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Mechanical Equipment Lubrication

Standardization and Sustainability

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Mechanical Equipment Lubrication

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Abstract

This report aims to reduce risk and minimize machinery damage by selecting the correct lubricant and at the same time address the lack of standardization for lubricant selection across U.S. Army Corps of Engineers (USACE) civil works. In addition, this report proposes ways to standardize lubricant selection and also incorporate sustainability into lubricant selection. The report examines current practices across USACE in regards to mechanical equipment lubrication including self-lubricated materials and identifies current and past case studies and technical reports. The report reviews modifications that USACE civil works can make to current lubricant selection practices, evaluates existing standards and provides performance requirements for lubricants.

The use of environmentally acceptable lubricants (EALs) is one option to incorporate sustainability into USACE civil works activities. However, EALs are often misunderstood, and uninformed selection of these (or any) lubricants can damage machinery. The report includes information to inform end users and designers on the selection and use of EALs, and detailed recommendations for testing, evaluation, and selection of lubricants, including EALs. This work also recommends pilot studies to test and refine the use of EALs at USACE sites. Although this report is focused on navigation it is also applicable to hydropower, flood control dams, reservoirs, and floating plant applications.

Contents

Abstract ... ii

Figures and Tables ... vi

Preface ... vii

Acronyms ... viii

1 Standardized Approach for Lubricant Selection and Sustainability ... 1

1.1 Introduction ... 1
1.2 Previous efforts to standardize lubricant selection ... 2
1.3 Sustainability ... 3
1.4 Opportunities for standardization ... 6
1.5 Opportunities for sustainability ... 7
1.6 DLA and Army Oil Analysis Program ... 8

2 Environmentally Acceptable Lubricants ... 11

2.1 The need for a workable definition of EALs ... 11
2.2 Food grade vs. EALs ... 12
2.3 Environmental effects from lubricants from dams and navigational structures ... 13
2.4 Base oil composition ... 14
2.5 Additives ... 16
2.6 EPA 800-R11-002 ... 16
2.6.1 Biodegradability ... *17*
2.6.2 Toxicity ... *18*
2.6.3 Bioaccumulation ... *20*
2.6.4 Base Oil ... *21*
2.6.5 Labeling ... *21*
2.7 USEPA vessel general permit (VGP) ... 22
2.8 Previous USACE documents on EALs ... 23
2.9 Operational tiered working EAL definition ... 23
2.9.1 Means of meeting criteria ... *24*
2.9.2 Tiered definition ... *24*

3 Self-Lubricated Materials ... 26

3.1 General recommendations ... 26
3.2 Design considerations ... 27
3.3 SLM properties ... 33
3.4 Applications ... 36

4 Synthetic Lubricants and Bio-based Lubricants ... 38

4.1 General ... 38
4.2 Defining synthetic lubricants ... 39
4.3 Synthetic oil production ... 39

4.3.1 PAO lubricants *40*
4.3.2 Synthetic esters *41*
4.3.3 Phosphate esters *42*
4.3.4 Polyalkylene glycols *42*
4.3.5 Silicones *43*
4.4 Biobased lubricants 44

5 Standardized Sampling and Testing Procedures 47
5.1 General recommendations 47
5.2 Standardized operating procedure for sampling and testing 47
5.3 Testing frequency 48
5.4 Test requirements 50
5.5 Key tests and warning limits 53
5.5.1 Acid number *53*
5.5.2 International Standards Organization (ISO) particle count *54*
5.5.3 Water content *55*
5.6 Hydraulic fluid 55
5.7 Gear oils 57
5.8 Oil monitoring program 57
5.9 Army oil analysis program 58

6 Performance Characteristics of Lubricants and Selection Criteria 60
6.1 General discussion 60
6.2 Grease selection 60
6.2.1 General *60*
6.2.2 Grease selection for wide applications *62*
6.2.3 Mineral oils *64*
6.2.4 Synthetic base oil grease *65*
6.2.5 EAL grease *65*
6.3 Grease selection for bearings 66
6.3.1 Tainter gate trunnion bearings *67*
6.4 Grease selection for open gearing 68
6.5 Grease for wire rope applications 72
6.6 Hydraulic oil selection 74
6.6.1 Pump requirements *75*
6.6.2 Determine viscosity requirements *75*
6.6.3 Mineral oil hydraulic fluid *76*
6.6.4 Synthetic hydraulic fluid *77*
6.6.5 Environmentally acceptable hydraulic fluid *79*
6.7 Gear reducer oil selection 83
6.7.1 Rust and oxidation inhibited gear oils *87*
6.7.2 Extreme pressure gear oils *87*
6.7.3 Compounded gear oils *88*
6.7.4 Synthetic gear oil *89*

7 Lubricant Survey 91
7.1 EAL survey 91

7.2 Lock and dam survey ... 92

8 Case Studies and Existing Reports ... 94

8.1 Existing lubrication reports ERDC ... 94

8.2 NWD and NWP and NWW (Walla Walla District) grease testing ... 94

8.2.1 Environmentally acceptable lubricant wire rope and hydropower submerged equipment testing in NWD ... 95

8.2.2 EAL Proof of concept plan lower monumental navigation lock tainter valve #4 ... 96

8.2.3 Environmentally acceptable lubricant grease for hydropower applications – Technical feasibility analysis for eight hydropower facilities in Washington and Oregon ... 98

8.2.4 Environmentally acceptable lubricant wicket gate bushing proof of concept testing plan ... 99

8.2.5 EAL proof of concept plan – Ice Harbor fish pumps ... 102

8.2.6 EAL proof of concept plan – Little Goose Navigation Lock – Downstream miter gate ... 103

8.2.7 EAL proof of concept plan – Lower Granite Navigation Lock – Upstream tainter gate trunnions and wire rope blocks ... 104

9 Conclusion and Recommendations of Report ... 106

9.1 General ... 106

9.2 Operation and maintenance and risk considerations ... 107

9.3 Pilot studies ... 107

References ... 109

Figures and Tables

Figures

1	Lock 19 Mississippi River	3
2	Lock 53 and LaGrange Lock hydraulic cylinders	14
3	Textile reinforced polymer self-lubricated materials for radial gate trunnion bushing (USACE)	28
4	Spillway radial gate trunnion bushing - freezing in liquid nitrogen (USACE)	30
5	Spray coated pintle bushing and Kamatics liner (USACE)	31
6	Miter gate self-lubricating pintle – The Dalles Lock and pintle puck system (USACE)	32
7	Plug type self-lubricated bearing from Panama Canal miter gate pintle replacement project (courtesy ACP)	33
8	Lock 6 and LPV 144 pintle installation	37
9	Open spur gear (USACE)	69
10	Sector gear (USACE)	69
11	Gear reducers (USACE)	84

Tables

1	Opportunities for standardization by performance requirements	6
2	Commonly used methods for measuring biodegradability (adapted from USEPA 2011)	17
3	Commonly used methods for measuring toxicity (adapted from USEPA 2011)	18
4	USFWS and USEPA toxicity rating scales for aquatic organisms	19
5	Criteria for labeling programs used by the USEPA to define EALs	21
6	Tolerance to debris and contamination	34
7	Comparison of different base oils	39
8	Test requirements for gear oils	50
9	Annual testing requirements for lubricating oils	52
10	ISO 4406 Cleanliness recommendations from Vickers (excerpt)	56
11	Bearing additives	66
12	Grease NLGI grade for bearings	67
13	Tainter gate trunnion bearing lubrication parameters	68
14	Required target performance values for open gear grease	70
15	New Cumberland hydraulic fluid evaluation matrix	82
16	Common viscosity requirements for gearboxes (from Noria Machinery Lubrication Handbook)	86

Preface

This study was conducted for the U.S. Army Corps of Engineers Headquarters (HQUSACE) by the Inland Navigation Design Center (INDC). The Inland Navigation Design Center Mandatory Center of Expertise (INDC-MCX) provides engineering, design, analysis, and review services for studies, new locks and navigation dams, major rehabilitation of existing inland navigation locks and dams, and significant inland navigation lock and dam Operations and Maintenance (O&M) projects. The INDC strives to deliver the highest quality products and services through design consistency, technical review, adherence to policy and regulation, standardization of design, risk analysis, collaboration with experts and stakeholders, and knowledge management of technical competency.

The Inland Navigation Design Center Mandatory Center of Expertise was tasked by US Army Corps of Engineers Headquarters to investigate opportunities across the enterprise for sustainability and standardization at navigation structures with emphasis given to mechanical and electrical components. This study and report was funded by HQUSACE and in part through the USACE ERDC Dredging Operations Technical Support (DOTS) program.

Acronyms

Term	Definition
ACE-IT	U.S. Army Corps of Engineers–Information Technology
ACP	Autoridad Del Canal De Panama (Panama Canal Authority)
A-E	Architect Engineer
AGMA	American Gear Manufacturers' Association
ANSI	American National Standards Institute
AOAP	Army Oil Analysis Program
API	American Petroleum Institute
AR	Army Regulation
ASTM	American Society for Testing and Materials
AVN	Defense Logistics Agency Aviation
AW	Anti-Wear
CEC	Coordinating European Council
CERL	Construction Engineering Research Laboratory
CONUS	Continental United States
CWA	Clean Water Act
DLA	Defense Logistics Agency
DN	Speed Factor
DOD	U.S. Department of Defense
DOTS	Dredging Operations Technical Support Program (USACE)
DSN	Defense Switched Network
EA	Environmentally Acceptable
EAL	Environmentally Acceptable Lubricant
EM	Engineer Manual
EP	Extreme Pressure
ER	Engineer Regulation
ERDC	U.S. Army Engineer Research and Development Center
FEDSTRIP	Federal Standard Requisition and Issue Procedures
FIST	Facilities Instructions, Standards, and Techniques
FKM	Abbreviation for fluoroelastomer (materials)
GSA	General Services Administration
HDC	USACE Hydroelectric Design Center
HDR	HDR Engineering, Inc.
HE	Hydraulic oil Environmental
HEES	Hydraulic Environmental Ester oil Synthetic
HEPG	Hydraulic Environmental Poly Glycol
HEPR	Hydraulic Environmental Polyalphaolefin and Related
HETG	Hydraulic Environmental Tri-Glyceride
HPU	hydraulic power unit

Term	**Definition**
HQ	Headquarters
ICP	Inductively Coupled Plasma
ID	Identification
IDIQ	Indefinite Delivery/Indefinite Quantity
IMTS	Inland Marine Transportation System
INDC	Inland Navigation Design Center
INDC-MCX	Inland Navigation Design Center Mandatory Center of Expertise
ISO	International Standards Organization
KOH	Potassium Hydroxide
LRD	USACE Great Lakes and Ohio River Division
LRE	USACE Detroit District
LRH	USACE Huntington District
LRN	USACE Nashville District
MDC	Marine Design Center
MILSTRIP	Military Standard Requisitioning and Issue Procedures
MVD	Mississippi Valley Division
MVN	USACE New Orleans District
MVP	USACE St. Paul District
MVR	USACE Rock Island District
NLGI	National Lubricating Grease Institute
NOAA	National Oceanic and Atmospheric Administration
NSN	National Supply Number
NWD	Northwestern Division
NWP	USACE Portland District
NWW	USACE Walla Walla District
O&M	Operations and Maintenance
OCONUS	Outside Continental United States
OECD	Organization for Economic Co-operation and Development
PAG	Polyalkylene Glycol®
PAO	Polyalphaolefin
PCB	Polychlorinated Biphenyl
PDT	Project Delivery Team
PM	Project Manager
POC	Point of Contact
PPM	parts per million
PTFE	polytetrafluoroethylene
PV	Pressure and Velocity
PVC	Polyvinyl Chloride
R&O	Rust and Oxidation
RCRA	Resource Conservation and Recovery Act
REMR	Repair, Evaluation, Maintenance, and Rehabilitation

Term	Definition
RO	Rapeseed Oil
RPVOT	Rotating Pressure Vessel Oxidation Test (FOR Oxidation Stability)
SAM	USACE Mobile District
SE	Synthetic Ester
SLM	Self-Lubricated Material
SOP	Standing Operating Procedure
SR	Special Report
SS	Swedish Standard
SSU	Saybolt Seconds, Universal (unit of viscosity)
SUS	Saybolt Universal Seconds
TAN	Total Acid Number
TB	Technical Bulletin
TN	Technical Note
TR	Technical Report
UFGS	Unified Facilities Guide Specification
USACE	U.S. Army Corps of Engineers
USACERL	U.S. Army Construction Engineering Research Laboratory (now known as the U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL)
USCG	United States Coast Guard
USDA	U.S. Department of Agriculture
USEPA	U.S. Environmental Protection Agency
USFWS	U.S. Fish and Wildlife Service
VGP	Vessel General Permit
VI	Viscosity Index
WEDA	Western Dredging Association

1 Standardized Approach for Lubricant Selection and Sustainability

1.1 Introduction

There is a great need for better consistency in lubricant selection and in standardized maintenance procedures for machinery and mechanical equipment across U.S. Army Corps of Engineers (USACE) civil works activities. Neither the Inland Marine Transportation System (IMTS) Maintenance Standard, nor the Great Lakes and Ohio River Division (LRD) and Mississippi Valley Division (MVD) Annexes to this standard address equipment lubrication or standardization of lubricants. Even with the IMTS Maintenance Standard, maintenance procedures throughout the Corps of Engineers civil works are not standardized. Many USACE civil works districts (e.g., Rock Island and St. Paul) use site-specific standard operating procedures (SOPs) for lubricant testing and selection. Even within a given civil works activity, lubricant selections can vary. For example, two adjacent lock sites in the same District often use entirely different sets of lubricants for gearboxes, hydraulic systems, and open gears.

One cause for this disparity in lubricant selections and maintenance practices is that equipment throughout the Corps of Engineers civil works portfolio, including locks and dams, is not standardized. The USACE civil works portfolio includes navigation locks, navigation dams, flood control dams, recreation sites, local flood protection projects, hydropower, and floating plants. This wide variation in the types of machinery across USACE makes the standardization of lubrication schedules and practices tremendously difficult. One result of this lack of standardization is that some lock and dam sites select lubricants by trial and error.

From a logistical standpoint, two other conditions make it difficult to standardize lubrication selection across all USACE civil works activities:

1. Environmental conditions, which affect lubricant selection, vary widely from one region of the country to another.
2. Procurement and contracting requirements also play a role. Purchases greater than $3,500 have to be solicited, which requires a contract. Purchasing one particular lubricant in large quantities requires a sole source selection that must be justified. At a typical lock site, lubricants are usually

purchased by the lock staff with a credit card from a local vendor. The purchases are typically under the $3,500 credit card limit. One advantage of purchasing lubricants locally is that the delivery and distribution is nearly always done by the vendor.

This report was undertaken to review current practices and to identify opportunities to standardize lubricant selection throughout USACE civil works activities.

1.2 Previous efforts to standardize lubricant selection

Over the past several decades, a number of attempts have been made to standardize the lubricant selection process. The USACE Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program, which was initiated in 1984 and brought to completion in 1998, surveyed lubricant users in an effort to provide some standardization in lubrication selection. The resulting report, REMR-EM-5 (Clifton and Beitelman 1989) is included as Appendix B to this report.

The Bureau of Reclamation (USBR) published two technical manuals related to lubrication and maintenance of its dams and powerhouses. The *Facilities, Instructions, Standards, and Techniques (FIST), Vol 4-1A, Maintenance Scheduling for Mechanical Equipment* (USBR 2009, included in Appendix K to this report) establishes minimum recommended practices for maintenance of mechanical equipment in Bureau of Reclamation hydroelectric power and large pumping plants. This document recommends specific maintenance activities and maintenance intervals, and includes references. The *Facilities, Instructions, Standards, and Techniques (FIST), Vol 2-4: Lubrication of Power Plant Equipment* (USBR 2004, included in Appendix D to this report) discusses lubrication fundamentals, lubricant characteristics, additives, maintenance of lubrication systems, and the selection of lubricants for common powerplant equipment.

Unlike USACE civil works activities, the Department of the Army has standardized its lubrication program. Unlike civil works programs, military applications maintain many combat vehicles, wheeled vehicles, aircraft, etc. that are fairly standardized and that have standardized lubrication requirements. The military side purchases lubricants through the Defense Logistics Agency (DLA), which provides commodities for the military/services and also for civilian agencies like the General Services Administration (GSA), National Oceanic and Atmospheric Administration

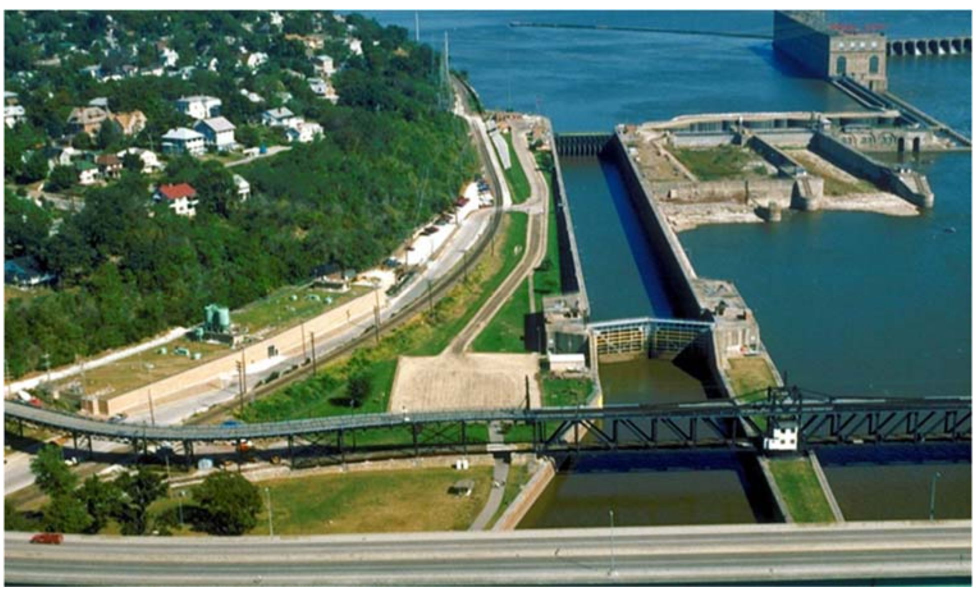
(NOAA), and others. These Government agencies can procure lubricants from DLA and, in turn, DLA is their primary supplier.

The Army Oil Analysis Program (AOAP) document standardizes the approach to oil sampling and frequency. Chapter 5 of this report discusses the AOAP, which is included in Appendix J to this report.

1.3 Sustainability

Nearly all USACE civil works sites are located over or near waterways (Figure 1). Leakage of oil and grease from machinery can lead to spills in these waterways. Oil spills into waterways can adversely affect the environment and generate a negative public opinion of USACE. A recent environmental settlement in USACE Northwestern Division (NWD) focused on in-water grease use in hydropower applications. Chapter 8 of this report discusses this settlement in further detail.

Figure 1. Lock 19 Mississippi River.



USACE defines the term “sustainability” as an overarching concept that encompasses energy, climate change, and the environment to ensure that “What we do today does not negatively impact tomorrow.” In the context of this discussion, opportunities for sustainability include the selection of environmentally acceptable lubricants (EALs) and the use of self-lubricated materials (SLMs). This report discusses both of these extensively. EM 1110-2-1424, *Lubricants and Hydraulic Fluids* (HQUSACE 2016a) also contains a wealth of information on the topic. EALs are considered "sustainable" because they break down (biodegrade) into carbon dioxide and water when spilled into waterways. SLMs (further discussed in Chapter 3 of this report) are also included in the sustainability initiative. As the name implies, the term SLM refers to components that need no external lubrication. For example, the Hydroelectric Design Center (HDC) is standardizing SLMs for wicket gate bushings.

The switch to EALs and SLMs can offer the following benefits:

- They can improve worker safety. SLMs, for example, require no greasing. Like biobased fluids, some EALs are safer to use than their mineral oil-based equivalents.
- SLMs can reduce operating and maintenance costs.
- Some EALs can provide better performance.
- The use of EALs and SLMs promotes environmental stewardship.

