1	1	4	4	4	4
Miscibility with Mineral Oil		1	5	2	2	1
Solubility of Additives	1	2	4	2	2	3
Lubircating Properties, Load Carrying Capacity	3	3	2	2	2	1
Toxicity	4	3/4	1/2	1/2	1/2	1
Biodegradability	4	3/4	1/2	1/2	1/2	1
KEY: 1 = excellent, 2 = very good, 3 = good, 4 = moderate, 5 = poor.						
Min. Oil = Mineral oil, Polyalpha = polyalphaolephines, polyalkl = polyalkyleneglycols, DAE = dicarboxylic acid esters						
N Polyest = Neopental polyesters, Rape seed = rape seed oil						
Adapted from Bartz (1998)						

In looking over the properties presented in Table 4, it is interesting to focus on the properties that would be most critical for in-water lubrication. These include oxidation stability (aging), evaporative loss (volatility), hydrolytic stability (reactions with water), and corrosion protection properties. In focusing on these, we see that — with some exceptions — EALs tend to outperform mineral oils in oxidative stability and evaporative loss. However, mineral oils outperform most EALs in terms of hydrolytic stability, low temperature performance (pour point), and corrosion protection (Aluyor et al. 2009).

It is clear from the literature that EALs are very effective, and can be used for most mineral oil applications. However, it is disappointing that some of the weaknesses of EALs (hydrolytic stability, low temperature performance, and corrosion protection) are incompatible with in-water application requirements. The limitations given in Table 4 are nonetheless generalizations for most products. Fortunately, there is a wide range of EAL products, and some have been developed that work better at low temperatures and have better hydrolytic stability (Birova et al. 2002, Erhan et al. 2006). For example, coconut oil has shown to be better at low temperature applications than most other vegetable oils (Jaydas and Prabhakaran Nair. 2006). Additives can also be used to improve performance (Erhan et al. 2006, Karmakar and Ghosh 2013), although these may also have undesirable environmental effects (Herdan 1997). Modification of vegetable oils via processes like epoxidation and hydroxylation can also improve low temperature performance and oxidative resistance, while maintaining high biodegradability (Arumugam et al. 2012, Sharma et al. 2006). Another strategy could be to investigate or even develop blends of existing mineral oils that have been proven to be effective and more readily biodegradable materials, to develop a mixture that meets EAL requirements (Nagendramma and Kaul 2012). For example, Haus et al. (2001) studied 32 mineral oil bases and found biodegradation ranged from 15 to 75%. Increasing aromatic and/or polar contents can increase biodegradability. Therefore, choosing the more biodegradable mineral oil stocks could meet EAL requirements for biodegradability, bioaccumulation, and toxicity. Ultimately, testing would be recommended to determine whether any lubricant replacement meets the protective needs of the equipment.

EALs have been used extensively in full-scale applications for decades. Pearson and Spagnoli (2000) documented on 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.

Water Washout. In-water structures in dams may be subjected to strong water currents and cavitation. In particular, violent water currents can occur in the draft tubes that house the wicket gate bearings. ASTM D1264 is the standard test for evaluating water washout resistance of lubricating greases (ASTM International 2012).

Costs. Table 5 summarizes base costs of EALs in comparison with mineral oil-based lubricant. This table is generalized, in fact, some synthetic ester formulations can cost 20 times more than their mineral oil equivalent (Nagendramma and Kaul 2012).

Table 5. Cost comparison of EALs to mineral oil (adapted from USEPA 2011).

Lubricant Base Oil	Cost Ratio to a Comparable Mineral Oil Base Lubricant Cost
Bio-based lubricants (Vegetable oils)	1.2
Synthetic ester	2 to 3
Polyalkylene glycols	2 to 3

These comparisons indicate that EALs are more expensive than mineral oil-based lubricants. However, this is only a comparison of the base costs. There are other life-cycle costs that might change the overall cost comparison. For example, in many cases, EALs can actually last longer and outperform mineral oils (see above), which could result in lower quantity requirements. Other factors could be environmental management costs, which would likely be favorable for EALs. On the other hand, recycling benefits might be more favorable for mineral oils. Furthermore, costs of bio-based lubricants (vegetable oils and synthetic esters) can become more competitive with petroleum-based mineral oils as petrochemical costs increase (Aluyor et al. 2009).