The development and transition to EALs in USACE civil works will take time. There is currently no Headquarters (HQ) directive to use EALs or SLMs at lock sites or field sites. However, an HQUSACE memorandum concerning the Clean Water Act compliance directed towards the hydropower business line (included in Appendix E to this report) is discussed below.

It is imperative to note that when switching to an EAL or SLM, the performance requirements of the system must be the primary consideration. For example, an EAL grease must work properly, must provide the proper lubrication to the mechanical part or equipment, and must not damage the equipment. If the EAL cannot do this, it should not be used. The Portland District (NWP) report (included in in Appendix C to this report) focuses on several applications where EALs could be used. These are primarily in-water grease applications. Extensive testing has been done on several greases to determine their performance and suitability; Chapter 8 of this report discusses these in further detail. U.S. Army Engineer Research and Development Center (ERDC) reports listed in the references and discussed in Chapter 8 also focus on EAL grease application for in-water use. These ERDC reports also evaluated and tested several greases from multiple manufacturers.

Standardization can also provide sustainability benefits by reducing the lubricant inventory, by standardizing the analysis program for monitoring and replacement decisions, and by mitigating environmental impacts. Standardization can also reduce operational risk (and increase savings) by avoiding unscheduled repairs and maintenance, and by improving the education of designers and end users.

This objective of this work is to investigate the feasibility of incorporating EALs and SLMs for any new USACE Civil Works project and major rehabilitations. The possibility of this becoming an HQUSACE directive will be explored as a follow-up activity. Nevertheless, the discussion of EALs and SLMs should be included in the project design documentation report. Appendix E provides a memorandum signed by Steve Stockton, Director of USACE Civil Works, regarding compliance with the Clean Water Act. This memorandum, which applies to the hydropower business line only, states its purpose as:

> All USACE hydropower facilities will implement the management practices listed below to the extent that it is economically practicable and technically feasible to do so. Such practices will be reviewed and updated as appropriate on a regular basis. (1) Implement operation/maintenance and housekeeping procedures that minimize oil/grease usage and leakage. (2) Capture and reuse and recycle or dispose, as appropriate, lubricant leakage when and where practicable and (3) Utilize environmentally acceptable lubricants. (4) When planning for major overhaul or replacement of equipment, evaluate installing new or replacement equipment which will reduce or eliminate use of lubricants (e.g., greaseless bushings). (5) Develop and implement an Oil Accountability Plan that accounts annually for lubricants added to and contained within equipment, as well as lubricants removed, recovered or disposed.

At this time there is no standardization for the use of EALs on USACE floating plants. For new construction, the systems are designed, constructed, and installed in accordance with the current U.S. Environmental Protection Agency (USEPA) Vessel General Permit (VGP). This permits essentially requires EALs for any vessels longer than 79 ft. Chapter 2 of this report discusses the VGP further. Unless it is determined that a “non-sheening” EAL is required, the type and selection of the EAL installed is generally left to the discretion of the contractor and equipment supplier. If a “non-sheening” fluid is required, a Polyalkylene Glycol® (PAG) type fluid should be specified. For vessels and systems in-service, individual operators and project offices and districts provide the direction and use of EALs.

1.4 Opportunities for standardization

As mentioned, completely standardization of lubricant selection throughout USACE civil works activities is not possible for several reasons. First, there is a vast range of equipment used, and machinery is often custom designed. There is a tremendous range of climate conditions across the country that can affect lubrication choices.

However, there are still opportunities for partial standardization (which can be very beneficial) including standardizing performance requirements. From a contracting and legal perspective, mandating a specific grease for a miter gate pintle or a specific hydraulic fluid is not possible. However, some basic performance requirements can be provided that the manufacturer has to meet. At least this method would provide consistency in the performance of the machinery lubricants. These performance requirements are included in Chapter 6 of this report. Table 1 gives a partial listing of some components that could be standardized this way.

Table 1. Opportunities for standardization by performance requirements.

Component	Lubricant
Miter Gate Pintle	Grease
Sector Gate Pintle	Grease
Tainter Gate Trunnion	Grease
Miter Gate Gearbox	Gear Oil
Tainter Valve Gearbox	Gear Oil
Miter Gate Hydraulic Power Unit (HPU)	Hydraulic Fluid
Tainter Valve HPU	Hydraulic Fluid
Tainter Gate HPU	Hydraulic Fluid
Tainter Gate Gearboxes (Parallel, Helical, and Worm)	Gear Oil
Miter Gate Drive Open Gears	Grease
Miter Gate Rack Gears	Grease
Tainter Valve Drive Open Gears	Grease
Pillow Block Bearings	Grease or Oil
Couplings	Grease
Dam Gate Open Gears	Grease
Motors	Grease
Wire Rope	Grease
Chain	Grease

Standardization can also be approached regionally. There should be no reason why two adjacent lock sites use entirely different sets of lubricants for the same machinery. At the very least, each USACE Civil Works District should standardize its machinery lubricants for key components. For example, Rock Island District has standardized their lubricants for the miter gate gearboxes (see Chapter 6).

Procurement and contracting practices may also be adjusted and standardized. The St. Paul District, for example, has used an indefinite delivery indefinite quantity (IDIQ) contract to purchase lubricants for the marine plant from a single manufacturer. The lubricants are used for a variety of systems including the cutter head dredge gear drive and for various diesel engines of the marine plant. This 5-year contract allows the end users to purchase standardized lubricants over the 5-year time frame. Prices of the lubricants are established in the contract. This could be a consideration for lock and dam machinery lubricants.

1.5 Opportunities for sustainability

The use of SLMs is an effective means to meet sustainability objectives when applicable. The second is to use EALs when applicable. In all cases, it is important to first establish the mechanical systems in which SLMs and EALs can be incorporated.

There are two key areas where EALs could readily be integrated. One is in hydraulic drive systems for miter gates, culvert valves, and dam gates. On European waterways, including the Danube River locks in Germany, Panolin (brand name for a synthetic ester [SE]) EAL hydraulic fluid is exclusively used for these applications. Panolin HLP Synth is a fully synthetic, readily biodegradable, non-toxic hydraulic fluid made from saturated esters (see Chapter 6). However, there are many other options for hydraulic system EALs (see Appendix H). Base fluids that meet EAL criteria include PAOs (polyalphaolefins), PAGs, SEs, and biobased (crop-based) fluids. These are further discussed in Chapter 6 of this report. ERDC/TN DOTS-16-1 (Keyser, Samuel, and Welp 2016) and Appendix H evaluate all these EAL hydraulic fluids. This should be referenced when considering an EAL hydraulic fluid.

One consideration for new locks and rehabilitation of existing locks is whether to use a hydraulic drive system or an electromechanical drive system. Hydraulic systems would eliminate some of the greasing requirements, but the hydraulic fluid requires additional maintenance. Cleanliness requirements for hydraulic fluids are greater than for gear oils.

A spill involving a hydraulic system can allow a greater amount of fluid to enter the waterway than would an electromechanical drive system. However, hydraulic drive systems may be able to limit some of the water lubricant interactions, such as would occur in open gear systems, which is the case when the lock becomes submerged during a flood.

Grease applications are the second key area for incorporating EALs. Several published studies and on-going studies in NWD (summarized in Chapter 8 of this report) are evaluating the performance requirements and applicability of EAL grease. ERDC has also evaluated a number of EAL greases from multiple manufacturers. Appendix I includes a proposed guide specification for EAL grease. This effort needs further development; this report recommends the implementation of this guide specification as a Unified Facilities Guide Specification (UFGS). It is imperative to note that EAL grease should have the same performance requirements as a mineral-based grease. Like hydraulic fluid, EAL grease base fluids could include PAGs, PAOs, SEs, and biobased fluids.

1.6 DLA and Army Oil Analysis Program

The Army military side uses far more fuels and lubricants than does the USACE civil works side. This is because the Army uses a vast number of vehicles and combat equipment. Consequently, the Army has standardized its lubricant selection by using military standards for lubricants. Lubricants are identified by military specifications. National Stock Numbers (NSNs) are used to order products from the Federal supply system. It is worthwhile to discuss briefly the role of the Defense Logistics Agency (DLA) in this process.

The DLA provides the Army, Marine Corps, Navy, Air Force, Coast Guard, other Federal agencies, and partner nations with the full spectrum of logistics, acquisition, and technical services. This includes supplying the nation's military branches and several civilian agencies, including GSA, with logistics, acquisition, and technical services.

DLA sources and provides nearly all of the consumable items America's military forces need to operate. This includes food, fuel, medical supplies, and construction material. For the purposes of this report, this includes lubricants. Of the six primary field activities of DLA, four provide different commodities or supplies. DLA Energy provides petroleum products and fuels and lubricants. DLA Aviation (AVN) provides repair parts for aviation weapon systems. Three commodities/supplies provided by DLA AVN, Richmond are:

- 6810 chemicals
- 6850 miscellaneous, chemical specialties
- 9150 oils and greases (cutting, lubricating, hydraulics).

These are called “Federal supply classes.” DLA also supplies 86% of the military’s spare parts and nearly 100% of fuel and troop support consumables; manages the reutilization of military equipment; provides catalogs and other logistics information products; and offers document automation and production services to a host of military and Federal agencies. DLA energy services offer a wide array of bio-based fuels and lubricants for military applications. DLA Energy is one of the six primary level field activities that provides bulk petroleum products, lubricants, and alternative fuel/renewable energy, among other commodities.

The AOAP (discussed further in Chapter 5 of this report) is a standardized oil sampling and testing program used by the Army on all its equipment. Some key parts of the AOAP program can be used to standardize testing requirements for USACE civil works applications.

USACE civil works districts can order machinery lubricants through DLA. This should be a consideration especially in any bulk quantity. Purchases are accomplished by using the lubricant’s NSN. All the lubricants have specifications associated with them. The 13 digit NSN has significant meanings. For example for the NSN 3210-01-138-5895:

- 32 is Federal supply group
- 3210 is Federal supply class
- 01 is country code of origin
- 138-5895 is unique serial number
- 01-138-5895 is national item Identification (ID) number.

Items are procured through NSNs by going through U.S. Department of Defense (DoD) FedMall (formerly called e-MALL):

- http://www.dla.mil/info/FedMall
- Customer Interaction Center: 1-877-352-225 / DSN CONUS/OCONUS 877-352-2255
- DLAcontactcenter@dla.mil.

Also, each service and government agency has its own automated ordering systems. Procurements can be done through these systems using MILSTRIP/FEDSTRIP (Standard Form 344) (where MILSTRIP stands for "Military Standard Requisitioning and Issue Procedures" and FEDSTRIP stands for "Federal Standard Requisition and Issue Procedures").

For help, access: http://www.logisticsinformationservice.dla.mil/CIC/self_default.asp

or call: 1-877-DLA-CALL (1-877-352-2255).

The DLA Headquarters' Public Affairs Office also created the linked video below. It can used to educate internal non-acquisition employees and DLA customers about the path of a requisition. This video is very high level, but it provides an overview of the requisition process as it flows through DLA. The video also is on DLA's YouTube channel.

- Where's My Stuff (open caption): https://youtu.be/3LXFw0WI-tA
- Where's My Stuff: https://youtu.be/WIYRFniA3Pw

2 Environmentally Acceptable Lubricants

The content for this chapter was derived from two technical reports and one HQUSACE Engineer Manual:

Medina, Victor F. 2015. *Evaluation of Environmentally Acceptable Lubricants (EALS) for Dams Managed by the U.S. Army Corps of Engineers* ERDC WQTN-MS-9, https://www.researchgate.net/publication/281179018_Evaluation_of_Environmentally_Acceptable_Lubricants_EALS_for_Dams_Managed_by_the_US_Army_Corps_of_Engineers_Victor_F_Medina

Medina, Victor F. 2017. *Evaluation of Environmentally Acceptable Lubricants (EALs) for NWD Dams*. Draft Technical Report (TR). Vicksburg, MS: Engineer Research and Development Center, Environmental Laboratory (ERDC-EL).

Headquarters, U.S. Army Corps of Engineers (HQUSACE). 2016. *Lubricants and Hydraulic Fluids*. Engineer Manual (EM) 1110-2-1424. Washington, DC: HQUSACE. This EM provides a much more extensive discussion on environmentally acceptable lubricants or EALs.

2.1 The need for a workable definition of EALs

Because it is difficult to completely eliminate spills and discharges of mineral oil based lubricants, and also difficult to alleviate public concerns about their impact on the environment, a new class of EALs is becoming available and is finding increased use. In contrast to mineral oil based equivalents, EALs are non-toxic and decompose into water and carbon dioxide (CO_2). To be an EAL, the base oil must be biodegradable, non-toxic, and must not bioaccumulate the environment. To be "biodegradable," a lubricant must have the capability to be fully decomposed by soil and water borne micro-organisms such that the micro-organisms consume the lubricant, leaving only residual natural substances like CO_2 and water.

Note that the term "Environmentally Acceptable Lubricant" should *not* be confused with other commonly used, but less specific labeling descriptors (e.g., "environmentally friendly" or "environmentally aware" lubricants), which vaguely suggest that a lubricant would have a neutral to slightly negative (within an acceptable level) impacts on the environment if released. The term "Environmentally Acceptable Lubricant" denotes that the lubricant product meets certain requirements. The USEPA (2011) defines EALs as products that meet specific criteria for biodegradation, aquatic toxicity, and bioaccumulation. Products labeled with misleadingly similar terms very likely do not meet the strict EAL criteria.

Further complicating matters, the USEPA definition of EALs is broad; determining whether a product meets the EAL criteria is not always clear. For example, tests may be given to demonstrate that a lubricant meets the EAL criteria. However, a lubricant may also be considered an EAL based on the lubricant's chemistry properties (like octanol water coefficient), or based on its base oil composition. The USEPA definition cites several labeling programs that do not necessarily require testing of all criteria. Consequently, many products that claim to be EALs do not actually have test data to demonstrate that they meet one of more of the EAL criteria. A working definition must account for the breadth of the USEPA definition.

Moreover, the test procedure itself for EALs can have some drawbacks. For instance, the specific gravity of a fluid can affect test results, e.g., a fluid that floats may negatively impact the test procedure. Also, there are often differences between laboratory testing and practical results; it is the practical results that dictate fines and hazardous response requirements.

The ASTM document, STP1521, Testing and Use of Environmentally Acceptable Lubricants, is also a good reference for a discussion of EALs. The document provides industry trends, test data, technical papers, and environmental policies.

2.2 Food grade vs. EALs

The term "food grade" is also sometimes confused with the term "environmentally acceptable lubricant." In fact, these are different classes of lubricants. Food grade lubricants are a class of lubricants that are governed by the U.S. Food and Drug Administration and that are acceptable for use in meat, poultry, and other food processing equipment. The U.S. Department of Agriculture (USDA) created the current original food grade designations H1, H2, and H3, to designate lubricant types that may be used in food-grade applications based on their likelihood to contact food.

The larger issue is whether a food grade lubricant can truly meet the performance requirements of the various machinery and applications within USACE civil works. Food grade lubricants are often made of white mineral oil, which is not toxic, but which does not always meet the biodegradability criteria commonly required of EALs. As a result, food grade lubricants may or may not work as lubricants in USACE civil works machinery. The selection of lubricants for USACE civil works should be based on EALs and not food grade lubricants.

2.3 Environmental effects from lubricants from dams and navigational structures

Brunner and Salmon (1997) documented that oil and lubricant leaks from hydroelectric dams pose a significant environmental risk, and they developed a model to assess risk for dams in Canada. Similarly, Verlind, Leonsson, and Videhult (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 Columbia Riverkeepers reported significant releases of oils of all kinds from dams on the Columbia and Snake Rivers (Johnson 2014). The Columbia Riverkeepers is an environmental organization whose mission statement is "*to protect and restore the water quality of the Columbia River and all life connected to it, from the headwaters to the Pacific Ocean*."

Some of the leaks were reported to contain polychlorinated biphenyls (PCBs), which are highly regulated and very resistant to biodegradation (Johnson 2014). Hydraulic power systems on navigation locks and dams in particular can be prone to leakage into the waterway. This is especially the case as seals on the hydraulic cylinders age and deteriorate. Hydraulic piping leaks are also common occurrences when hydraulic pipe corrodes, as happened at Locks 52 and 53 on the Ohio River (Figure 2). Some locks such as the Lagrange Locks (Figure 2) can become submerged during floods, further increasing the risk of hydraulic fluid entering the waterway.

EALs are designed to minimize environmental damage. This is an important consideration for many USACE civil works sites on waterways. Leakage of the best EAL would cause a neutral to slightly negative impact. Even so, whenever possible, releases of any kind should be avoided or minimized.

Figure 2. Lock 53 and LaGrange Lock hydraulic cylinders.

2.4 Base oil composition

The base oil of a lubricant plays a critical role in its environmental impact. The base oil often has the most effect on a lubricant's biodegradability. 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 oils. Mineral oil lubricants can biodegrade, but the process is generally slow, and the toxicity of mineral oils tends to be problematic. So, mineral oils are generally the most damaging base oil when released to the environment.

Other types of base oils can lessen the impact of release into the environment. Biobased lubricants are lubricants derived from natural sources with minimal modification (Salimon et al. 2012). Vegetable oils are the most common; these 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). Biobased lubricants have some limitations, particularly at low temperatures. However, when correctly selected for the 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. This is often done by augmenting the base oil with additives, or by blending it with other base oils. Biobased lubricants generally biodegrade quickly and are usually far less toxic than are mineral oils, especially in the smaller quantities that get released into the environment.

Chapter 4 of this report more extensively discusses some of the drawbacks of biobased lubricants. Interestingly, one USEPA report (USEPA 2017) states that vegetable oils and animal fats have the same negative impacts on the environment as mineral oils. The releases discussed in the USEPA report, however, are generally larger in scale than quantities typically representative of a typical USACE civil works facility, and the report does not specifically call these "EALs."

Biobased lubricants will often have the greatest volume of additives. This is in an attempt to extend the fluid's life. Biobased lubricants generally have the shortest life expectancy compared to other EALs. Biobased fluids are often blended with other base oils to extend life, but this generally reduces biodegradability. These blends and high volume of additives can also increase toxicity.

Synthetic lubricants are formulated via chemical synthesis to create materials with desirable lubrication properties (Nagendramma and Kaul 2012). Chapter 4 of this report discusses synthetic lubricants in more depth. Chemicals used in synthetic lubricants can be derived from petroleum, from plant sources, or even from mixtures. 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, most synthetic lubricants include labile structures that facilitate biodegradation while reducing toxic exposures compared to mineral oil lubricants. These include synthetic esters (SE), polyalkaline glycols (PAGs), and polyalphaolefins (PAOs). Synthetic esters are more prevalent at this time especially for grease applications.

PAOs are synthesized hydrocarbons and have only recently been used as EALs. PAOs have a narrow bandwidth where they are biodegradable, generally at lower viscosities. They are also sometimes blended with a biobased lubricant.

As noted, mineral oil biodegradation is slow and may be incomplete. EALs tend to biodegrade more quickly 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 Coordinating European Council (CEC) L-33-A-93 test (CEC 1982) 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 < Biobased lubricants (Vegetable Oils)

Normally, mineral oil lubricants have relatively high toxic effects, while PAGs, synthetic esters, and biobased lubricants have lower toxic effects. However, in some instances, PAGs can have higher levels of toxicity due to their increased solubility resulting from the glycol groups.

2.5 Additives

Additives improve a lubricant's performance. EM 1110-2-1424 (HQUSACE 2016a) discusses many types of additives, including oxidation inhibitors (anti-oxidants), rust inhibitors, extreme pressure (EP) agents, antiwear agents, and friction-reducing materials (Duzcukoglu and Acaroglu 2010, Wright 2008). In general, additives contribute to a lubricant's toxicity. Many additives formulated for mineral oil based lubricants will not work for EALs because they are toxic.

Additionally, the USEPA discussion of EALs focuses only on the base oil. Since additives can also affect the environmental effects of the lubricants, most commonly making them less environmentally acceptable (particularly by increasing their toxicity), USEPA sources should not be the sole determining factor regarding environmental adequacy. Additives can be developed using environmentally acceptable materials that further improve the product's environmentally sustainability.

2.6 EPA 800-R11-002

Section 4 of EPA 800-R-11-002 (USEPA 2011) and also EM 1110-2-1424 (HQUSACE 2016a) specify the definition of an EAL: the lubricant must be biodegradable, minimally toxic, and non-bioaccumulative. The tests to determine biodegradability, toxicity, and bioaccumulation are further defined in EM 1110-2-1424 and EPA 800-R-11-002; summarized in the paragraphs below.

2.6.1 Biodegradability

Tests for biodegradability measure the breakdown of the chemical structure of the lubricant by microorganisms (USEPA 2011). Two types of biodegradation are identified in evaluating lubricants: (1) primary biodegradation occurs through the loss of one or more active groups that reduces or eliminates the toxicity of the lubricants, and (2) ultimate biodegradation occurs through the mineralization of the compounds to carbon dioxide and water. Compounds that are "inherently biodegradable" are those that can degrade in any test; compounds that are "readily biodegradable" show a fraction of removal within a specified time frame. Table 2 summarizes tests commonly that are used to determine the biodegradability of chemicals and that are, or can be, used to assess lubricants. ASTM D5864 is one such standard in the United States. Interestingly, EPA 800-R11-002 (USEPA 2011) does not limit testing to only those listed. It is possible another (unlisted) test could be used.

Table 2. Commonly used methods for measuring biodegradability (adapted from 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.

There also needs to be a distinction between inherently biodegradable and readily biodegradable. EM 1110-2-1424 (HQUSACE 2016a) states that lubricants that are not readily biodegradable and only inherently biodegradable will not be considered by USACE to be environmentally acceptable. "Inherent biodegradability" is only an indicator of whether a substance has any potential for biodegradation. Many substances will biodegrade, but it may take years for them to do so.

Biodegradation is a complicated process; testing for biodegradation may not completely connect testing results with real world conditions or outcomes. Oil condition is also an important factor. In the laboratory, oil is new and without issues of wear or contamination. In real world spills and leaks, the fluid is rarely new and may well have more harmful effects.

2.6.2 Toxicity

The second criterion that an EAL must meet is low aquatic toxicity. Like biodegradability, a number of toxicity tests can be applied (Table 3). The most common test methods used by the lubricant industry for evaluating the acute toxicity of their products are described in EPA560/6-82-002, Sections EG-9 and ES-6 (USEPA 1982), and Organization for Economic Cooperation and Development (OECD) 203 (OECD 1992). These tests determine the concentration of a substance that produces a toxic effect on a specified percentage of test organisms in 96 hours.

Table 3. Commonly used methods for measuring toxicity (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)

Toxicity tests, such as OECD 201 (OECD 2011) and 202 (OECD 2004), were developed to test chemicals that solubilize in water. These tests assume that the solution to be taken in through a fish's gills to demonstrate the concentration at which it becomes toxic. Mineral and vegetable oils are not soluble in water and have a higher specific gravity than water, and therefore will float. This means that these oils will not form a solution that will pass through the fish's gills, so that these tests will result in a false positive for mineral and vegetable oils. The same applies for some esters and PAOs. This style of toxicity test was not developed for use on these types of fluids, even though they are still used. This does not mean those fluids are toxic, rather some of the current testing methods do not adequately measure all fluids equally.

The U.S. Fish and Wildlife Service (USFWS) also has a rating system for toxicity (Table 4). The scale ranges from relatively harmless to super toxic. The USFWS Research Information Bulletin No. 84-78, "Acute-Toxicity Rating Scales" (August 1984), defines the ecotoxicity for the aquatic environment (acute toxicity), in terms of concentration levels measured for an effect concentration, EC_{50} and lethal concentration, LC_{50}. The USFWS defines acute toxicity concentrations for the aquatic environment as:

- LC_{50} - *...a 96-hour LC_{50} value is the concentration of chemical that would be lethal to 50% of a population of the test organisms (invertebrates, fishes, and amphibians) within 96 hours.*

- EC_{50} - *Toxicity to some invertebrates (daphnids and midge larvae), expressed as 48 hour EC_{50}, is the estimated concentration of chemical that would produce an effect (immobilization, loss of equilibrium, etc.) within 48 hours.*

Table 4. USFWS and USEPA toxicity rating scales for aquatic organisms.

	USFWS	USEPA
Relative Toxicity	EC50 or LC50 (mg/L or ppm)	LC50 (ppm)
Super Toxic	< 0.01	Not Defined
Extremely Toxic	0.01-0.1	< 0.1
Highly Toxic	0.1-1.0	0.1-1
Moderately Toxic	1.0-10.0	>1-10
Slightly Toxic	10-100	>10-100
Practically Nontoxic	100-1000	>100
Relatively Harmless	>1000	Not Defined

For use in USACE facilities, an environmentally acceptable (EA) lubricant should be rated to meet or exceed the minimum requirements of EPA 560 and the noted USFWS standard as follows:

- EC50 or LC50 concentration levels defined for ***"Practically Nontoxic"*** rating as defined by EPA (and USFWS), or IC50 concentration level defined by USFWS.

2.6.3 Bioaccumulation

The third criterion for an USEPA defined EAL is that it must fall below certain thresholds for bioaccumulation. Bioaccumulation is the build-up of organic chemicals in the fatty tissues of an organism over time. Such buildup is harmful to the organism, and can pass up through the food chain. The longer the organism is exposed to a chemical, and the longer the organism lives, the greater the accumulation of the chemical in the tissues. The criteria and rate of 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, if the buildup consists of organic constituents, it 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 (Kow) is the common basis for assessing bioaccumulation. In a Kow 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, Kow is typically presented as a logarithmic scale (log Kow).

Log Kows for marine environments tend to vary between 0 and 6. Substances with Log Kow < 3 tend not to bioaccumulate and acceptable for meeting the definition of an USACE EAL. Lubricants with Kow > 3 are considered as bioaccumulating. OECD 107 and 117 are common methods used to measure Kow values for EAL purposes (OECD 2013a).

2.6.4 Base Oil

Although EPA 800-R-11-002 recommends testing to demonstrate that a lubricant meets EAL criteria, it actually does not require it. The USEPA indicates that lubricants with specific base oils 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 readily biodegradable, have no potential for bioaccumulation, and low toxicity, even without supporting testing. The USEPA also indicated that synthetic ester and PAG based greases also generally meet EAL criteria. Although this general criteria appear to be less authoritative than measurements based on supporting laboratory data, it is acceptable based on EPA 800 R11-002.

2.6.5 Labeling

Various labeling programs are available in the marketplace for EALs (Table 5). Many of these are European labeling programs. The intent of these labeling programs is to minimize confusion over EA lubricants and to increase public awareness for environmentally preferable products. For the USACE end user, these labeling programs may be enough to qualify certain lubricants as EALs (see the Tiered definition in Section 2.9.2 below). Some labels will qualify a lubricant as a Tier 1 EAL while other labels will qualify the same lubricant as a Tier 2 EAL. These labeling programs have defined, established methods to measure the properties of a lubricant that would qualify it as being environmentally acceptable.

Table 5. Criteria for labeling programs used by the USEPA to define 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)	

EPA 800-R-11-002 lists several labels that are used to define a lubricant as an EAL (Table 5):

- *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 that includes standards for hydraulic fluids (SS 155434) and greases (SS 155470).
- *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/

Note that some of the labels require only a portion of the testing for the three criteria, although they do have other requirements that must be met.

2.7 USEPA vessel general permit (VGP)

The USEPA Vessel General Permit (USEPA 2013) is a document for waterborne vessels (there is an exemption for recreational vessels) regulating their discharges in "*waters of the United States*," which includes all navigable water. The document is set to expire in 2018 unless it is renewed. This standard covers 27 ship discharges that are incidental to normal commercial vessel operations. The law affects any commercial vessel over 79 ft that provides transportation and operates within the 3-mile territorial waters, Great Lakes, and inland U.S. waterways. The standard basically requires EALs for systems with "*oil-to-sea*" interface; such as wire rope, thrusters, stern tubes, propulsion drives, etc. The document recommends the use of EALs in all above deck equipment, and also essentially mandate EALs in all oil-to-sea interfaces unless technically infeasible. EALs are also required for the use of two-stroke motors, although there is an exemption if technically infeasible. Special requirements allow the use of non-EALs in documented cases that can justify why the use of EALs is not feasible, and that record the amounts of non-EALs used.

Appendix A of the VGP contains definitions for EALs, biodegradability, toxicity, and bioaccumulation. The EAL definition is essentially identical of that to the USEPA 800-R-11-002. However, the definitions for the criteria are more detailed and specify that testing is required. For VGP compliance, base oil composition is not suitable as a definition.

2.8 Previous USACE documents on EALs

Two ERDC documents on EALs (Medina 2015; Medina et al. 2017, in press) focus primarily on greases that would be used in water or above water at dams. Medina 2015 is an introductory document that describes base oil differences. It covers the properties of an EAL and discusses performance of EALs from a very general perspective.

Medina et al. (2017) focuses on an application for the Northwest Division (NWD) dams. In-water and above water sources were assessed. A comparison was then made of potential EAL products to determine if they had the performance criteria for NWD use. The assessment compared EALs with existing greases and with published performance criteria, and included the results of interviews with personnel at projects that had adapted EAL greases. The conclusion was that EAL products at least potentially meet performance criteria. However, the study also found that most EAL products had not completed testing for all the EAL criteria. Specifically, data for bioaccumulation tended to be missing. So, a tiered system was proposed.

2.9 Operational tiered working EAL definition

A review of EPA 800-R-11-002 clarifies that there are currently several methods to determine whether a lubricant could be considered an EAL:

1. Testing is recommended to show that the lubricant meets the three criteria of biodegradation, toxicity, and bioaccumulation.
2. However, an EAL could go through a labeling program that would qualify it as an EAL.
3. It is also possible for a lubricant to qualify itself on its base oil alone.

Testing for all the criteria would represent a most stringent approach, while declaration due to base oil composition would be a less rigorous means. Because of this variability, a tiered approach is proposed, where a Tier 1 EAL has passed the most stringent criteria and Tier 2 is less so.

2.9.1 Means of meeting criteria

To start, we define three ways that a lubricant could pass each criterion (biodegradation, toxicity, and bioaccumulation):

- *Testing*. EPA 800-R-11-002 (USEPA 2011) has defined several tests for each criterion. By presenting test results as a report or in a specifications sheet, a grease or oil can conclusively prove that it passes the criteria.
- *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 and is a strong endorsement for meeting a given criteria.
- *Base Oil Composition*. The USEPA indicates that EALs 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 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.
- *Labeling*. The USEPA definition indicates that specific labeled products are considered as EALs. Several are cited including: Blue Angel; Swedish Standard(s); Nordic Swan; European Eco-label; and OSPAR. Section 5 of EPA 800-R11-002 (USEPA 2011) also identify these labeling programs. In addition, some EALs are certified as VGP compliant (USEPA 2013). ERDC has determined this to be an equivalent label and all EALs and greases defined as VGP compliant are determined to be EALs.

2.9.2 Tiered definition

Acknowledging that some candidate EALs have more complete data than others and that the USEPA definition can be interpreted either tightly or more broadly, ERDC has developed a tiered definition that might help USACE field sites choose EAL oils and greases. A Tier 1 USACE EAL is one that conforms to a strict interpretation of the USEPA definition and will either:

- Be a product labeled by European Eco-label, and/or Ospar (other product labeling could be considered by an Environmental Officer), or
- Be a product classified as USEPA VGP document Appendix A compliant, or

- Have test data as specified in USEPA 800-R11-002 or in USEPA VGP document Appendix A. Test reports shall indicate that it meets all 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, but:

- It is labeled by one or more of the following: Blue Angel, Nordic Swan, or Swedish Standard and/or,
- It contains a manufacturer’s statement that it meets one or more of the test criteria (bioaccumulation, toxicity, and biodegradability) as per the USEPA 800-R11-002 definition or USEPA VGP document Appendix A definition, with appropriate test data to confirm the other criteria, and/or
- Its base oil indicates that it meets one or more of the test criteria (see USEPA 800-R11-002, 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. Allowing a broader set of EALs (i.e., Tier 2 definition) allows a much easier transition to EALs with a much higher degree of confidence. Since Tier 2 EALs have base oil compositions that are more environmentally benign, they represent a better alternative, from an environmental perspective, than mineral oil lubricants. However, if there are situations where the EAL definition could be contentious, then the choice should focus only on lubricants with a Tier 1 definition.

3 Self-Lubricated Materials

3.1 General recommendations

Self-lubricated materials (SLMs) allow another option for sustainability. There is a growing role of SLMs across USACE civil works including self-lubricated pintle bearings. Within USACE civil works these materials can be applicable to the slow moving machinery that operates under boundary lubrication. However, there is much misunderstanding about these materials. Designers and operators are also cautious about their use. SLMs are normally used in applications where grease is required such that they eliminate the need for greasing bearings and other components. However, there are applications in USACE where the end user still greases the material even when the SLM is used. EM 1110-2-1424 (HQUSACE 2016a) discusses this topic extensively. Other sources of information on this topic are USACE EM 1110-2-2610 (HQUSACE 2013) and UFGS 35 05 40.17, *Self-Lubricated Materials, Fabrication, Handling and Assembly* (USACE 2014).

Self-lubricating or greaseless bearing systems, which have been produced for a number of years, play a significant role in the aircraft and aerospace industry. Self-lubricating bearing materials have been used in both the United States and Europe for various gate drive applications including hinge and pintle bearings on sector gates and miter gates and trunnion bearings for radial gates. These systems eliminate the need for grease lines, prevent the introduction of grease into the marine environment, and provide a very low friction bearing system. Traditional bearings, such as bronze bearings, have a long history of successful performance and are typically an excellent choice for use. However, for gate drives and gate pivot points, self-lubricated materials can offer performance improvements for low speed and boundary lubrication conditions with limited required maintenance. Some of the benefits of self-lubricating bearings include the ability to withstand much higher bearing pressures. This allows bearings to be smaller, which helps minimize the size of adjacent members and reduce the size and weight of components, which in turn can help to minimize fabrication costs.

EM 1110-2-1424 (HQUSACE 2016a) further discusses solid lubricants. Perhaps the most commonly used solid lubricants are the inorganic compounds graphite and molybdenum disulfide (MoS_2) and the polymer material polytetrafluoroethylene (PTFE). Self-lubricated materials are materials in which the primary bearing or bushing lubricant is integral to the base material that provides lubrication for the life of the part. Self-lubricated materials use polymers with solid lubricants dispersed throughout the polymer matrix. SLM systems generally fall into one of the following types:

- fabric/textile reinforced polymers composites
- extruded homogeneous polymer materials
- sprayed homogeneous systems (liner systems and puck systems)
- plugged bearings.

3.2 Design considerations

For SLMs, wear material is typically enhanced with solid lubricants that help lubricate the bearing. The primary advantage of a lubrication free system is that lubrication is not required to be supplied from an external source like a greased bronze bearing. Other advantages include:

- the use of a more reliable lubrication method (especially in the loaded zone)
- lower coefficients of friction
- higher allowable loads (sometimes—this must be verified with manufacturer)
- potential reduction in operations and maintenance (O&M) labor
- the ability to provide electrical isolation to minimize or eliminate galvanic corrosion
- reduction in the potential for contaminating waterways by eliminating or minimizing the use of petroleum lubricants.

SLMs have disadvantages also. Among these is the lack of history of use for gate drive applications and a general lack of testing standards. Design details and proper preparation are crucial for successful installation. Other disadvantages include:

- For hydraulic gate applications, self-lubricated bearings are generally limited to low speed boundary lubrication applications.
- They have potential higher initial costs.
- Consequences of misalignment can be more severe and catastrophic (crushing failure modes instead of plastic deformation as is seen with bronze and metals).

- They have wide variation of proprietary material properties.
- Installation methods are generally more complex and often require interference fits.
- They are susceptible to impact damage during installation.
- They are susceptible to brittle failure modes.
- They typically requires stainless steel running surfaces (for example on a radial gate this will often require a stainless steel pin).
- They are a newer technology with newer design paradigms.
- They are not as tolerant of debris like a bronze bearing.
- Water absorption is an issue on some types of self-lubricated materials.
- Dimensional stability can be an issue when subjected to heat.
- More care must be taken when doing repair working around the bearings, especially in high heat operations.

The design of fabric/textile reinforced polymers for bushings has to consider several factors. Figure 3 shows an example of an application for a radial gate trunnion bearing. These (probably the most common) types of SLMs are constructed of composites made up of three basic components; textile, resin, and lubricants.

Figure 3. Textile reinforced polymer self-lubricated materials for radial gate trunnion bushing (USACE).

The textiles and fabric are often polyesters, polytetrafluoroethylene (PTFE), or Aramid fabrics. The textile serves to reinforce the base polymer resin material and provide mechanical strength and stiffness similar to the way steel rebar is used to reinforce concrete. The lubricants are disbursed through the base material matrix. As the material wears, new lubricant is constantly exposed. Polymers are ideal for a number of reasons. First, polymer construction methods allow for easy incorporation of solid lubricants. Second, the tribological properties of polymers offer advantages over metallic bearings. Polymer materials tend to experience highly elastic deformations when used as a bearing. In general, this elastic deformation requires less energy and results in lower friction. Third, polymer materials are lighter than metals and are generally easy to work with and cut.

Polymer materials have limitations. The main property that limits their range of use is thermal conductivity. For high speeds, polymers cannot dissipate the heat generated by friction fast enough to maintain their ideal mechanical properties. This limits their applications to slow speed bearings such as for the radial gate application. They can be harder to machine accurately due to the highly elastic deformations. The types of polymers used for self-lubricated materials tend to experience brittle failure modes. Situations where metallic bearings would elastically deform and redistribute stress can cause self-lubricated materials to crush or fracture and experience little to no plastic deformation. The polymers used for most self-lubricated materials are subject to water absorption. Swelling from water absorption can reduce bearing clearances or cause seizing if clearances are sized improperly.

Figure 4 shows the installation of a self-lubricated bushing for a radial gate by freezing in liquid nitrogen. Interference fitting is by far the most simple, cost effective, and common method to install self-lubricated sleeve bushings. SLMs can be more complicated to install and require greater care than traditional grease lubricated bearings and bushings. The SLM can be damaged much more easily than bronze bushings and bearings. It is critical to follow the manufacturer's installation instructions.

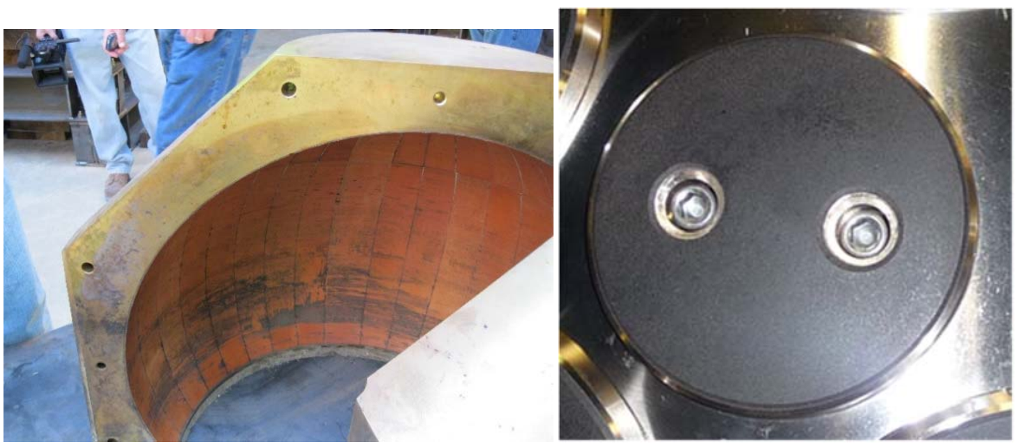
Figure 4. Spillway radial gate trunnion bushing - freezing in liquid nitrogen (USACE).