Miller et al. (2007) performed a life-cycle analysis (LCA) on a proposed replacement of a mineral oil lubricant with a soybean-based lubricant for an aluminum manufacturing facility. Although the soybean lubricant was somewhat more expensive, this factor was offset because the use rate for the vegetable oil was actually lower than that for the mineral oil. The LCA also assessed overall environmental impact. The soybean oil had positive effects on the release of climate change constituents and reduced fossil fuel usage, but it did have the potential for overall increases in nutrient releases to the environment, which could have a negative, eutrophicating impact.

Start up. A key factor in considering a replacement material is its miscibility with the existing mineral oil lubricant. If the replacement lubricant had good miscibility, then it could simply be added as a makeup material over the existing lubricant. This saves the need to clean the surface, which might require the shutdown of the system during the cleaning. Consequently, in the short term, miscibility compatibility could be a very valuable parameter. However, if a replacement lubricant has significant advantages, then it might turn out to be better to go through the cleaning step if it is not compatible with the existing lubricant. Fortunately, some types of EALs tend to be highly miscible with mineral oil (Table 4). In particular, rape seed (vegetable) oil and polyalphaolefins (PAOs) have excellent miscibility with mineral oil while synthetic esters have good miscibility. PAGs, on the other hand, are not compatible to most mineral oils.

EAL testing for Dam Application. Some studies have been conducted on hydroelectric dam EAL applications. Hanna and Pugh (1998) conducted a Bureau of Reclamation study looking at environmentally acceptable alternatives to mineral oil. Food-grade greases, which are greases approved for incidental contact with food, but that do not necessarily meet EAL criteria, did not perform well. Two EAL greases, conversely, performed comparably (and in one case, significantly better) to a lithium-based mineral oil product. Darr (2002) discusses actual applications of EALs at Parker Dam in CA. Particular success was found with a canola-based VSG product (which was one of the products tested by Hanna and Pugh). As discussed above, The Dalles and and John Day reportedly used EALs, and data provided by Redman (2014) also indicates that an EAL is used on Dworshak's wicket gates. USACE 1999 indicated that the Huntington and Nashville Districts used EALs in lock-gate operations.

Alternatives to Lubricants in Dams. There are alternatives to using either mineral oil or EAL lubricants for in-water structures. First, a water-lubricated process could be used. This essentially means that no lubricant is used, only the surrounding water. Hanna and Pugh (1998) evaluated water lubrication and found that torque to move the test structure approximately doubled, and wear was expected to increase. Another alternative is to use self-lubricating surfaces. These are essentially coated surfaces in which the lubricant is incorporated into the parent material, which reduces friction and wear. There are plans to use self-lubricating structures on replaced pintle bearing bushings in lock structures in The Dalles dam (Ingram 2011). The Little Goose, Lower Monumental, Bonneville and McNary Dams also have self-lubricating bearings installed on some of their in-water structures (USACE 1999). These reduce operating costs and have an environmentally friendly benefit of not having any need for grease applications. However, this approach requires the replacement of the equipment, which is very expensive (on the order of tens of millions of dollars, USACE 2012 gives major lock renovation costs for numerous locks in the Rock Island District). There is also concern that self-lubricating bearings may actually need to be replaced sooner than conventional brass bearings.

LUBRICANTS IN THE COLUMBIA RIVER DAMS: Redman (2014) prepared a white paper on the lubricating practices of the six dams operated by the Walla Walla District (McNary, Ice Harbor, Lower Monumental, Little Goose, Lower Granite, and Dworshak). The following sections are based on this document.

In-Water Lubrication Structures for Walla Walla Dams. Two primary structures were identified requiring in-water lubrication: wicket gates and pintle bearings. Wicket gates are structures that control the amount of water flowing through the intake tunnel (penstock) through the hydroelectric turbine (Zimesnick 2010, Figure 4). As gates are opened, the turbines spin faster, generating more electricity. Wicket gates can be partially closed to slow down energy production during low-energy use periods and completely shut to allow for maintenance on the turbines.