Smaller bushing sizes can sometimes be interference fit using a force fit method. Adequate protection should be provided to shield the self-lubricated materials from damage during force fitting. In general, force fitting methods should use smooth constant force and should avoid hammer blows or other impact loads to force components together. Larger bushing sizes can be interference fit using a shrink fitting method. The most common method is to cool the bushing in a freezer or submerge in liquid nitrogen to establish the shrink required to assemble components. This is typically done for the larger radial gate trunnion bushings. Dry ice (CO_2) can also be used to freeze the bushing for installation. After the bushing has warmed and returned to ambient temperatures it may be necessary to field machine to restore bore and pin fit tolerances. Designers should consult with the self-lubricated material manufacturer to determine the recommended amount of interference. Designers should also remember that, after interference fitting is performed, the inner surface of the bushing will shrink in diameter and change the bushing/bearing running clearance.

The design of extruded homogeneous polymer materials has some different considerations. The polymer extrusion process is used widely to mass produce plastic parts. Common household items fabricated with a polymer extrusion process include polyvinyl chloride (PVC) pipe, plastic gutters, trim, and moldings. With the right mix of thermoplastic polymer materials, this same extrusion process is used to create self-lubricated materials. The homogeneous nature of the formed materials tends to have low stiffness when compared to other self-lubricated polymer parts and, as such, the stiffness needs to be provided in the design of the bearing housing. The extrusion process is limited to using thermoplastic materials that will melt if exposed to high temperatures. These materials also tend to be softer and exhibit lower abrasion resistance properties.

Sprayed homogeneous coatings or liner systems are another type of self-lubricated material (Figure 5). The spray coating systems are used extensively for various gate drive and gate pivot point applications. This includes miter gate pintles, sector gate pintles, and sector gate hinge bearings. Spray coated self-lubricated parts are made up of two basic components, a spray applied, self-lubricated coating and backer material. The backer material provides the stiffness and strength for the part. Backers are typically made of metallic materials such as a bronze alloys or stainless steel, but hard polymer composites have also been used. The self-lubricated coating is a homogeneous polymer resin with solid lubricants such as PTFE.

Figure 5. Spray coated pintle bushing and Kamatics liner (USACE).



The coating is typically no more than 0.794 mm (1/32-in.) thickness. Materials with coefficients of friction in the range of 0.08 to 0.10 are typical. The sprayed self-lubricated coatings have machining capabilities similar to a soft bronze. After the spray coating is applied and cured, conventional machining methods are used to bring the coating to a final size. The rigid backer materials tend to create parts with high stiffness compared to other self-lubricated materials. Sprayed coatings tend to have a high hardness that provides excellent abrasion resistance and higher allowable design pressures. The spray coated systems can tolerate higher bearing pressures and have been used for bearing pressures over 34Mpa (5000 psi).

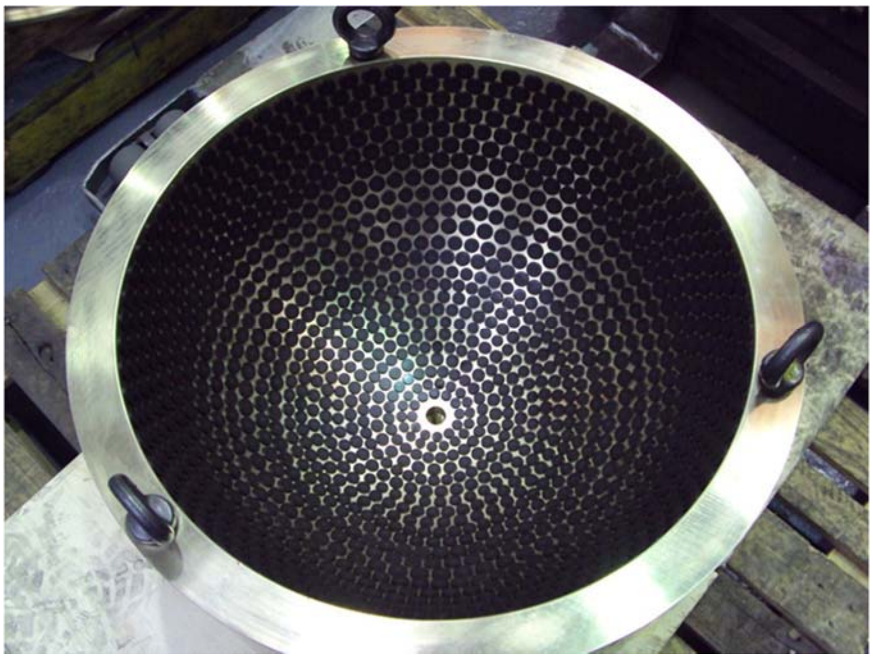
A variation on the liner system is the puck-type system where, instead of a continuous liner, the same type of synthetic material is placed on an array of bearing inserts (Figure 6). Puck systems have been used on a number of miter gate and sector gate pintle systems. Puck systems typically use the same types of material as liner systems, except they are applied to individual inserts mounted in recesses on what otherwise would be the bushing surface. The insert's face is raised above the mounting surface, such that the interstitial space between inserts does not contact the stainless steel bearing face. Puck systems facilitate fabrication on large bushings and aid in replacement, as they do not require removal of the entire bushing or pintle from the work site for recoating. This would be necessary for a liner system of machining and lapping for a greased system.

Figure 6. Miter gate self-lubricating pintle – The Dalles Lock and pintle puck system (USACE).

Plugged metals are the final type of self-lubricated material. Plugged metal self-lubricated parts are made up of two basic components, a bronze base material and polymer self-lubricating plugs. The bronze base material provides stiffness and strength for the part, while the plugs provide lubrication. As the bearing operates, the self-lubricated plug material wears. The plug wear material is pulled across the bronze surfaces by the shaft providing lubrication for the bearing. Lubricating plugs are typically a homogeneous polymer material. Common lubricating additives are polytetrafluoroethylene (PTFE) and graphite.

Plug-type systems essentially are a bronze bushing with lubrication for the life of the bearing supplied internally (Figure 7). They are most similar to traditional greased bronze systems. The bronze base materials provide a bearing stiffness comparable to traditional bronze supplied lubricant bearings. The degree to which the plugs act as a bearing surface, in addition to a lubricant, needs to be considered when determining effective bearing area. Plug-type systems might require break-in grease until the plugs wear adequately. Typically, they do not benefit from the same reduction in friction of a liner or puck-type system; however, plug-type systems do not risk liner delamination or grease system failure and are generally resilient regarding maintenance neglect.

Figure 7. Plug type self-lubricated bearing from Panama Canal miter gate pintle replacement project (courtesy ACP).



The intermittent spacing of the self-lubricating plugs is not ideal for applications that have small ranges of movement such as a radial gate. For the bearing to lubricate the full running surface, the bearing needs enough rotation for adjacent plugs to move over the same area. Also, the bronze base material does not provide electrical isolation between the bearing and running surface. Graphite is also a commonly used plug material that can cause severe galvanic corrosion in a marine environment. A graphite-based lubricant is prohibited in UFGS 35 05 40.17 (USACE 2014) due to corrosion issues associated with graphite in wet applications.

3.3 SLM properties

Solid polymer self-lubricated materials, such as textile reinforced composites and extruded homogeneous materials, have significant differences in failure behavior from metallic bearings. Solid polymer self-lubricated materials can sustain small amounts of overload or damage without impact to performance. However, significant overloads often leads to fracture of these types of material, which can progress into complete failure of the component. When significantly overloaded, most solid polymer materials experience brittle failure modes such as fracture and crushing. Crushing failures start to occur when the component loading exceeds the compressive yield point of the material. For rigid polymers, the compressive yield point is defined as the first point on the stress vs. strain curve where an increase in strain occurs without an increase in stress. Exceeding the compressive yield point of a material is most often caused by uneven part loading resulting from a severe misalignment. However, underestimating operating loads can also result in exceeding material yield points and crushing failures. There is also a large difference in the tolerance to debris and contamination between the self-lubricated materials (see Table 6).

Table 6. Tolerance to debris and contamination.

Material	Abrasion Resistance	Notes:
Fabric Reinforced Polymer	Medium to High	Fabric reinforces against abrasive wear
Extruded Polymer	Low	Soft material, not much to resist abrasion
Sprayed Coatings	High	High hardness gives good abrasion resistance
Plugged Bronze	Medium to High	Medium to high bronze hardness - soft plugs

Self-lubricated materials have a large range of materials types, constructions, performance properties, etc. However, the running surface requirements for most materials are virtually identical. The most important consideration for self-lubricated running surfaces is the surface finish. Almost all self-lubricated materials require very smooth surfaces. Most manufacturers require running surfaces no rougher than 0.8μm (32 micro-in.) for infrequent use and surfaces no rougher than 0.4μm (16 micro-in.) for frequent use. A stainless steel running surface, such as a stainless steel trunnion pin, is generally required to provide a smooth surface to prevent wear.

A critical design consideration for self-lubricated polymer materials (both fabric reinforced and extruded) is the combined effect of pressure (P) and velocity (V) or “PV” rate. The PV rate can be a quick indicator to tell if a self-lubricated material will or will not work for an application. The PV rate can be provided by the manufacturer and is an important consideration for sprayed coatings. The PV rate (the pressure P multiplied by the velocity V) measures the ability of the bearing material to accommodate the temperature limit generated by the frictional energy during operation. The PV value can also be used as a load-speed limit providing a basis for estimating relative wear rates. Most self-lubricated bearing manufacturers generate PV charts (with pressure and velocity both plotted on a graph) to show general acceptability of their product for an application.

Finding a standardized testing format for self-lubricated materials can be challenging. The U.S. Army Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL) and Powertech Labs, Inc. (Surrey, B.C., Canada) have developed a variety of self-lubricated material performance tests, described in Construction Engineering Research Laboratory (CERL) Technical Report TR-99-104, *Greaseless Bushings for Hydropower* (Jones 1999) and CERL Special Report, SR-04-8, *Evaluation Self Lubricated Components* (Race, Kumar, and Stephenson 2004). These are discussed further in USACE EM 1110-2-1424 (HQUSACE 2016a). USACE CERL and Powertech Labs developed the standardized testing to evaluate self-lubricated bearing performance under a variety of conditions. Both wet testing and dry testing were conducted. Self-lubricated material manufacturers submitted their product for testing and materials were ranked in order by performance. Designers should familiarize themselves thoroughly with performance test reports available for the material types they are selecting. Some factors considered in the Powertech tests include:

- static and dynamic coefficients of friction
- stick-slip ratio
- wear rate
- damage susceptibility
- surface damage.

Design bearing pressures will depend on the characteristics of the composite material being considered, the type of movement intended for the bearing, and the rotational or sliding speed at the bearing surface. Slower rotational speeds will tolerate bearing pressures at the higher end of this range.

Laboratory testing has measured coefficients of friction for most self-lubricated materials between 0.1 and 0.22, with some below 0.1. However, as with supplied lubricant bronze bearings, dirt, debris, and contamination can enter into the bearing and degrade the coefficient of friction that is seen in actual operation. Designers should select conservative coefficients of friction that account for debris and contamination for the design of self-lubricated bearing systems and related operating systems. These values should be above the manufacturer's stated values. For example, EM 1110-2-2610 states that a coefficient of friction of 0.3 should be used for tainter (radial) gate trunnion bearings. Composites that have static and dynamic coefficients of friction equal to each other result in smoother operating equipment, even if the friction load is high. When the static and dynamic friction coefficients are closer in value, a lower difference in strain energy exists as the system transitions from a static to dynamic condition. This helps to reduce the stick-slip phenomenon, allowing for a smoother operating system with less vibration, noise, and possible damage to the equipment.

3.4 Applications

Applications for self-lubricated materials within USACE civil works include:

- miter gate pintles
- sector gate pintles
- floating mooring bitts (installed at Bonneville Lock for example)
- tainter (radial) gate trunnion bearings
- tainter (radial) gate wire rope connection pin bushings
- vertical lift gate guide rollers
- vertical lift gate guide blocks and wear pads
- vertical lift gate reaction rollers and trains
- hydropower wicket gate bushings
- pin connections – trunnions / gudgeons
- roller chain
- axial-slide – push rod guides / crowder slides
- spherical bearings – pintles /self-align rollers
- gate guide/seals – knife gate slides/seals
- thrust washers – valve or gate trunnions
- rub blocks/wear pads – lifting beams
- pumps - vertical, wet end shaft bearings (hydrodynamic).

The spray coated puck system has been used on the 225 ft. New Orleans West Closure Complex sector gate pintle (36-in. diameter). The same system is used for several miter gates pintles in St. Paul District (Figure 8) and the NWP Dalles miter gate pintle (22-in. diameter). New miter gates currently being constructed in the St. Paul District will utilize the spray coated puck system. Self-lubricated materials are installed on 25 spillway tainter gates in NWP and 12 tainter valves in NWP. A self-lubricated pintle was initially installed at the New Orleans LPV 144 sector gate (Figure 8).

A new Unified Facilities Guide Specification (UFGS 35 05 40.17, "Self-Lubricated Materials, Fabrication, Handling, and Assembly") is now also available for use and should be used for procuring self-lubricated materials.

Figure 8. Lock 6 and LPV 144 pintle installation.

4 Synthetic Lubricants and Bio-based Lubricants

4.1 General

Oils are generally classified as refined and synthetic. For over 100 years, lock and dam navigation structures have traditionally used (refined) mineral oil or petroleum based lubricants. More recently, synthetic lubricants, biobased lubricants, and EALs have assumed a growing role within USACE. Self-lubricated materials are also being used more extensively throughout the Corps of Engineers. There are three types of lubricating oils: mineral, synthetic, and biobased (crop-based) (Table 7).

Mineral oil is derived from crude oil; its quality depends on the refining process. Mineral oil is mainly made up of four different types of molecules – paraffin, branched paraffin, naphthene, and aromatic. Paraffinic oils are used mainly in engine oils, industrial lubricants, and processing oils. Naphthenic oils have a saturated ring structure and are most common in moderate temperature applications. Aromatic oils have a non-saturated ring structure and are used for manufacturing seal compounds and adhesives.

Synthetic oils are man-made fluids that have identical straight chained structures, much like the branched paraffinic oils. One of the benefits of a synthetic is that the molecular size and weight are constant, making their properties very predictable. (By contrast, the molecular size and weight of mineral oils vary greatly.)

Biobased lubricants are primarily crop and vegetable-based. These include vegetable oil, rapeseed oil, sunflower oil, coconut oil, palm oil, or soybean oil. These are all considered biodegradable fluids.

All lubricants, whether hydraulic fluid, grease, gearbox oil, etc. start with a base oil. Different kinds of lubricating oils are produced by a blending process between a base oil and additives. The characteristics of the finished (blended) lubricant is determined by the type of base oil used and its additives. Grease, for example, is produced by adding a soap thickener. Oil quality is designated using a grading scale, and different applications require different oil qualities.

Table 7. Comparison of different base oils.

Properties	Mineral	Vegetable or Bio-Based	Synthetic
Biodegradability Temperature Range Oxidative Stability	Very Low Wide Good	Very High Moderate to Low Moderate	High Very Wide Very Good
Thermal Stability	Good	Moderate	Very Good
Mineral Oil Miscibility	Yes	Yes	Varies

4.2 Defining synthetic lubricants

Synthetic oils are making up a larger portion of the lubrication market especially in automobile oils. Synthetic oils are increasingly being used at USACE lock and dam sites. Synthetic oils are a man-made fluid with scientifically designed molecules. The molecules have identified structure. As such, fluid properties are very predictable. One example is greater hydrolytic stability (ability to resist chemical decomposition or hydrolysis in the presence of water). Synthetic lubricants are produced from chemical synthesis rather than from the refinement of existing petroleum or vegetable oils. These oils are superior to petroleum (mineral) lubricants in most circumstances. There are two American Petroleum Institute (API) base oil categories that include synthetics. The first is API Group IV and the only synthetic base oil included in this group is polyalphaolefin or PAO.

The second category is API Group V. These are non-PAO synthetic bases. Examples include diesters, polyolesters, alkylated benzenes, PAG’s, phosphate esters, etc. Some API Group III oils are also marketed as synthetics. These are highly processed crude oils that are very close in property to Group IV oils. The use of synthetic oils is increasing due to their popularity with many lubricant end users and marketing by manufacturers. Synthetic lubricants will typically be double or more the cost of petroleum-based lubricants.

PAO and Polyalkylene Glycols (PAG) are two common products produced in the synthetic base oil market. Of the two, PAO is the more common and used extensively in the automobile industry and are heavily marketed as engine oils. Both PAOs and PAGs are used for hydraulic fluids and as the base oil for some greases.

4.3 Synthetic oil production

Synthetic lubricants are produced from chemical synthesis rather than from the refinement of existing petroleum or biobased (vegetable) oils.

These oils are generally superior to and usually have longer life than petroleum (mineral) lubricants in most circumstances. The primary drawback of synthetic lubricants is their higher cost. Synthetic oils perform better than mineral oils in the following respects:

- better oxidation stability or resistance
- better viscosity index
- much lower pour point, as low as minus 50 °F (minus 46 °C)
- lower coefficient of friction
- better high temperature stability and protection against breakdown
- better low temperature viscosity
- lower operating temperatures
- extended life.

The advantages offered by synthetic oils are most notable at either very low or very high temperatures. Good oxidation stability and a lower coefficient of friction permits operation at higher temperatures. The better viscosity index and lower pour points permit operation at lower temperatures. It is worth noting that seal compatibility is not consistent with the various types of synthetic oils. Some industries have always used compatible seals, but others would need to use new seals. All fluid types, PAGs, PAO, biobased, mineral, etc., have to deal with compatibility issues and this needs to be a consideration, especially so if switching from a mineral-based fluid to a synthetic fluid.

4.3.1 PAO lubricants

Engine oils (Mobil, Shell, etc.) are the most common and are heavily marketed in this area as either full synthetic or partial synthetic. PAO synthetics are also used in greases and hydraulic fluids. These lubricants provide performance characteristics closest to mineral oils and are compatible with them. They are produced from crude derivatives (such as natural gas) and polymerized to different viscosity. In industrial applications, they may be combined with organic esters to be used in high temperature gear and bearing oils, as well as gas turbines. They are also used as a base fluid in some wide temperature range greases.

PAOs are gaining acceptance as high-performance lubricants because they exhibit certain inherent and highly desirable characteristics. These favorable properties include:

- a wide operational temperature range

- low pour point
- high viscosity index
- thermal stability
- oxidative stability
- shear stability
- compatibility with mineral oils
- some PAOs have low toxicity and qualify as EALs.

Disadvantages include:

- limited ability to dissolve some additives
- tendency to shrink rubber seals and hoses
- require addition of anti-oxidant additives to resist oxidation
- limited properties on boundary lubrication.

4.3.2 Synthetic esters

Synthetic esters are made from modified animal fat and vegetable oil reacted with alcohol. Synthetic esters are widely used as hydraulic fluids especially so in European waterways and as a base oil for greases. Some types of synthetic esters are used as EALs. The chemistry to produce esters also involves some petrochemicals. Esters are thermally stable and have a high viscosity index. Organic esters such as diabasic acid and polyol esters are the most common types. The properties of these oils are easily enhanced through additives. Properties include:

- excellent low temp fluidity (pour point in range from -58 to 149 °F (-50 to 65 °C)
- high viscosity index (above 140)
- good lubricating properties (high shear resistance)
- good thermal and oxidation resistance
- lower volatility than mineral oils.

Some disadvantages include:

- poor hydrolytic stability (diesters)
- tend to shrink rubber seals and hoses
- requires addition of anti-oxidant additives to resist oxidation
- limited properties on boundary lubrication
- affects paints and finishes.

There are other drawbacks. Some esters can be toxic to plants. If water content becomes high enough in the system, the fluid can degrade rapidly and can result in major equipment damage.

4.3.3 Phosphate esters

Phosphate esters are produced by reaction between alcohols and phosphoric acid. These oils are suited for fire-resistance applications and one of the more common applications is fire resistant hydraulic systems. Properties include:

- excellent fire resistance
- pour point in range from -13 °F to -58 °F (-25 to -50 °C)
- high viscosity index (above 120-160)
- excellent boundary lubrication properties
- good thermal stability
- fair hydrolytic stability
- a specific gravity >1 (water contamination floats on top).

Some disadvantages include:

- very low viscosity index (VI)
- limited capabilities at higher temperatures
- decomposition byproducts are corrosive
- poor compatibility with mineral oils
- degradation products are phosphate soaps with black sludge-like consistency.