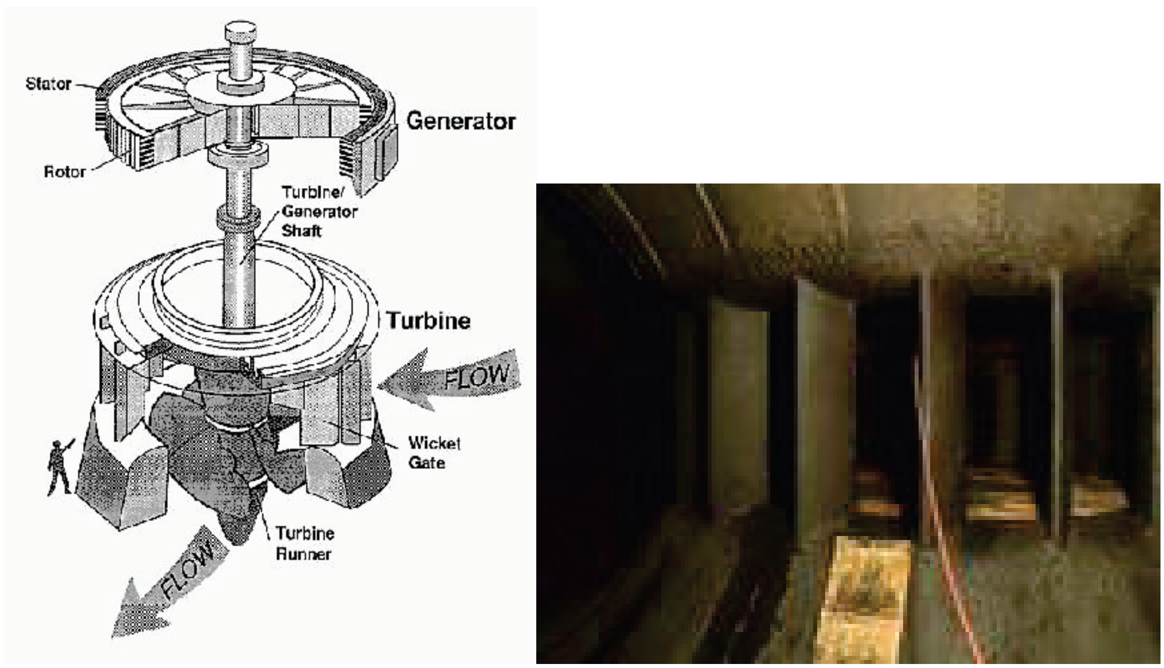

Figure 4. Schematic and picture of wicket gates (Parker Dam, Lake Havasu, CA).

Pintle bearings are hinge-like devices that support the weight of the gate and allow the gates to swing open and shut (Figure 5). These bearings are found on locks to allow shipping to navigate the dam and on gates that allow the dam to release water when needed. These have commonly been grease-lubricated bronze bearings, although self-lubricated bearings are becoming more prevalent.