4.3.4 Polyalkylene glycols

Polyalkylene Glycols (PAG) lubrication applications are diverse including gears, bearings, and compressors. They are used for hydraulic fluids and as the base fluid for some greases. As a hydraulic fluid, low temperatures and the effect on viscosity needs to be considered. They can increase the viscosity and increase the necessary pump horsepower (See Chapter 6 for more discussion). They have a growing role in EALs. PAG fluids have the greatest stability with a range from -45 to 250 °C (-49 to 482 °F). PAG lubricants excel where fire hazard is a concern. PAG lubricants are a mix of propylene and ethylene oxides. The use of the water soluble type is the most common and is the type used for EALs. They were the first biodegradable oils on the market. The biodegradability of PAG-based products depends on the relative percentage of ethylene/propylene oxide in the polymer. The higher the proportion of ethylene oxide the more biodegradable. They can be incompatible with a number of paint systems and varnishes and are completely incompatible with mineral oil. Because of this incompatibility, they may have the highest changeover costs of any class of EALs. Several PAG products are blends, however, that negate some, if not all, of these disadvantages.

PAG lubricants especially so in hydraulic fluids are able to tolerate more water in the system than all other lubricants without affecting oil performance. Also, all other oils will deposit increased varnish or sludge when water is present, but a PAG will not deposit any varnish or sludge.

The advantages of the use of PAGs must be balanced with their aquatic toxicity when mixed with lubricating additives, and with their incompatibility with mineral oils and some seal materials. PAGs are generally compatible with a vast majority of seals used in the industry, especially the most commonly used. Properties include:

- a tendency to volatilize rather than form deposits or sludge at high temperatures
- wide thermal range and high thermal conductivity
- high viscosity index above 150
- low solubility with hydrocarbon gases and some refrigerants
- good biodegradability and aquatic toxicity
- as a hydraulic fluid, ability to tolerate very high water concentrations
- very low coefficient of friction, which results in PAGs having some of the best lubricity.

Disadvantages include:

- incompatibility with mineral oils or their additives
- incompatibility with PAOs or esters.

4.3.5 Silicones

Silicones lubricants are chemically inert, nontoxic, fire-resistant, and water repellant. They also have low pour points and volatility, good low-temperature fluidity, and good oxidation and thermal stability at high temperatures. They are one of the older types of synthetic fluids and often used for brake fluid. Properties include:

- very high viscosity index (300 and more)
- chemically inert
- nontoxic
- good low temperature fluidity
- fire-resistant
- low volatility
- water repellent
- good thermal and oxidation stability up to quite high temperature.

Disadvantages include:

- high compressibility (low lube properties)
- oxidation products are abrasive (silicon oxides)
- low surface tension (does not form adherent lubricating films)
- poor anti-wear protection.

4.4 Biobased lubricants

Biobased lubricants can provide some advantages over mineral oil-based lubricants and synthetic lubricants provided they are properly selected. This is particular the case for their environmental benefits. Biobased lubricants, in particular crop-based grease products, tend to have poor low temperature performance and degradation at high operating temperatures; these properties must be considered in machinery applications. Biobased lubricants, however, can be blended with other lubricants to overcome the low and high temperature issues. Biobased lubricants have been used in the following applications where hydraulic systems and grease are the most common:

- hydraulic systems
- grease lubricated components (gears)
- gear boxes
- pumps
- wire rope and chain
- penetrating oil and multi-purpose oil.

The usable biobased lubricants can offer excellent lubricating properties (within a limited temperature range); they are also nontoxic and highly biodegradable, are relatively inexpensive compared to synthetic fluids, and are made from natural renewable resources. In general, biobased (in particular crop-based) lubricants:

- can have poor high temperature performance
- have a narrow viscosity operating range
- exhibit rapid oxidation at high temperatures and poor thermal stability
- thicken and gel at low temperatures
- are characterized by excellent biodegradability
- are relatively inexpensive.

Rapeseed oil (RO) or canola oil, is a base for the most popular of the biobased hydraulic fluids. RO quality has improved over time, and has become increasingly popular, but it has problems at both high and low temperatures and tends to age rapidly. The cost of rapeseed oil is approximately double that of mineral oil, which makes it more affordable than many alternative EALs.

On a life cycle basis, biobased lubricants can cost more than synthetics when one considers how often they need to be replaced. This primarily depends on their use and the particular application. For example, for in-water greases, washout is much more important than life cycle, and many biobased greases are among the best in washout.

Biobased oil lubricants, including rapeseed, castor, and sunflower oils, tend to age quickly. At high temperatures, they become dense and change composition; at low temperatures, they thicken and gel. This has been an issue with some EA grease products. It is important when using biobased fluids to make sure the temperature range is adequate for their use. Some products are not recommended for use in ambient temperatures above 32°C (90 °F) or below -6°C (21°F), but other products gel only after extended periods below -18°C (0°F) and will perform well up to 82°C (180°F).

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

Another important property of vegetable oils, and an advantage in some applications, is their high flash/fire points; 610°F/670°F (321°C/354°C) for natural ester vegetable oils compared to 400°F/450°F (204°C/232°C) for conventional petroleum (mineral) oils. This makes natural ester vegetable oil based fluids suitable for use in fire resistant hydraulic fluid applications and in transformers. Because of this property, the use in industrial transformer use is growing. Cargill is a major manufacturer in this market. Vegetable-based fluid is typically a soybean oil based product for use as a coolant and insulator in high-voltage electric transformers. For the past 30 years, mineral oil has been the dominant dielectric fluid used in transformers. However, mineral oil is flammable and can be toxic to the environment. Vegetable oil is much less flammable than mineral oil and can handle a much higher rise in temperature than mineral oil. This means manufacturers can design fluid-filled transformers 15-20% smaller and can deliver up to 20% overload capacity. What's more, vegetable-based fluid actually protects the transformer insulation making it last up to five times longer than transformers filled with mineral oil.

5 Standardized Sampling and Testing Procedures

5.1 General recommendations

Sampling and testing lubricants, and then analyzing and trending the data, is critical and should be part of every USACE facilities maintenance program. EM 1110-2-1424 (HQUSACE 2016a) states that: "*All USACE facilities, including navigation sites, field sites, and hydropower sites, shall establish an oil sampling and testing program for their equipment.*" This need for standardization can be met by establishing consist sampling and testing procedures for lubricants, and then by defining common warning limits for the test data.

Sampling and testing are very important measures. Creating a wear check database of lubricant performance history will allow for a better understanding of maintenance requirements for equipment. It is also important to examine, trend, and catalogue lubricant changes over time as their performance often diminish from usage.

Sampling and testing procedures should include tracking and trending of data. The frequency of testing will be discussed below. For an oil analysis program, the central question becomes how exactly is this data interpreted and trended. It is critical that data be interpreted correctly and the correct warning limits used. Table 8 describes some of the tests for various equipment that should be done. Ultimately, oil replacement should be done based on testing and monitoring data.

5.2 Standardized operating procedure for sampling and testing

Oil sampling is the most critical aspect of oil analysis and is discussed extensively in EM 1110-2-1424 (HQUSACE 2016a). Failure to obtain a representative oil sample impairs all other oil analysis efforts. Oil sampling and testing can be performed for several different purposes including:

- purchasing new oil to verify oil properties
- testing the health of in-service oil
- testing oil after reconditioning such as filtration.

The most common application is testing in-service oil. Oil monitoring serves as a maintenance tool to check not only the condition of the oil, but the condition of the machinery as well. It can be used as a mean of preventing failures or sometimes as a means of failure analysis. American Society for Testing and Materials (ASTM) D6224, *Standard Practice for In-Service Monitoring of Lubricating Oil for Auxiliary Power Plant Equipment* (ASTM 2016), can be used for some guidelines on this subject. However, note that ASTM D6224 pertains to mineral oils, and *not* to synthetics. ASTM D6224 is intended to help users, particularly power plant operators, maintain effective control over their mineral lubricating oils and lubrication monitoring program. This practice may be used to perform oil changes based on oil condition and test results rather than on the basis of service time or calendar time. It is intended to save operating and maintenance expenses. This standard is also intended to help users monitor the condition of mineral lubricating oils and to guard against excessive component wear, oil degradation, or contamination, thereby minimizing the potential of catastrophic machine problems that are more likely to occur in the absence of such an oil condition monitoring program.

It is important for USACE civil works facilities to establish a working relationship with a credible testing laboratory. Proper communication promotes accurate interpretation and leads to increased confidence and interest in maintaining an active oil analysis program. Complete and correct sample information speeds processing and increases the data analyst's ability to fully interpret the test results.

5.3 Testing frequency

Some guidelines on sampling frequency and testing requirements are provided in this chapter. Establishing an appropriate sampling frequency depends on several factors:

- Whether a predictive or proactive strategy being used
- age of the machine
- the age of the oil
- the consequences of failure
- the severity of the environment and the life expectancy of the lubricant
- whether there has been a history of oil related issues.

For civil works equipment such as locks and dams, a minimum sampling and lubricant testing frequency of once per year should be established. On certain systems, where more information about the system is available, this sampling frequency can be refined. Depending on equipment application, this testing frequency may need to be increased.

Often dam gates on USACE civil works structures are operated very infrequently. It is still recommended to at least sample oil and lubricants in gearboxes for example once a year. This data needs to be trended to determine replacement of the lubricant.

The AOAP discussed below also provides some guidelines for testing frequency. Appendix B of that program provides sampling frequencies for a variety of non-aeronautical equipment including cranes, watercraft, and diesel engines.

The U.S. Coast Guard (USCG) Technical Standard 262 document (Appendix A) provides the following sampling frequencies:

- Where specified, the oil samples shall be taken at oil change intervals.
- Sampling intervals for reduction gears, thrusters, controllable pitch propellers, and hydraulic systems that do not have defined oil change intervals shall be taken quarterly.
- Samples from reduction gears, thrusters, controllable pitch propellers, and hydraulic systems with defined oil change periods shall be taken a minimum of three times between oil changes at even increments of elapsed time. Oil samples shall be taken no less frequently than quarterly.
- Samples shall be taken before oil is changed. Samples of new oil being installed shall be taken. In addition, newly overhauled engines shall have break-in oil samples drawn and submitted after 10, 25, 50 hours, and thereafter at the regularly scheduled sampling intervals.
- If at all possible, an oil sample shall be drawn and submitted after any major engine or component casualty.

The Bureau of Reclamation has two documents related to lubrication. FIST 2-4 (USBR 2004) states that:

> Samples should be drawn from all guide bearings and governors (NOTE: Governors are hydraulic systems) annually and submitted for laboratory analysis. In addition to the annual tests, samples should be visually inspected periodically. In most cases, annual laboratory testing is sufficient, but more frequent testing may be warranted if a visual inspection of the oil

indicates the presence of water or sediment or if previous laboratory tests had indicated a sudden increase in contaminants or oxidation products.

FIST 4-1A, Maintenance Scheduling for Mechanical Equipment (USBR 2009), provides even more maintenance guidelines for a variety of equipment including cranes, compressors, and pumps.

5.4 Test requirements

The tests to be performed depend on the application. Appendix N provides an actual test report from a miter gate gearbox at Lock and Dam 4 on the Mississippi River. Tables 8 and 9 list recommended tests for equipment common in civil works. The data in Table 9 are extracted from EM 1110-2-1424(HQUSACE 2016a), and are noted for turbine oils, but are also applicable for many lubricating oils. The frequency of testing for some lubricants such as hydraulic oils may need to be increased depending on the application. Adjustments can be made based on the specific application. It is also acceptable to follow the guidance of American ASTM D6224 (ASTM 2016) for tests to be performed.

Laboratory tests for gear oils, hydraulic oils, and turbine oils should include viscosity, water content, total acid number, particle count, oxidation stability test, and elemental analysis for wear metals and additives. Based on the initial testing, other tests may be recommended by the laboratory. The tests can usually be accomplished by any laboratory equipped for lubricant testing, but the tests should preferably be performed by someone knowledgeable in the use and formulation of the lubricants being tested. Since the composition and additive content of oils is usually considered proprietary information, the manufacturer may have to be contacted to determine the extent of additive depletion. The manufacturer should also be contacted any time the tests indicate there is some question about the continued serviceability of an oil.

Table 8. Test requirements for gear oils.

Requirement*	Test
Particle Count	ISO 4406
Spectrochemical by ICP	ASTM D5185
Direct Read Ferrography	ASTM D7684
Viscosity at 40 and 100 °C-Cst (104 and 212 °F)	ASTM D445
Water by Karl Fischer	ASTM D6304
Total Acid Number	ASTM D664

Requirement*	Test
Oxidation Stability (EP oils)	ASTM D2893
Air Compressors	
Spectrochemical by ICP	ASTM D5185
Water by Karl Fischer	ASTM D6304
Viscosity at 40°C and 100°C (104 °F and 212 °F)	ASTM D445
Total Acid Number	ASTM D664
Grease	
Oxidation Stability	ASTM D942
Apparent Viscosity	ASTM D1092
Extreme Pressure Properties (4 ball method)	ASTM D2596
Timken OK Load	ASTM D2509
Spectrochemical by ICP	ASTM D5185
Hydraulic Oil	
Spectrochemical by ICP	ASTM D5185
Water by Karl Fischer	ASTM D6304
Viscosity at 40 °C and 100 °C - Cst (104 °F and 212 °F)	ASTM D445
Total Acid Number	ASTM D664
Particle Count	ISO D4406
Infrared Spectrometry	ASTM E2412
Copper Strip Corrosion	ASTM D130
Corrosion Protection	ASTM D665(A&B)
Hydro turbine oils	
Viscosity Measurement at 40°C and 100°C (104 °F and 212 °F)	ASTM D445
Total Acid Number	ASTM D664
Spectrochemical by ICP (Inductively Coupled Plasma)	ASTM D5185
Particle Count	ISO 4406
Water by Karl Fischer	ASTM D6304
Viscosity Index (Calculated)	ASTM D2270
Foaming Characteristics	ASTM D892
Water Separability of Oils @ 54 °C (129 °F)	ASTM D1401
Rust Preventative Characteristics	ASTM D665
Copper Corrosion by Copper Strip	ASTM D130
Oxidation Stability (Rotating Pressure Vessel Oxidation Test [RPVOT])	ASTM D2272
Oil compatibility testing	ASTM D7155
*Also see American Gear Manufacturers' Association (AGMA) 9005-E02 for further requirements.	

Table 9. Annual testing requirements for lubricating oils.

Turbine Oil Characteristic	Testing Method	Results Reporting Format
Viscosity	ASTM D 445	Report result as cSt @ 40°C
Water Content	ASTM D 6304	Report moisture content in parts per million (ppm)
Acid Number	ASTM D 664	Report result as (mg KOH/g)
Elemental Spectroscopy	ASTM D 5185	Report concentration in ppm of the following elements: Fe, Cr, Cu, Sn, Al, Ni, Ag, Si, Ca, Mg, P, Ba, Pb, Sb and Zn.
ISO Cleanliness	ISO 4406/99	Report µm(c) particle sizes (>4, >6, and >14)
Oxidation Stability (RPVOT)	ASTM D 2272	Report the time (minutes) required for pressure drop of 25.4 psi.

Laboratories use spectroscopy to determine the kind and quantity of contaminants in the oil, such as metal particles, fuel, coolant, or water. (Spectroscopy is the science that studies the way light interacts with matter, which can indicate what the matter is made of and how much of each component is present.) Ferrography (wear particle analysis) detects metals that cannot be identified by spectrometric analysis and also determines the kind of wear, such as spalling (fragmentation), cutting, and rubbing.

Spectrometric analysis for wear metals should be done by a qualified laboratory. Data shall be reported in parts per million (PPM) and results should be trended over time. Labs should use both wear metal levels and wear metal trend levels to make determinations regarding the existence and severity of machinery problems. Labs also make diagnostic determinations based on the types of wear metals exhibiting abnormally high wear metal concentrations and trend levels. The following wear metals levels should be measured and reported (some of these may or may not apply depending on the specific application):

- Iron
- Aluminum
- Lead
- Tin
- Copper
- Chromium
- Nickel
- Silver
- Silicon
- Titanium
- Magnesium
- Zinc
- Calcium
- Sodium
- Boron
- Potassium
- Molybdenum
- Phosphorus
- Antimony
- Barium.

5.5 Key tests and warning limits

The most important single property of a lubricant is its viscosity. It is a factor in the formation of lubricating films under both thick and thin film conditions. For any piece of equipment, the first essential for satisfactory results is to use oil of proper viscosity to meet the operating conditions. EM 1110-2-1424 further discusses the different types of viscosity measurements and the conversions between cSt centistokes (kinematic viscosity), cP (dynamic viscosity), and SSU (Saybolt Seconds, Universal [unit of viscosity]). Viscosity changes for all types of lubricants is a key test measure. It is common for viscosity to increase as the oil ages due to the addition of oxidation products. However, some oils can experience viscosity decreases. A significant change from baseline values is a red flag to look at closely as it indicates degradation. Some ways viscosity might decrease include mixing of fuel with oil, water contamination, electrostatic removal of oxides, shear thinning of VI enhancers, and cracking of lubricant. Ways viscosity can increase include the addition of more viscous make up oil, boiling off of light hydrocarbon fractions (solvents), oxidation, and polymerization. Testing and trending the viscosity of lubricating oils can provide a basis for determining when to change the oil. For industrial oils, a +5% change in viscosity is at the caution level, and a +10% change is at the critical level. For engine oils a +20% change is critical, +10% change is caution, -5% is caution and -10% is critical. For industrial oils, the viscosity should be measured at 104 °F (40 °C). For engine oils, the viscosity should be measured at 212 °F (100 °C).

5.5.1 Acid number

The total acid number (TAN) is another key parameter to test and trend for a number of different lubricants. Acidity indicates the extent of oxidation of a lubricant and its ability to neutralize acids from exterior sources such as combustion gases. A severely degraded lubricant indicated by a high TAN may be very corrosive. The acidity of lubricants is measured by the amount of potassium hydroxide required for neutralization (mgKOH/g). The resultant number is called the TAN. For turbine oils and hydraulic fluid, an acid number greater than 0.2 mg KOH /g is typically at warning level, indicating that oil is degraded. An acid number of 0.4 mg KOH/g is considered at the critical limit. Acid number is an indicator of oil health. It is useful in monitoring acid buildup in oils due to depletion of antioxidants. Oil oxidation causes acidic byproducts to form. High acid levels can indicate excessive oil oxidation, or depletion of the oil additives, and can lead to corrosion of the internal components. By monitoring the acid level, the oil can be changed before any damage occurs. For gear box oil, these values will be higher. An acid number of 1.0 mg KOH/g is typically a warning level indicating that oil is degraded, and an acid number of 2.0 mg KOH/g is considered the critical limit.

5.5.2 International Standards Organization (ISO) particle count

It is imperative to track the cleanliness of lubricants using the particle count per International Standards Organization (ISO) 4406. Achieving better cleanliness of any lubricant will increase equipment life. Warning levels can vary somewhat depending on criticality of the system and expectations of equipment life and reliability.

ISO 4406 (1999) is an internationally recognized standard that expresses the level of particulate contamination of a lubricating fluid. This is the preferred standard for particle counting and should be used in testing lubricants. ISO 4406 is a cleanliness rating system that is based on a number of contamination particles in a 1-milliliter (ml) fluid sample. Once the number and size of the particles are determined, the points are plotted on a standardized chart of ISO range numbers to convert the particle counts into an ISO 4406 rating. The ISO 4406 rating provides three range numbers that are separated by a slash, such as 16/14/12. All three values for applicable range numbers can be determined through the use of the ISO 4406 standardized chart based on the actual number of particles counted within the 1-ml sample for each size category.

The first number in the ISO 4406 standard represents the number of particles present measuring greater than 4µm, the second represents particles greater than 6µm and the third represents those greater than 14µm. As the range number increases by one value, the number of particles in a sample of oil will double. On the range code, each number is double the range below. For example, an oil with a code of 19/17/14 should contain twice as many particles in each size category as the code of 18/16/13. For critical components, particle counting and testing should be repeated to confirm the ISO rating.

5.5.3 Water content

Water content should be tracked and trended for all lubricants. This is a more critical consideration for hydraulic systems. Generally speaking, water content below 100 to 200 ppm is considered good for hydraulic systems where for gearbox oils below 500 ppm is considered good. The specific manufacturer should provide their target saturation levels. Water contamination in the oil affects viscosity, increases oxidation, forms acids, and causes corrosion of components. The three states of water include dissolved, emulsified, and free water. The Karl Fischer test calculates percentages of dissolved, emulsified, and free water in the oil. The point at which an oil contains the maximum amount of dissolved water is termed the saturation point. The saturation point depends on the oil's temperature, age, and additive composition. The higher the temperature, the higher the saturation point and hence more water held in solution, in the dissolved phase. Temperature changes affect the saturation level of the oil. As an example, an oil with 200 ppm water may be suitable for use at an operating temperature of 180 °F (82 °C), but if the equipment cools down to 60 °F (16 °C), saturated water can be released as potentially damaging free water. Testing the oil in-service and correcting for temperature allows operators to discover and correct water problems before they reach the stage where water drops out.

5.6 Hydraulic fluid

Hydraulic systems are used extensively in USACE civil works. Hydraulic fluid typically requires the most cleanliness of all the lubricants used at USACE civil works site (see Table 10). It is imperative that hydraulic systems be clean and dry. Many hydraulic system failures are a direct result of fluid contamination. Contamination of hydraulic fluid is by far the most common cause of hydraulic pump, valve, and actuator failure. Many sources and literature will peg the number at 70-90% of those failures being related to poor fluid condition.

The hydraulic fluid is both a lubricant and a power transmitting medium. The presence of solid contaminant particles in the liquid interferes with the ability of the hydraulic fluid to lubricate and causes wear to the components. The extent of contamination in the fluid has a direct bearing on the performance and reliability of the system. Contamination interferes with the four functions of hydraulic fluids:

- to act as an energy transmission medium

- to lubricate internal moving parts of components
- to act as a heat transfer medium
- to seal clearances between moving parts.

If any one of these functions is impaired, the hydraulic system will not perform as designed. The data in Table 10 are excerpted from Eaton Corp. (2002) on the cleanliness requirements for various hydraulic system components. It is important to work with the manufacturer to establish the required cleanliness for their particular components.

Water in hydraulic oil can compromise oil viscosity, can cause acid levels to increase, and can initiate corrosion in system components (such as cylinders, valves, filter housings, pumps). In reservoirs, it can spoil anti-foam additives, compress into vapor, and cause damage to both oil, internal components, and system performance. Since the effects of free (also emulsified) water is more harmful than those of dissolved water, water levels should remain well below the saturation point. However, even water in solution can cause damage. Therefore every reasonable effort should be made to keep saturation levels as low as possible.

Table 10. ISO 4406 Cleanliness recommendations from Vickers (excerpt).

Pressure <3000 PSI	**>3000 PSI**
Pumps --- ISO RATINGS ---	
Fixed Gear Pump **19/17/15**	**18/16/13**
Fixed Vane Pump **19/17/14**	**18/16/13**
Fixed Piston Pump **18/16/14**	**17/15/13**
Variable Vane Pump **18/16/14**	**17/15/13**
Variable Piston Pump **17/15/13**	**16/14/12**
Valves	
Directional (solenoid) **20/18/15**	**19/17/14**
Flow Controls (standard) **19/17/14**	**19/17/14**
Check Valves **20/18/15**	**20/18/15**
Cartridge Valves **20/18/15**	**19/17/14**
Load-sensing Directional Valves **18/16/14**	**17/15/13**
Proportional Cartridge Valves **18/16/13**	**17/15/12**
Servo Valves **16/14/11**	**15/13/10**
Actuators	
Cylinders **20/18/15**	**20/18/15**
Vane Motors **19/17/14**	**18/16/13**
Axial Piston Motors **18/16/13**	**17/15/12**
Gear Motors **20/18/15**	**19/17/14**
Radial Piston Motors **19/17/15**	**18/16/13**

A water level of 500 ppm should be considered a warning for hydraulic systems, in particular for those that use mineral-based hydraulic oils. Mineral oil usually has a water content of 50-300ppm, which it can support without adverse consequences. Once the water content exceeds approximately 500 ppm, the oil starts to appear hazy. This value can change, however, with the type of oil and the temperature.

Above saturation levels, there is a danger of free water accumulating in the system in areas of low flow. This can lead to corrosion and accelerated wear. Similarly, fire resistant fluids have a natural water content. Some PAG hydraulic fluids can tolerate a very high water content (2000 ppm) and still function. It is imperative to have the hydraulic oil supplier provide the actual saturation level of their product, especially for synthetic fluids.

5.7 Gear oils

Gear oils are more tolerant of dirt and water than are hydraulic system oils. That being said, it is still important to keep gear oils clean and dry to the maximum extent possible. The requirements placed on a gear oil depend on the type of gearing (for example, spur, helical, bevel, hypoid, or worm), gear tooth sliding speed, and gear loading. Oil requirements also depend on whether the gear box is splash lubricated or if there is pump. Due to the nature of gear lubrication, lubricants are often required to have high levels of EP additives. Additionally, antifoaming, antioxidant, and anticorrosion additives are common. Water content in gear oils should stay below 500 ppm regardless of whether it is a mineral oil or synthetic gear oil. As in hydraulic fluids, it is important to have the gear oil manufacturer provide their water saturation level. Some suggested warning limits for mineral-based gear oil are:

- Water: Warning: 1000 ppm Critical: 2000 ppm
- Particle Count: Warning: 23/21/18 Critical: 24/22/19
- TAN: Warning 1.0 Critical 2.0.

5.8 Oil monitoring program

The oil monitoring program should evaluate, track, and trend oil test data. The savings achieved by a developing and following a well regimented oil analysis program at USACE projects should be related to benefits of sustainability emphasized and discussed in Section 5.1. The program should establish baseline data, especially on the following tests:

- viscosity
- particle count
- sufficiency of additives
- water content
- acidity
- oxidation stability
- trace metals content.

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

5.9 Army oil analysis program

The AOAP, administered by the Army Materiel Command Logistics Support Activity at Redstone Arsenal, Huntsville, Alabama, is part of a Department of Defense effort to detect imminent component failures and determine the condition of used oils by periodically collecting and evaluating samples. The AOAP procedures and sampling intervals can be adaptable to USACE civil works for a variety of machinery. It appears, however, that USACE civil works sites cannot use the AOAP testing laboratories. A follow-up action item for this project will be to determine this conclusively.

Early detection of problems allows maintenance to be performed before more severe damage to the equipment occurs. Since its inception in 1975, the AOAP has prevented consumption of millions of barrels of oil; eliminated disposal of used oil and filters; and saved resources that would have been required to pump, refine, transport, and package new oil. Savings from the program have increased as more tactical wheeled vehicles and construction and support equipment have been enrolled in the program.

Currently, the Army has enrolled 1,751 individual ground system components in the AOAP. Oil and filters in these components are changed only when recommended by an AOAP laboratory. Oil samples are evaluated in one of the AOAP's 5 laboratories located outside of the continental United States (OCONUS) or in one of its 19 Continental United States (CONUS) labs. Oil analysis diagnoses the physical condition of the lubricant, such as its viscosity, fuel dilution, or water content, and the condition of the engine, transmission, and hydraulic systems from which the sample is taken. The analysis can determine problems such as contamination, faulty air-induction systems, leaking cooling systems, loose fuel-return lines, and abnormal wear rates of moving metal parts.

6 Performance Characteristics of Lubricants and Selection Criteria

6.1 General discussion

This chapter provides some guidelines and considerations for lubricant selection in various mechanical systems including greases, hydraulic fluids, and gearbox oils. This provides a means to standardize the selection process of lubricants for USACE civil works applications.

Maintenance staffing at navigation facilities varies greatly. O&M work is constantly being delayed or cut back due to fiscal constraints. Changing oil in a gearbox or hydraulic system and replacing grease on open gears are time consuming and costly undertakings. It is important that the lubricants on both hydraulic drives and mechanical drives not degrade quickly, and that they have a long service life (durability). EM 1110-2-1424 (HQUSACE 2016a) discusses lubrication issues and lubrication basics in depth, and is a good primary resource for lubrication design.

Open gearing and gearboxes and hydraulic cylinders on navigation structures are used more intermittently than are similar equipment in industrial installations. Machinery on dam structures may be only operated once or twice per month; in northern climates, they may be completely shut down over the winter. Corrosion resistance, lubricant durability, and suitable lubricant properties over a wide range of temperatures are critical. It is important that the lubricants not degrade quickly, and that they have a long service life (durability).

Although hydraulic drive systems and cylinders are becoming more common in USACE and being specified for many new projects, existing mechanical drive systems are probably more common. Open gearing on mechanical drive systems is probably the most time consuming to lubricate.

6.2 Grease selection

6.2.1 General

Grease is probably the most commonly used lubricant in USACE civil works. This section will provide some basic selection criteria. Many grease applications have the potential to interface with waterways. As such, over-greasing should be minimized and EA grease should be considered where practical. The frequency of greasing equipment and machinery is a function of the frequency of use of the equipment, the type of equipment, the environment of the equipment, and manufacturer's operating and maintenance instructions. It is imperative to understand these requirements to prevent over greasing. Grease is used for many applications including:

- open gears
- couplings
- anti-friction bearings (roller bearings)
- journal bearings
- tainter (radial) gate trunnion bearings
- tainter valve trunnion bearings
- pump bearings
- motor bearings
- wire ropes.

Step 1. Determine the application.

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

Note that base oils will be mineral-based (petroleum), biobased, or synthetic. Environmentally acceptable greases will use either biobased or synthetic base oil. Lithium and calcium soaps can be used for a majority of applications in USACE. Higher temperature applications can use complex soaps.

Determine which of the following applications (or combinations of applications) the grease will be used for:

- general applications
- bearings
- motors
- wire ropes
- couplings
- open gears
- low temperature grease
- high temperature grease
- submerged application
- applications for which environmentally acceptable grease is required and/or appropriate.

Step 2. Determine test requirements.

The manufacturer should provide a complete performance list of the grease including:

- National Lubricating Grease Institute (NLGI) Consistency
- Prevention of Rust – ASTM D1743
- Water Washout – ASTM D1264
- Pumpability – ASTM D217 and ASTM D1092
- Base Oil Viscosity – ASTM D445
- Anti-Wear and Scuffing – ASTM 2596 and G99
- Shelf life and Storage – ASTM D1742
- Oxidation Stability – ASTM D942 and D2893
- Dropping Point – ASTM D2665
- Timken OK Load – ASTM D2509
- 4-ball EP Test – ASTM D2596
- 4-ball wear Test – ASTM D2266
- Standard Test Method for Detection of Copper Corrosion from Lubricating Grease – ASTM D4048
- Pumpability in Hand Operated Grease Gun – ASTM D1264.

For USACE civil works applications, the following are some key parameters for grease:

- anti-wear, high lubricity
- high/extreme pressure grease suitable for low speeds
- low washout/high washout resistance
- corrosion inhibiting
- appropriate viscosity for pumping
- low oxidation and high oxidation stability
- water washout for any in-water use.

6.2.2 Grease selection for wide applications

Step 1. Determine the performance properties of the grease.

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

Step 2. Determine the required consistency of the grease.

The consistency of grease is controlled by the thickener concentration, thickener type and the viscosity of the base oil. The NLGI has established a scale to indicate grease consistency, which ranges from grades 000 (semifluid – like ketchup) to 6 (block grease – like cheddar cheese spread). The most common NLGI grade is 2 (like peanut butter) and is recommended for most applications in USACE. Lower temperature applications can utilize NLGI grade 1.

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

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

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

- For in-water lubrication several factors are critical. These include oxidation stability (aging), evaporative loss (volatility), hydrolytic stability (reactions with water), water wash off, and corrosion protection properties. In-water structures in locks and dams and hydro turbines may be subjected to strong water currents and possible cavitation.

Step 4. Determine the base oil selection.

Three available options include:

- mineral oil
- synthetic oils (which may or may not also be EALs)
- biobased oils.

6.2.3 Mineral oils

Most common grease lubricants are composed of petroleum fractions called mineral oils. These are medium to heavy weight refined fractions with viscosities ranging from 103 to over 140. NLGI 2, a lithium-based grease, will work for a majority of USACE applications and is probably the most common. In extremely cold applications, NLGI 1 could be considered. Lithium complex grease has a higher dropping point and should be selected when higher operating temperatures are required. Additives can be provided depending on specific requirements. This type of grease can work on open gearing, couplings, and bearings.

- excellent oxidation stability
- good mechanical stability
- excellent water resistance and rust inhibiting properties.

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

NLGI 3 has:

- excellent rust inhibiting properties
- high oxidation stability within its recommended temperature range.

NLGI 3 is appropriate for use on:

- bearings >100 mm (3.9 in.) shaft size
- outer bearing ring rotation
- vertical shaft applications
- continuous high ambient temperatures >95 °F (35 °C)
- propeller shafts
- large electric motors.

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

6.2.4 Synthetic base oil grease

Synthetic greases should be considered for high temperature and low temperature applications. There are generally four options available for synthetic grease. This includes PAOs, PAGs, esters, and silicones. For in-water applications, these greases also work better since they have better hydrolytic stability. Synthetic grease generally perform better than mineral oil based grease because it has:

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

6.2.5 EAL grease

There are several options available for environmentally acceptable greases. The first consideration is the base oil type. There are three base oil types to consider. SEs and biobased greases are the predominant forms available. It is important to work with the manufacturer to ensure they meet the requirements for an EAL (see Chapter 2). A guide specification for EAL grease is provided in Appendix I. EAL greases include:

- synthetic ester base oil with a lithium/calcium soap thickener
- PAO base oil with a lithium or lithium complex soap thickener
- PAG base oil with a lithium or lithium complex soap thickener
- biobased base oil (canola oil, rapeseed oil, etc.)

6.3 Grease selection for bearings

Step 1. Determine proper base oil viscosity.

Base oil viscosity is important because the use of an oil with too high a viscosity will overheat the bearing. The use of an oil with too low of a viscosity will result in improper lubrication of the bearing and possible bearing damage. There are several common methods for determining minimum and optimum viscosity requirements for rolling element bearings, most of which use speed factors, commonly denoted as DN. Ultimately, the bearing manufacturer can also help determine proper base oil viscosity.

Step 2. Consider additives and base oil type.

Once the viscosity has been determined, additives need to be evaluated and the base oil type determined. Most performance-enhancing additives found in lubricating oils are also used in grease formulation and should be chosen according to the demands of the application. Table 11 lists some common additive requirements by application (Scott, Fitch, and Leugner 2011). Most grease applications in USACE can be formulated using mineral oil base stocks, which are appropriate for most applications. However, some applications might benefit from the use of a synthetic base oil, e.g., applications that involve high or low operating temperatures, or a wide ambient temperature range; or any application where extended re-lubrication intervals are desired.

For bearings, speed factor and operating temperature can be used to determine the best consistency or NLGI grade for a given application. The data in Table 12 provide a general guide to selecting NLGI grade based on speed factor and operating temperature (Scott, Fitch, and Leugner 2011).

Table 11. Bearing additives.

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

Additive*	Journal Bearings	Ball Bearings	Thrust Bearings	Roller Bearings	Needle Bearings
• Required, - Depends on application *Source: Scott, Fitch, and Leugner (2011)					

Table 12. Grease NLGI grade for bearings.

Operating Temperature*	DN (Speed Factor)	NLGI No.**
-30 to 100 °F (-34 to 38 °C)	0 - 75,000 75,00 - 150,000 150,000 - 300,000	1 2 2
0 °F to 150 °F (-18 to 66 °C)	0 - 75,000 75,00 - 150,000 150,000 - 300,000	2 2 3
100 to 275 °F (38 to 135 °C)	0 - 75,000 75,00 - 150,000 150,000 - 300,000	2 3 3
*Source: Scott, Fitch, and Leugner (2011) **Depends on other factors as well, including bearing type, thickener type, base oil viscosity and base oil type		

6.3.1 Tainter (radial) gate trunnion bearings

USACE civil works has hundreds of tainter gates along with their associated trunnion bearings. The vast majority of these bearings are grease lubricated. The requirements for sector gate and miter gate pintle grease will have similar criteria. Table 13 lists some selection criteria. Other general criteria include:

- Measurement of Extreme-Pressure Properties of Lubricating Grease (Four-Ball Method). It is recommended that the criteria be set as follows:
  - Minimum Wear Load Index of 40 kgf
  - Minimum Weld Point of 140 kgf
  - Trunnion application is a typical boundary condition, and it is appropriate to set these parameters to make sure excessive wear and/or welding does not occur at the exhibited loads and speeds.
- Good adhesion to bearing surfaces. No test.
- Maximum separation allowed should be limited to 0.5% or 1.0%. This characteristic is not only an important consideration for storage of grease, but also for grease in automatic greasing system lube lines, due to possible long pauses between actual greasing. It is important that oil not separate from thickeners and additives while static.

Table 13. Tainter gate trunnion bearing lubrication parameters.

Test	Purpose	Requirement
ASTM D-1743	Rust Prevention	Pass
ASTM D-1264	Water washout	Max. 3% and for submerged applications maximum less than 1%
ASTM D-217	Worked Penetration	NLGI 1 or NLGI 2 depending on climate conditions Ease to pump and distribute
ASTM D-445	Viscosity	High viscosity mineral or synthetic oil base - Minimum 300 cSt at 40°C depending on load, location, in-water or out of water, and environmental conditions
ASTM D-2596	Antiwear/scuffing	Wear load index 40 kgf Weld point 140 kgf
ASTM D-4048	Prevention of Bronze Corrosion	1A or 1B
ASTM D4049	Resistance of Lubricating Grease to Water Spray	Less than 2
ASTM D-1742	Non-separation in storage	0.5 to 1%
ASTM D2782	Timken OK Load (EP Lubricants)	45 minimum
ASTM D2509	Timken OK Load	75 minimum

6.4 Grease selection for open gearing

Open gears are used extensively on USACE navigation structures and within USACE civil works (Figure 9). Lubricants are integral to gears and gearboxes and are subject to some unique challenges on navigation structures. This includes extreme temperatures, infrequency of use, high humidity, submersion during floods, and high operating loads and pressures. Open gears are typically custom made and any failure could result in a lengthy shutdown of the lock and/or dam.

Mineral-based, multi-purpose, lithium soap, NLGI 2 can be used for a majority of these applications. Grease needs to be manufactured for open gear lubrication to resist fling-off. The need for EP additives should be evaluated such as for sector gears, which transfer very high torque (Figure 10) on electromechanical drive systems. Environmentally acceptable grease can also be evaluated.

Figure 9. Open spur gear (USACE).

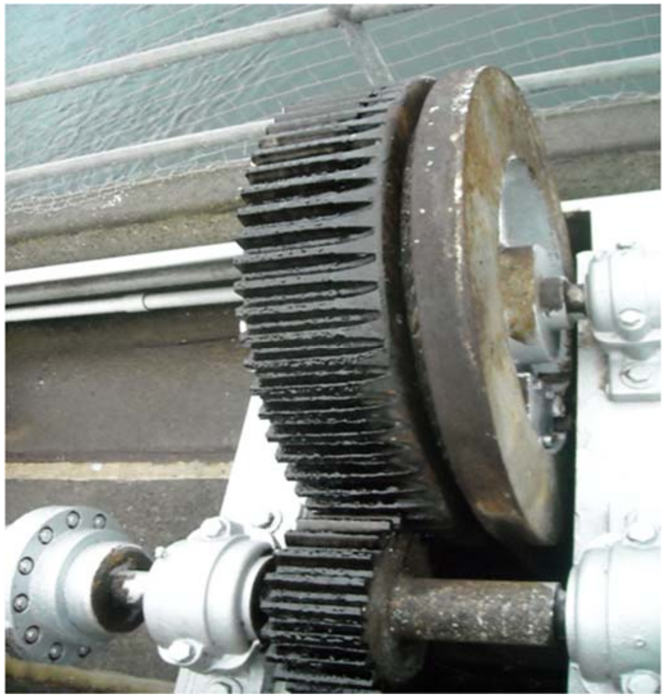


Figure 10. Sector gear (USACE).