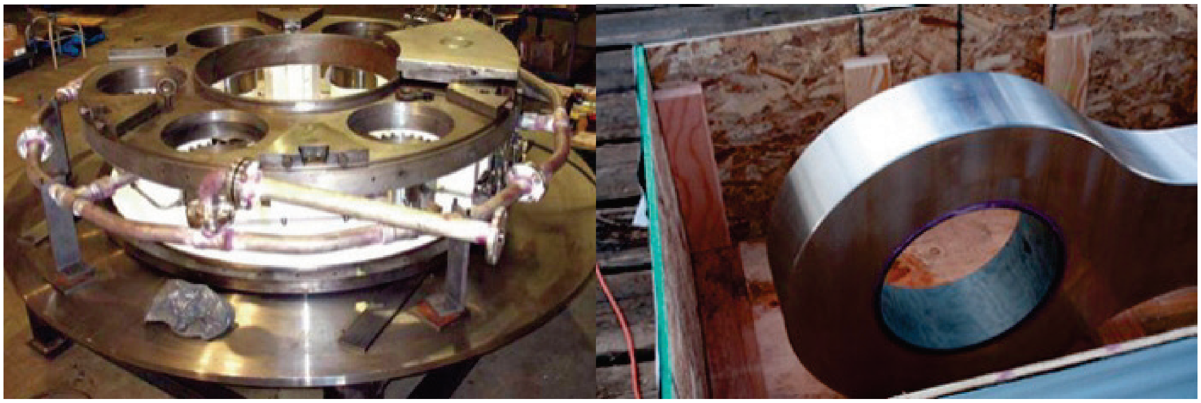

Figure 5. Pintle gate bearing (from the Rock Island Dam) and bushing (a self-lubricating bushing from The Dalles Dam).

One point to consider is the sheer size of the structures under discussion. Figure 6 is a lock gate that is undergoing repairs at The Dalles dam. The size is massive.

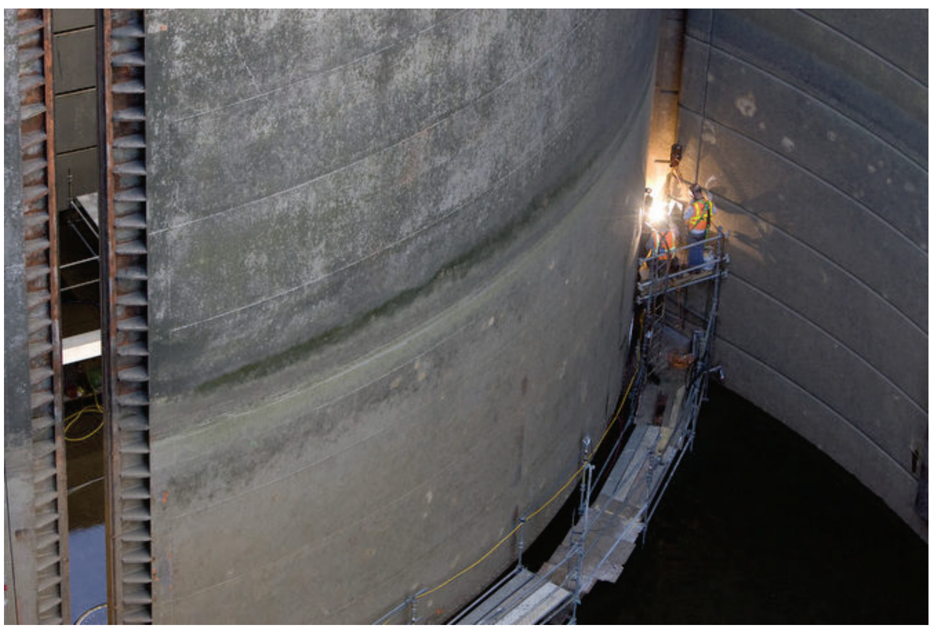

Figure 6. Repairs conducted on a lock gate at The Dalles Dam.

In-Water Lubricants Used for Walla Walla District-Managed Dams. Table 6 summarizes lubricating materials used for the wicket gates and pintle bearings for the Walla Walla Dams. One of these is classified as an EAL, ECO Fluids VSG Wicket Gate Grease (although this lubricant does not have associated bioaccumulation test data), although the Chevron FM ALC EP2 Food Grade is a foodgrade material (see section below).

Table 6. In-water lubricants used for Walla Walla district-managed dams (from Redmon 2014).