Step 1. Consider open gear lubricant requirements and industry standards.

Due to the operating environment and load requirements, open gearing applications are considered some of the most difficult applications a lubricant can encounter. Many USACE applications are either in water or become submerged during floods. Open gear lubricants must possess the following characteristics and properties:

- tackiness (adhesive/cohesive properties) – excellent adhesion to the gears
- resistance to water washout and spray-off
- load-carrying capability to protect against friction and wear
- protection of the gears against wear and corrosion
- cushioning ability (vibration reduction)
- sprayability and/or ease of dispensability
- alleviation of housekeeping and maintenance problem
- resistance to fling-off
- no buildup in the roots of the gear teeth
- properly selected dropping point and low temperature pumpability.

Step 2. Determine key test requirements.

Table 14 lists some key test requirements with suggested ratings. Note that these are suggested ratings and guidelines only. It is **imperative** to work with the gear manufacturer and the lubricant supplier to provide the correct lubricant for the specific application.

Some general criteria are:

- Water washout @ 79°C, wt% ASTM D1264 <2 (for applications frequently submerged suggest Rating <1)
- Four Ball EP Weld Point, kgf, ASTM D2596: 300 minimum
- Four Ball EP Load Wear Index, kgf, ASTM D2596: 100
- Oxidation Stability, ASTM D2893
- Prevention of Rust – ASTM D1743: Pass
- Pour Point, degrees Fahrenheit, ASTM D97
- Pumpability – ASTM D217 and ASTM D1092
- Anti-Wear and Scuffing – ASTM 2596 and G99
- Shelf life and Storage – ASTM D1742 – limit to 1%
- Oxidation Stability – ASTM D942 and D2893.

Table 14. Required target performance values for open gear grease.

Test	Purpose	Requirement
ASTM D-1743	Rust Prevention	Pass
ASTM D-1264	Water washout	Max. 3.0% and for submerged applications maximum less than 1%
ASTM D-217	Worked Penetration	NLGI 1 or NLGI 2 depending on climate conditions
ASTM D-445	Viscosity	Minimum 300 cSt at 40C
ASTM D-2596	Antiwear/scuffing	Wear load index 100 kgf (minimum) Weld point 400 kgf (minimum)

Test	Purpose	Requirement
ASTM D4049	Resistance of Lubricating Grease to Water Spray	Less than 2
ASTM D-1742	Non-separation in storage	0.5 to 1%
ASTM D2782	Timken OK Load (EP Lubricants)	45 minimum
ASTM D2509	Timken OK Load	50 minimum

Step 3. Select the types of open gear lubricants.

Open gear lubricants generally fall into the following categories:

- asphaltic type (also referred to as residual compounds)
- semifluid greases (also known as paste type)
- semifluid grease cutbacks
- gel/polymer-thickened types
- high-viscosity synthetics oils.

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

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

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

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

6.5 Grease for wire rope applications

USACE has thousands of applications of wire rope on locks, dams, and hydropower sites. EM 1110-2-3200 (HQUSACE 2016b) discusses extensively wire rope requirements. All wire rope should be lubricated to the maximum extent possible (especially the portion of the rope drums), including stainless steel. Stainless steel wire rope is lubricated to prevent abrasion as the rope is wound on the drum. Wire rope lubricants have principal functions as follows:

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

Step 1. Determine the type of wire rope lubricant.

There are two types of wire rope lubricants, penetrating and coating. Penetrating lubricants contain a petroleum solvent that carries the lubricant into the core of the wire rope then evaporates, leaving behind a heavy lubricating film to protect and lubricate each strand. Penetrating lubricants need to be provided for galvanized wire rope and carbon steel wire rope. Coating lubricants penetrate slightly, sealing the outside of the cable from moisture and reducing wear and fretting corrosion from contact with external bodies. Coating lubricants are required for stainless steel wire rope. Because most carbon steel and galvanized steel wire ropes fail from the inside, it is important to make sure that the center core receives sufficient lubricant. A combination approach in which a penetrating lubricant is used to saturate the core, followed with a coating to seal and protect the outer surface, is recommended. It is also recommended to use pressurized lubricators when possible. This is discussed further in EM 1110-2-1424.

Mineral-based lubricants, with the proper additives, provide excellent corrosion and water resistance and are recommended for most applications. Asphaltic compounds are the coating type and generally dry to a very dark hardened surface, which makes inspection difficult. They adhere well for extended long-term storage, but will crack and become brittle in cold climates.

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

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

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

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

Step 2. Determine lubricant performance measures.

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

6.6 Hydraulic oil selection

The required application should be the most critical attribute when selecting a hydraulic fluid to ensure the system's ability to function properly and attain long life. Many hydraulic systems in USACE applications are near water and are subject to a variety of environmental conditions. This includes possible submersion, heat, cold, rain, and snow. When selecting a hydraulic fluid, it is very critical to determine the system's needs in terms of viscosity, additives, operation, etc. There are three primary types of hydraulic oils plus a 4th type for water-based hydraulic fluid:

- fire-resistant applications – hydraulic oils
- hydraulic systems for mobile and industrial systems (typically either mineral-based or synthetic hydraulic oils)
- EA hydraulic oil
- water-based hydraulic oil.

Fire resistant applications are not common within USACE especially for civil works applications and will not be discussed further. Water-based hydraulic oil is further discussed below. Most applications in USACE civil works fall under the industrial and mobile system category such as for construction equipment like excavators. Environmentally acceptable hydraulic oils are becoming more common and their use is encouraged. In addition, hydraulic oils can be synthetic-based, mineral oil based, or biobased. There are two primary considerations for hydraulic systems: the viscosity grade and the hydraulic oil type. These specifications are typically determined by the type of hydraulic pump employed in the system, operating temperature and the system's operating pressure.

6.6.1 Pump requirements

There are three major design types of pumps used in hydraulic systems, vane, piston, and gear (internal and external):

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

Internal gear pumps offer a wide range of viscosity choices, the highest of which can be up to 2,200 cSt. This pump type offers good efficiency and quiet operation, and can produce pressures from 3,000 to 3,500 psi. External gear pumps are less efficient than their counterparts, but have some advantages, including ease of maintenance, steady flow, and lower purchase and repair costs. As with the internal gear pump, these pumps can produce pressures ranging from 3,000 to 3,500 psi, but their viscosity range is limited to 300 cSt.

6.6.2 Determine viscosity requirements

Viscosity should be determined by the pump type. ISO Grade 32 and 46 and 68 are the most common. Not having the correct viscosity for the application will dramatically reduce the average life of the pump and system, thereby directly reducing its reliability and production. When selecting the appropriate viscosity grade, look for the optimum viscosity required by the pump. This can be determined by collecting data from the pump original equipment manufacturer, actual operating temperature of the pump, and the lubricant properties referenced to the ISO grading system at 40 and 100 °C (104 and 212 °F).

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

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

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

6.6.3 Mineral oil hydraulic fluid

Mineral oil hydraulic fluids are the most common within USACE and will work for a majority of applications. They are refined with the addition of additives, which range from anti-wear (AW), rust and oxidation inhibitors (RO), anti-foaming, and viscosity index (VI) improvers. These fluids offer a lower cost alternative to synthetics and can be very comparable in performance when certain additive packages are included.

Mineral oil based hydraulic fluid comes in many different forms and varieties, which differ largely in how they are processed or refined. Low grades of hydraulic mineral oil come from early stages of the refinement process and generally cost less than higher grades that have been more thoroughly refined. Different types of hydraulic oil are also distinguished by their compressibility. In high pressure systems, specialty oils may be required to successfully transfer power or energy.

Generally, the easiest way to choose between different types of hydraulic oil is to consult the manufacturer's recommendations for the equipment or machinery in question. Most owner's manuals or instruction books specify the best type of hydraulic oil to maximize performance. Many oil manufacturers create their own unique blends of mineral oil, then sell these trademarked formulas under patented brand names.

6.6.4 Synthetic hydraulic fluid

Synthetic hydraulic fluids have better hydrolytic stability when exposed to water. They can operate at higher and lower temperatures than mineral oil based hydraulic fluids. Many synthetic-based hydraulic fluids can also be considered as EALs. The primary categories of synthetic base hydraulic fluid include:

- PAGs - polyalkylene glycols
- PAOs - polyalphaolefins
- esters.

PAG hydraulic fluids have been available for decades and are widely used in construction machinery and industrial applications. The EAL hydraulic fluid is HEPG — hydraulic environmental poly glycol (water soluble polyalkylene glycol). PAGs have excellent lubricity characteristics and a high viscosity index. PAGs offer good temperature stability. PAG base fluids are available in both water soluble and insoluble forms, and in a wide range of viscosity grades. PAGs can be used in both high and low temperature environments. The viscosity of PAG hydraulic fluid at low temperature needs to be evaluated. PAGs can increase the hydraulic pump horsepower requirements in extremely cold weather (below 0 °F [-18 °C]).

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

PAG hydraulic oils are able to tolerate more water in the system than all other lubricants without affecting oil performance. Also, all other oils will deposit increased varnish or sludge when water is present, but a PAG will not deposit any varnish or sludge.

PAO hydraulic oils typically not been used for environmentally acceptable applications. However, that is changing. Normally, PAO base oils are not biodegradable. These synthetic base oils are made through a process called synthesizing. The PAO hydraulic fluids that can be considered EALs are called HEPR fluids (hydraulic environmental polyalphaolefin and related). These are water-insoluble polyalphaolefins (PAO) and related hydrocarbon-based fluids. These synthetic hydrocarbons are made by polymerizing alpha olefins to produce PAO. Only low viscosity PAOs are considered environmentally friendly. PAO lubricants are typically initially produced with ISO light viscosity grades and then chemically modified (viscosity modifiers) to produce higher ISO viscosity grades. When considering PAOs as an environmentally acceptable lubricant, it is imperative to work with the manufacturer and supplier. PAO hydraulic fluids offer excellent oxidation stability and good corrosion protection. They also have good lubricity and aging characteristics, and a long service life. They offer good viscosity performance over a wide temperature range with very low pour points to -40 °F (-40 °C).

Synthetic ester hydraulic fluids are used extensively on European navigation structures and have been in use for decades. Synthetic esters with suitable additives can also be nontoxic and are often used as EALs. Synthetic esters used for EALs have an ISO classification of HEES (Hydraulic Environmental Ester oil Synthetic) (see Section 6.6.5). They have excellent lubrication properties including a high viscosity index and low friction characteristics. Their liquidity at low and high temperatures is excellent, as is their aging stability. Although they mix well with mineral oils, this characteristic negatively influences their biodegradability. SE fluids offer good corrosion protection and lubricity and usually can be used under the same operating conditions as mineral oils. They are applicable for extreme temperature-range operations. Synthetic esters do have a very high first cost (the highest of all the synthetic products) and are incompatible with some paints, finishes, and some seal materials. However, it may be possible to extend oil-change intervals and partially offset the higher cost.

6.6.5 Environmentally acceptable hydraulic fluid

Depending on whether it is a new installation or a retrofit, some considerations on using EA hydraulic fluid include:

- viscosity over operating temperature range
- equipment compatibility (Steel pumps and cylinders cannot use water-based fluids)
- fluid compatibility
- seal compatibility
- field serviceability
- fluid maintenance
- down time for switch over of fluids
- fluid cost difference
- environmental risks.

For further information, refer to “Appendix H: ERDC DOTS 16-1 - Understanding, Classifying, and Selecting Environmentally Acceptable Hydraulic Fluids – August 2016” (Keyser, Samuel, and Welp 2016). ISO 15380 identifies four categories of biodegradable hydraulic oil: (1) HETG (hydraulic environmental tri-glyceride[s]), which are biobased or vegetable oils such as rapeseed; (2) HEES, synthetic ester; (3) HEPG, polyglycol or PAG; and (4) HEPR, hydrocarbon and ester mix (typically PAOs). ASTM D6046, Standard Classification of Hydraulic Fluids for Environmental Impact, can also be referenced for EA hydraulic fluid considerations.

EALs are classified by the International Standards Organization (ISO) Standard 6743-4:1999 (ISO 1999). Specifications for four of the groups classified by ISO 6743-4:1999 are contained in ISO 15380:2016 (ISO 2016). ISO 15380:2016 specifies the requirements for environmentally acceptable hydraulic fluids and is intended for hydraulic systems, particularly hydraulic fluid power systems. These four categories of EA hydraulic fluids include:

- Synthetic Esters (SE) – ISO Classification HEES*
- Polyglycols (particularly Polyalkylene Glycols [PAG]) – ISO Classification HEPG
- Triglycerides (vegetable oils and biobased oils) - ISO Classification HETG

* The ISO fluid class prefix “HE” denotes “hydraulic oil environmental.”

- Polyalphaolefins (PAO) and related hydrocarbon products – ISO Classification HEPR.

Water-based hydraulic fluids are also a consideration, although not widely used. Water is currently being used in some hydraulic systems for navigation in Germany. Water hydraulic systems are also being considered and experimented with on dredges within USACE (Todd and Bossert 2013). Pure water has poor lubricity and cannot function as a lubricant in the traditional sense, but water has been used as hydraulic fluid in specialty applications where leakage contamination and fire hazard are major concerns. New designs and use of highly wear-resistant materials have opened up possibilities for new water hydraulic applications. The rate and extent to which water hydraulics are adopted depends on the motivation for further technical development and EAL additive development by lubricant producers. Some advantages of water-based hydraulic systems include:

- Water costs a fraction of mineral oils and other EA lubricants.
- Water disposal has little or no impact on the environment.
- Water is nonflammable and can be used where the combination of high temperatures and oils could create fire hazards.
- Water has better thermal conductivity than oil and can transfer heat better allowing smaller heat exchanger to be used.

Water does have several performance drawbacks, however. Conventional hydraulic oil system components will not work with water. The following list describes performance drawbacks of water and solutions for overcoming them:

- Water has low viscosity, so leakage is a concern. Components with tighter clearances are being manufactured to compensate for this.
- Water has low viscosity and low film strength, which means lower lubricity and higher wear. Also, water corrodes metal parts. Stainless steel, high-strength plastic, and ceramic bearings and component parts designed for high wear resistance are being developed.
- Water has higher vapor pressure than mineral oil, which makes it more prone to cause cavitation. Pumps are being manufactured with smoother and larger flow areas, and throttling valves are being redesigned with innovative flow geometries to mitigate the cavitation potential.
- Water freezes. Nontoxic antifreezes have been developed to lower water's freezing point and pour point.

USACE Pittsburgh District conducted a study of various hydraulic fluids for the New Cumberland Lock and Dam on the Ohio River (Pittsburgh District 2017) including a water-based system. When New Cumberland was originally constructed in 1960, a centralized system was a cost effective option that was built into the lock. A new hydraulic system is now being retrofit into the existing lock. There are also numerous leaks in the crossover piping arrangement at New Cumberland Lock. These leaks prompted the district to reevaluate the design of the centralized hydraulic system, and to evaluate a 4-corner hydraulic system. This also led to an effort to implement an environmentally safe design as part of the replacement system for New Cumberland Lock. The report notes the minimization of risk can be accomplished through three primary measures:

- reducing system fluid volume
- minimizing potential leak points
- selecting hydraulic fluid.

An excerpt from the report states that:

> The existing centralized hydraulic system at New Cumberland contains around 5,000 gallons of hydraulic fluid for both the main and auxiliary chamber combined (calculation in the Appendix). Each corner of the 4-corner system would contain approximately 302 gallons. This would equate to 1,208 gallons for the main chamber and totals around 2,422 gallons for both lock chambers combined, cutting the volume by over half. The dedicated system has a comparable reduction of the overall system volume. Between these two options, the 4-corner system provides fewer serviceable components, and lower anticipated cost. For the purpose of this report, the hydraulic fluid selection will be evaluated based on a 4-corner system.

The report addressed three types of hydraulic fluid. This includes conventional petroleum-based oils, EALs, and water with special additives to enhance the fluid properties. A matrix (Table 15) was developed to evaluate the system that best satisfies desired criteria for New Cumberland. Cost was separated from the total ranking and included as a cost of magnitude for reference.

The ranking factors for design importance and performance level were established as follows:

- Poor – 4

- Fair – 3
- Good – 2
- Best – 1.

Table 15. New Cumberland hydraulic fluid evaluation matrix.

NEW CUMBERLAND HYDRAULIC SYSTEM FLUID EVALUATION MATRIX						
	Conventional Oil		Environmentally Acceptable Oil		Water-based	
EVALUATION FACTORS	Comment	Ranking	Comment	Ranking	Comment	Ranking
Cylinder compatibility	Yes. Current oil used.	1	Seal compatibilty depends on type	2	No, refurbishment required	4
Field serviceability	Yes. Current oil used.	1	Yes but seals may be special	2	Valves have to be factory serviced	4
Component availablity	Industry standard	1	Industry standard	2	Niche market	4
Fluid Maintenance	Low. Current oil used.	1	Low. Similar to conventional but more frequent change-out	2	Limited sheld life. Flushing required to eliminate bioaccumulation	4
Environmental Impact - Toxicity	Negative Impact	4	Depends on type	3	No impact. Skin irritant	2
Environmental Impact - Biodegradability	Negative Impact	4	Depends on type	2	Readily biodegradable	1
Bidibility	Many companies	1	Many companies	1	Specialty companies	3
Contract Staging/lock downtime	Minimal	1	Minimal	1	Requires cylinder refurbishment time	3
TOTAL RANKING	(Lower score desirable)	14		15		25
Cost of Fluid (order of magnitude)		1.0		2.5-7.0		1.1*
Cost of HPU (order of magnitude)		1.0		1.0-1.2		3.0
Cost Incurred from Spill		YES		YES**		NO

There are a few areas to focus on in the matrix. The first is the total ranking of each option, which ranks EAL the best, followed by conventional oil, and water-based hydraulics. However, the district made a decision to use conventional petroleum-based hydraulic oil.

Some hydraulic fluids that have been used at USACE field sites and European waterways that are considered EALs include:

- Trident PAG from Dow Chemical - PAG http://www.dow.com/ucon/formulated/fluids/anhy.htm. This product is being used at the new Folsom Dam tainter gates. However, at the time of the writing of this manual, a performance evaluation has not been done. EnBio PAG hydraulic fluids are another consideration and were evaluated for the new hydraulic system at LaGrange Lock (but were not used) - https://enbiousa.com
- Panolin - synthetic ester. This is used extensively and throughout Europe on multiple lock and dam sites. http://www.panolin.com/inten/products/environmentally_considerate_lubricants/panolin_hlp_synth/hlp_synth_overview.php
- RSC Bio Solutions – PAO. This is being used for the hydraulic system at Coon Rapids Dam in Minnesota. Their product literature indicates

they are compliant with the USEPA Vessel General Permit requirements, http://rscbio.com/products/envirologic/hydraulic-fluids
- BioBlend – Biobased hydraulic fluid - https://www.bioblend.com/. The product website and product literature indicate they are VGP compliant.

6.7 Gear reducer oil selection

Gear reducers are also used extensively in USACE civil works applications (Figure 11). They are a common form of power transmission used on a variety mechanical drives. Some more common types of gear reducers include parallel shaft with helical gearing and worm gear reducers. Gear reducers simply are a combination of open gears that are enclosed in a sealed box or housing. They are generally used for speed reduction within USACE. Gear reducers can use a number of gear types including worm gears, spur gears, bevel gears, and helical gears. A lubricant is used to control friction and wear between the mating surfaces, and in enclosed gear drive applications, to transfer heat away from the contact area. It also serves as a medium to carry the additives that may be required for special functions. There are many different lubricants available to accomplish these tasks.

For systems in which water contamination is likely, gear oils conforming to AGMA Standard 250.4, Grade 7 compounded, are recommended. These oils contain a fatty oil additive that enhances their surface wetting ability under high moisture conditions.

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

Selecting the proper gear lubricant is important to the long-term, efficient operation of the gear drive. There are many factors to consider when selecting an industrial gear lubricant for a particular application. However, two key factors are:

- the type of gear reducer
- the application.