Dam	Wicket Gates	Pintle Bearings
McNary	Chevron Ultra Duty EP NGLI-0	Chevron Ultra Duty EP NGLI-0
Ice Harbor	Chevron Ultra Duty EP NGLI-0	Chevron Ultra Duty EP NGLI-0
Lower Monument	Chevron Ultra Duty EP NGLI-1	N/A
Little Goose	Chevron Ultra Duty EP NGLI-0	Chevron Ultra Duty EP NGLI-0
Lower Granite	Chevron FM ALC EP2 Food Grade	Chevron FM ALC EP1 Food Grade
Dworshak	ECO Fluids VSG Wicket Gate Grease	N/A

Table 7 summarizes the properties of these lubricants and Mobil 100 SHC Series EAL greases, which are used at The Dalles. The first two lubricants on the table are conventional mineral oil lubricants (Chevron Ultra Duty EP NGLI-0 and Chevron Ultra Duty EP NGLI-1). The next two are food-grade-quality greases, but are also mineral-oil-based and are not EALs (Chevron FM ALC EP1 Food Grade and Chevron FM ALC EP2 Food Grade). The last three greases (Mobil EAL 101 and 102 and VSG) are EAL greases. The Mobil greases are synthetic esters, while the VSG product is canola oil, bio-based grease. The EAL greases are comparable to the mineral oil greases for most of the data given, although the Mobil greases have a somewhat lower Four Ball Weld Pt forces (VSG is comparable). In a critical measure for in-water use, %Washout, the EALs have excellent numbers, particularly the VSG grease. This very preliminary assessment suggests that EAL products are available that can perform comparably to mineral oil greases.

Food Grade Lubricants. Redman (2014) reports that several dams use food-grade lubricants (Chevron FM ALC EP2 Food Grade) as environmentally friendly lubricants. However, these materials are not documented as EALs. Food-grade materials may not meet EAL criteria, such as biodegradability or toxicity. However, some food-grade materials do meet EAL standards. If there is a food-grade material of strong interest, then it should be possible to conduct basic testing to determine whether these meet EAL requirements — and if so — have then classified as such.

VSG Wicket Gate Grease. 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 at (*http://fluidcenter.com/vsg.html*, see *http://fluidcenter.com/pdf/vsgtechdata.pdf* for a download of its technical sheet). 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 upon water contact, allowing it to stay in bearing. VSG grease has an ASTM D-1264 washout loss (at 79.4 C, 175 F) of 1.21%. VSG is reportedly compatible with more lithium-based mineral oil greases. VSG is more expensive than most comparable mineral oil lubricants, but according to ECO Fluid, the small amounts needed annually mean that the actual increased costs assuming equivalent usages are minimal. Furthermore, some users have indicated that they actually use less VSG lubricant than they previously used, resulting in a net savings. The VSG product is equivalent to one of the EALs tested by Hanna and Pugh (1998) and used at the Parker Dam in CA (Darr 2002).

Table 7. Properties of in-water lubricants used in Walla Walla district-managed dams (from Redman 2014).

			Lubricant				
Properties	**Ultra Duty EP NGLI-0**	**Ultra Duty EP NGLI-1**	**FM ALC EP1**	**FM ALC EP2**	**Mobil SHC 101 EAL**	**Mobil SHC 102 EAL**	**VSG Wicket Gate Grease**
NLGI Number	**0**	**1**	**1**	**2**	**1**	**2**	**1**
Operating Temp, F Min Max	-15 270	-15 350	-4 325	-4 325			
Penetration @ 77 F	370	325	280	325	325	280	325
Dropping Pt, F	342	491	500	500	356	356	480
Four Ball Weld Pt. kgf	315	500	500	500	200	200	400
Four Ball Wear Scar, mm	0.45	0.43	0.60	0.60			0.42
Timken OK Load, lb	55	70	40	40			55
Water Washout, wt%	15	7			8.0	6.5	1.21
Lincoln ventmeter, psig @ 30 @ 70 F 30 F 0 F	100 200 1700	-- 250 975					20 110 42
Copper corrosion	--	1B			1A	1A	1B
Thickener, % Type	5.6 Lithium	7.0 Lithium complex	6.9 Aluminum complex	7.7 Aluminum complex	Lithium	Lithium	-- Calcium sulfanate
ISO Viscosity	460	320			100	100	
Kinematic Viscosity cST @ 40 C	400	383	200	200			

Mobil Oil EALs. Redman (2014) identified EALs manufactured by Mobil that might also be useful for the Columbia River Dams; the Mobil SHC 100 EAL series (see *http://www.mobil.com/USA-English/Lubes/PDS/GLXXENGRSMOMobil_SHC_Grease_100_EAL_Series.aspx*). The series consists of two products, 101 and 102 (Table 7). 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 "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. Both products use lithium thickeners, which are compatible with current lubricants used in the dams.

Huskey Specialty Lubricants ECOLube EP2 & Hydrolube. Huskey Specialty Lubricants produces two green lubricants that might be appropriate for in-water dam use: Ecolube EP2 and Hydrolube (see *http://huskey.com/PRODUCTS/IndustrialGreases/igrl/1/app/igrl*). 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 (see *http://huskey.com/Product/item/12/Ecolube-EP2* for a specifications sheet). It is classified as readily biodegradable and contains no ozone-depleting chemicals, no SARA (Superfund Amendment and Reauthorization Act) Title 313 chemicals, no heavy metals, no greenhouse gases, no chlorine, no phenols, no volatile organic compounds, and no Proposition 65 chemicals. It is acceptable for use where incidental food or potable water contact may occur. Water washout data is not provided for Ecolube EP 2.

Hydrolube (see *http://huskey.com/Product/item/66/Hydrolube* for a specifications sheet) 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.

CONCLUSIONS/RECOMMENDATIONS: The following conclusions were drawn from this study:

- EALs can reduce the environmental impacts of in-water lubricant usage due to lower toxicity and higher biodegradability.
- The performance of EALs is comparable to mineral oil lubricants. In some areas, EALs can significantly outperform mineral oils lubricants. However, each lubricant type has relative strengths and advantages. Considering the focus on in-water use, EALs tend to outperform mineral oils in oxidative stability and evaporative loss, but mineral oils appear to have performance advantage in hydrolytic stability and corrosion protection. It appears likely that EALs will be able to meet the requirements needed for in-water uses.
- Two products in particular are promising. VSG Wicket Gate Grease is already being used at Dworshak Dam and has a history of effective use. And the Mobil SHC series 100 EALs are greases designed for in-water use and appear to have strong performance characteristics. Both the VSG and the Mobil products appear to be compatible with the lithium-thickened greases currently used.

- The base costs of EALs are higher than those of mineral oil lubricants. The EALs base costs can be as low as 1.2 times — or even as high as 4 times — higher than mineral oil base costs. Some reports even indicate that high performance synthetics can be up to 20 times higher. However, it is likely that life cycle costs of EALs are more competitive — and even advantageous — in some cases compared to mineral oils.

The following recommendations are proposed:

- ERDC should be prepared to conduct any testing to support EAL certification for any lubricant that is not labeled, but that could be a good choice for the northwest dams. Testing could be conducted on the food-grade greases currently used at Lower Granite Dam. Similarly, the Huskey Hydrolube is a promising grease product that is designed to be environmentally friendly, but is not categorized as an EAL. Testing could be performed to allow its use in order to meet the conditions of the settlement.
- Laboratory testing and field demonstrations may be warranted for new EAL application. ERDC could lead or assist in these studies.
- EALs are generally more expensive. However, in many cases, EALs can last longer than conventional lubricants, and EALs may not require the environmental management costs associated with mineral oils. Life cycle analysis would be a valuable tool to use for assessing the overall costs associated with EAL use as compared to those associated with conventional mineral oil grease use.

ADDITIONAL INFORMATION: This technical note was prepared by Victor F. Medina, Ph.D., P.E., Research Engineer, Environmental Laboratory, U.S. Army Engineer Research and Development Center. The study was conducted as an activity of the Water Operations Technical Support (WOTS) program. For information on WOTS, please contact the Program Manager, Dr. Pat Deliman, at Patrick.N.Deliman@usace.army.mil. This technical note should be cited as follows:

> Medina, V.F. 2015. *Evaluation of environmentally acceptable lubricants (EALs) for dams managed by the U.S. Army Corps of Engineers*. ERDC TN-WOTS-MS-9, Vicksburg, MS: U.S. Army Engineer Research and Development Center.

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