The appropriate viscosity and oil selection criteria for a particular type of industrial gear drive can be determined using AGMA 9005-E02, *Industrial Gear Lubrication* (AGMA 2002). The AGMA 9005-E02 standard shows suggested viscosity grades for industrial gear drives operating under normal loads over a range of speeds and ambient temperatures.

Figure 11. Gear reducers (USACE).

As the oil in a gear reducer heats and cools, it expands and contracts, allowing moist outside air into the gear reducer through the breather. To limit the entrance of moisture into gear reducers, the use of an appropriately sized oil bath or disposable desiccant breather is necessary. This type of breather must not only be designed and installed correctly, it must also be replaced when the desiccant is saturated. Gear reducer outdoor exposure to humidity and sunlight will draw water into the gear reducer oil. Fabricated protective covers or roofs are justified to limit the direct exposure to sunlight and the elements. A closed loop breather system is also a consideration. The Parker Kleenvent has been used at several sites in USACE: http://ph.parker.com/us/en/hydraulic-reservoir-isolator-kleenvent-kve

Lubrication requirements for gear reducers are prescribed by the equipment manufacturer(s), based on the operating characteristics and ambient conditions under which the equipment will operate. Often the nameplate data on the equipment will indicate the type of lubricant required. If the manufacturer is unknown or no longer in business, a lubricant supplier should be consulted for recommendations. Means of lubricating gear reducers include splash lubrication, pressure lubrication, gravity drip, spray systems, and idler immersion systems.

The most common viscosity grade for both parallel shaft and right-angle intersecting gears is ISO VG 220. A common mistake has been to use the wrong weight of oil in gear reducers. For example, worm gear reducers typically require oil that is approximately twice as heavy as that required for parallel shaft gear reducers. This is due to the nature of the sliding action between the worm gear and the worm wheel. It is not unusual to find that the same weight oil that is appropriate for the parallel shaft gear reducers used in the worm gear reducers. This will lead to accelerated wear.

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

In addition, the gear lubricant selected for a particular application should match the recommendations of the original equipment manufacturer. These lubrication specifications can be found inscribed either on the industrial gear drive's nameplate or in the published specifications found in the operator's manual. These lubrication specifications are designed to balance the lubrication needs of the bearings, which generally require a light-viscosity lubricant. The specifications are also designed to balance the lubrication needs of the gears, which usually require the use of a medium- to high-viscosity lubricant. This balance can be achieved only through proper viscosity selection.

Step 1. Determine viscosity requirements and select proper viscosity oil.

Viscosity provides the proper thickness of the oil film at the operating temperature and conditions to keep the mating surfaces of the gears and bearings apart during hydrodynamic lubrication conditions. It also allows for the proper flow of the lubricant to carry frictional heat away from the stress points along with any wear debris or contaminants present. In addition, the viscosity of the industrial gear lubricant selected is important to the overall load-carrying ability of the gear lubricant. For new equipment, the manufacturer will select the proper viscosity of the gear oil and provide this as part of the project operation and maintenance manual. Table 16 lists some general guidelines for viscosity selection (Scott, Fitch, and Leugner 2011).

Table 16. Common viscosity requirements for gearboxes (from Noria Machinery Lubrication Handbook).

Gear Type	ISO Viscosity Range	Oil Type
Spur, Helical, and Herringbone	150-320	EP, PAO, PAG, Mineral
Bevel	150-320	EP, PAO, PAG, Mineral
Worm	460-1000	Compounded, PAO, PAG
Hypoid	460	EP

Many older gearboxes still reflect the old AGMA rating system, in which viscosity grades were indicated by a single digit number. The new rating system uses ISO viscosity grades or shortened as ISO VG. The EM 1110-2-1424 provides a conversion between the rating systems as does the Noria Lubrication Handbook (Scott, Fitch, and Leugner 2011).

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

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

If the gear reducer manufacturer does not specify a particular viscosity grade to use, or if the lubrication recommendations are no longer available due to lost maintenance records, misplaced operator's manuals, or painted-over nameplates, the correct viscosity grade for a particular industrial gear lubricant can still be determined. AGMA 005-E02 can be used to determine the correct viscosity. AGMA 9005-E02 provides calculations to determine proper viscosity based on speed and load.

Step 2. Review other relevant considerations.

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

The pour point of the gear oil should be at least 9 °F (5 °C) below the minimum expected ambient temperature during start-up. If this cannot be achieved, use a gear lubricant that has a lower pour point, such as one that is formulated with synthetic base fluids, or use a heater to heat the oil before starting the industrial gear drive. Any heater should be minimum wattage and not allow the oil to get any hotter than 120 °F (49 °C).

Step 3. Select oil.

The four general types of gear lubricants that could be used in the lubrication of gear reducers include: (1) rust and oxidation (R&O) inhibited oils, (2) EP gear oils, (3) compounded gear oils, and (4) synthetic gear oils.

6.7.1 Rust and oxidation inhibited gear oils

These are typically formulated with highly refined petroleum or synthetic base oils and contain additives that enhance oxidation stability, provide corrosion protection, and suppress foam. Their superior oxidation stabilities typically set them apart from other gear oil types. However, their load carrying capabilities may be less than other gear oil types. These oils are generally associated with higher speed and lighter load applications. Rust and oxidation inhibited gear lubricants can perform well over a wide range of gear sizes and speeds with ambient temperatures ranging from -5 to 250 °F (-21 to 121 °C). R&O inhibited oils are commonly used to lubricate high-speed single helical, herringbone reduction gear sets that have pitch-line velocities greater than 3,500 ft/minute (17.5 meters/second) and are subjected to light to moderate loads. They are also used in the lubrication of spur, straight bevel, and spiral bevel gear drives that are subjected to light loads.

6.7.2 Extreme pressure gear oils

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

On worm gear drives, avoid the use of EP additives when possible. When used in worm gear drives, EP lubricants must resist the thinning due to high temperatures and the wiping effect of sliding action, and they must provide adequate cooling. Mineral oils compounded with lubricity additives are recommended. EP additives usually are not required for worm gears and may actually be detrimental to a bronze worm gear. Because some types of EP gear lubricants contain chemically active additives systems, care must be taken if they are used in systems where the gears and bearings are lubricated from the same system, or if they are used in heavily loaded worm gear drives. EP gear lubricants can contain additives that are corrosive to brass or bronze components. When used in these applications, the lubricant supplier should be contacted to determine if the EP gear lubricant can be used in such applications. Some EP gear lubricants will also contain solid lubricants such as graphite or molybdenum disulfide that are held in a suspension. These solid lubricants are formulated into the industrial gear lubricant to further improve the gear lubricant's load-carrying capabilities.

EP gear lubricants perform well over a range of gear sizes and speeds with ambient temperatures ranging from -5 to 250 °F (-21 to 121 °C). Constant re-lubrication by the use of either splash lubrication or circulation lubrication systems of the gear teeth is preferred because EP industrial gear oils do not adhere to the surface of the gear teeth. They can be used effectively to cool the gear mesh and flush the tooth surfaces of wear particles or debris.

6.7.3 Compounded gear oils

Compounded gear oils are a blend of petroleum base oils with 3 to 10% of natural or synthetic fatty oils. These lubricants are frequently used in worm gear drives where the high sliding action of the gear teeth requires a friction-reducing agent to reduce heat and improve efficiency. The surface active agent, which is a fatty or synthetic fatty oil, prevents sliding wear and provides the lubricity needed to reduce sliding wear. Their use is limited by an upper operating temperature of 180 °F (82 °C). Most worm gear drives normally require an ISO VG 460 or VG 680 compounded oil. In some cases, an ISO VG 1000 viscosity grade is required. The viscosity grade required depends on the worm gear drive's speed and operating temperature. Generally the lower the worm's gear speed, the heavier the viscosity grade.

6.7.4 Synthetic gear oil

Synthetic gear oils are primarily used in spur, straight bevel, spiral bevel, helical, herringbone, and hypoid worm enclosed gear drive applications whenever petroleum-based industrial gear lubricants have reached their performance limits. Synthetic gear lubricants can contain R&O inhibited additive systems, or anti-wear or EP additives. They are used in enclosed gear drive applications where very low or high ambient and/or operating temperatures are encountered. Synthetic gear lubricants offer the following advantages in enclosed gear drive applications:

- improved thermal and oxidation stability
- improved viscosity-temperature characteristics (high viscosity index)
- very good to excellent low temperature characteristics
- lower volatility and evaporation rates
- reduced flammability (depending on the type of synthetic base used)
- improved lubricity at mesh temperatures above 365 °F (185 °C)
- resistance to the formation of residues and deposits at high temperatures
- improved efficiency due to reduced tooth-related friction losses (low traction coefficients)
- lower gearing losses due to reduced frictional losses (low traction coefficients)
- extended oil drain intervals
- reduced operating temperatures especially under fully loaded conditions
- reduced energy consumption.

Many of the USACE St. Paul District gearbox drives use Mobil SHC 630 synthetic gear oil with EP additives (ISO 220 viscosity grade). Recently, Schaeffer 293 has been used at several sites in St. Paul District. This is an API Group III blended with PAO. In Rock Island District, the policy has been to replace the Mobil SHC 630 with CEN-PE-CO oil when the Mobil SHC 630 becomes contaminated (based on oil testing results).

In USACE Huntington District, parallel shaft and worm gear box oils are standardized across the entire portfolio (locks and dams and reservoir projects), with:

- Mobil SHC 630 (ISO VG 220) for parallel shaft with 8 to 20-in. gear centers
- Mobil SHC 632 (ISO VG 320) for parallel shaft reducers with centers >20 in.
- Mobil SHC 634 (ISO VG 460) for worm gear reducers.

7 Lubricant Survey

7.1 EAL survey

A sampling survey of lubricants in use at USACE facilities and marine plants was conducted to provide some insight into the level of standardization and the extent that EALs are used (see Appendix L). The survey included feedback from operators on performance of lubricants and an inventory of existing facility lubricants.

From the survey, 64 replies were returned primarily from MVP (St. Paul District), MVN (New Orleans District), SAM (Mobile District), LRE (USACE Detroit District) and LRN (USACE Nashville District). A few observations on the survey:

1. EAL Use on Floating Plant. The use of EALs is limited. Marine Design Center (MDC) is aware of some of the applications and these were the only ones identified, with one exception (D/B Nicholet on the hydraulic drive). MDC is aware of other installations, but surveys were not returned.
2. EAL Use on Locks and Dams. Several instances of "Food Grade" greases and oils were reported that the operators believe are EALs. However, the vast majority of responses indicated no use of EALs.
3. Most facilities have heard of EALs.
4. Most facilities are not aware of any USACE publication concerning either lubrication or EALs
5. Most facilities are not aware of any guidance concerning EALs.

The use of EALs is very limited, but the real value in the survey are the responses to Questions 2 and 3:

2. If your facility or vessel currently do not use EALs:
   a. Are aware of EALs? *Most sites are aware of EALs, but there is much confusion on the definition. Many sites do not differentiate between food grade lubricants and EALs.*
   b. Have you considered using EALs? *Most sites have not or have never used EALs.*
      (1) If so, what applications?
   c. Have you been in contact with representatives from EAL companies or industry experts? *Primarily, the answer was "no."*
      (1) If so, please provide contacts/Points of Contact (POCs)

   d. What reason(s) have prevented converting to EALs? *Lack of information and guidance was* the *primary answer.*
   e. Will you specify EALs if/when a system requiring lubricants is replaced? *Primarily, the* answer *was "no."*
3. Are you aware of USACE publications regarding lubricants and EALs – *Primarily, the* answer *was "no."*

7.2 Lock and dam survey

The survey included feedback from lock and dam operators on the performance of lubricants and an inventory of existing facility lubricants. Survey information was provided from Huntington (LRH), Rock Island (MVR), and St. Paul Districts (MVP). Information from the 13 lock sites in MVP is provided in Appendix M. Many interesting observations can be made from an examination of the survey data. While this work focused on lock and dam operating machinery, some projects reported back on the lubricants they use in their maintenance equipment such as lawn mowers, utility vehicles, road vehicles, etc., in which they described use of a wide range of products for these purposes.

The Mississippi River locks generally do not use hydraulic fluid (except for three sites) so all of the results for hydraulic fluid are from LRH and MVR (Illinois Waterway). One project reported having six different hydraulic fluids between their lock machinery and maintenance equipment. However, the projects generally use an ISO VG 32 hydraulic fluid for their lock operating equipment, which therefore represents a good opportunity for standardization.

Both MVP and MVR primarily use electromechanical gear drives for the miter gates and tainter valves. Gearbox oils are standardized within MVR. In MVP, the gearboxes oils are nearly standardized with the exception of a couple of sites. Grease usage is not at all standardized in either MVP or MVR. MVR has established a comprehensive testing and cleaning program for their gearbox oils. A significant issue in Rock Island District is flooding, which occurs frequently, submerging the lock machinery, including gearboxes.

The bearing greases appear to be mostly NLGI #2 greases with various additives from a variety of manufacturers. While this result appears to support standardization, the fact that these greases are readily available from so many different retail outlets may make it difficult to get end user buy-in on standardizing on a centrally sourced grease.

During the survey, the operations personnel were asked to provide any feedback they had on the products that they are using. Feedback comments were few, but no comments were received indicating dissatisfaction with the lubrication performance of the products in use. Feedback comments were related to ease of use, cost, equipment inspection (clear lubricants versus opaque), and cleanup. Therefore implementing any standardization and EAL program should address these issues to get maximum end user buy-in.

8 Case Studies and Existing Reports

8.1 Existing lubrication reports ERDC

ERDC has recently evaluated published two technical reports that evaluate the use of EALs. The first, *Evaluation of Environmentally Acceptable Lubricants (EALS) for Dams Managed by the U.S. Army Corps of Engineers* (Medina 2015), was published in August 2015. The purpose of this report was to provide a preliminary assessment of EALs for application in dams that are managed by USACE. The report explored the environmental aspects of EALs and also their operational characteristics. The second ERDC report, *Evaluation of Environmentally Acceptable Lubricants (EALs) Non-Hydropower Uses for NWD and NWW Dams*, focused on EAL greases for several non-hydropower sites in Northwest Division. This technical report is provided in Appendix G and introduced a tiered definition for EALs, as summarized in Chapter 2 of this report. Nineteen lubricants were evaluated. These were identified as environmentally friendly greases already used in USACE dams or as potentially applicable environmentally friendly greases from other sources. Each grease was checked against the USEPA criteria for bioaccumulation, biodegradation, and toxicity. ERDC considered the composition of the greases where direct data was not available. ERDC also checked for labels that indicated EAL acceptability.

8.2 NWD and NWP and NWW (Walla Walla District) grease testing

Several technical reports were written in response to an environmental lawsuit regarding primarily in-water grease usage. This result of the lawsuit was a settlement between USACE and the Columbia Riverkeeper in the USACE Northwest Division (NWD). The Riverkeeper website states that:

> Riverkeeper's vision is to restore a Columbia Basin with clean, clear waters flowing cold from the headwaters to the Pacific Ocean. Our vision is for a Columbia with healthy salmon runs that can support traditional harvest by Native Americans and non-native fishermen.

In NWP and NWW hydropower applications, past history of use and standardization of grease is lacking. A survey was conducted on eight hydropower plants on the Columbia and Snake rivers on current and past grease use. Past history of the greases used was poorly documented as well as the decision to use the current grease. Grease used at the eight plants varied, and standardization is lacking. Grease selection was left up to the maintenance staff. Selection criteria and guidance were also lacking. Compatibility was generally an afterthought or not considered.

8.2.1 Environmentally acceptable lubricant wire rope and hydropower submerged equipment testing in NWD

Field testing of EAL wire rope lubricant was conducted by HDC and NWD to assess the feasibility of using EAL wire rope lubricant (HDC 2017). Four different EALs were field tested to evaluate the ability of the lubricant to perform its function without risk of damage to the equipment. In addition to the four EALs tested, an existing non-EAL lubricant was tested to provide a baseline for comparison purposes. Field testing was conducted over a 12-month duration at Bonneville Powerhouse II and Ice Harbor Dam.

The four EAL wire rope lubricants were subjected to field testing in two different ways: (1) accelerated life testing by 12-month continued submergence in water and (2) normal use testing by applying them on an existing wire rope on powerhouse intake and tailrace cranes. The lubricants were evaluated based on corrosion protection of the wire rope core, retention of rope strength, retention of lubricant properties, and expected life span. In addition, the EAL lubricant could not interfere with visual inspections of the wire rope.

New unused wire ropes were segmented and the lubricant applied and submerged for 12 months in the river. In addition, wire rope samples were prepared and placed in saltwater in a sealed container.

Wire rope on the powerhouse cranes spend the majority of their time exposed to the atmosphere. The crane wire rope is infrequently subjected to short duration immersion in the river any time the crane places or removes a gate or bulkhead.

The wire ropes were inspected after 6 months and again at 12 months. Visual inspection techniques were used to evaluate the condition of the wire ropes and the lubricants. After the 12 month inspection, the wire rope samples were sent to be destructively tested to determine if loss of strength occurred.

The ropes that were continuously submerged showed almost complete biodegradation of the lubricant after 1 month of exposure. By the end of the 12-month test period, all the wire rope test samples had no lubricant left and were developing heavy rust. Destructive testing showed loss of strength. This leads to the conclusion that EALs are not technically acceptable for applications where the rope will be submerged for extended period of time. The test did not establish limits for hours of water exposure, but rather showed a trend that the more the rope is submerged, the more the lubricant is degraded.

The destructive testing of the wire rope did not provide data that one lubricant performed better. All rope samples showed a decrease in strength, including the rope sample with the non-EAL lubricant. There were no significant differences in the performance of the four EAL lubricants tested.

The results of this test indicate that EALs are not technically acceptable for applications on wire ropes that are submerged in water for extended period of time (More than 80 hours in a 12-month period). EALs will biodegrade when exposed to river water. This biodegradation is so severe that the lubricant will not be serviceable after 1 month of exposure. Use of EALs in submerged applications would require maintenance intervals once per month or more frequently.

For non-submerged and crane applications, the testing indicated that EALs are technically acceptable for wire ropes that are not submerged for extended periods of time and spend the majority of life exposed to the atmosphere. For all applications, it is recommended that a pressurized applicator be used to apply the wire rope lubricant.

8.2.2 EAL Proof of concept plan lower monumental navigation lock tainter valve #4

Field testing of the use of EAL grease on the fill and drain valves was conducted on Lower Monumental Lock and Dam Fill Valve No. 4 by Walla Walla district (Portland and Walla Walla Districts 2017e). This testing was conducted over a 12-month period. The existing trunnion bushings and pins were replaced under an existing repair contract. The existing grease line of Tainter Valve No. 4 was replaced and existing grease was purged and replaced with Panolin Biogrease EP2.

Panolin Biogrease EP2 was selected for this testing based on compatibility and performance testing conducted by HDR Engineering, Inc. (HDR) and HDC (Portland District 2015). The prior grease used at Lower Monumental is Chevron Ultra-Duty Grease EP (NLGI 1). Panolin Biogrease is thicker grease (NLGI 2), but the consistency of this thicker grease was considered acceptable based on acceptable performance of NLGI 2 greases currently in service on the Little Goose Lock and Dam and Ice Harbor Lock and Dam fill and drain valves.

A data logger was used to capture data throughout the operating cycle. The gate position, system pressure, and hydraulic pump motor amperage data was collected.

Testing will be considered successful if the valve raises and lowers without sticking or binding, the operating pressure does not increase more than 10% during the entire testing cycle, and the hydraulic pump motor does not experience and overcurrent condition. In addition, visual inspection of the valve and grease distribution was also done.

Based on the reviewed data, the operating pressure during the periods of May through November time period are within 10% of each other. Discussion with the Lower Monumental Project crew indicated that, overall, there were no major problems with using the EAL and they would find it acceptable to use on the remaining three tainter valves. The project observed the following:

- The mechanics recognized that the NLGI 2 EAL was thicker than the existing mineral oil based grease (NLGI 1). There was some difficulty pumping the grease down to the tainter valve machinery room where the automatic grease reservoir is located. The use of a heated oil drum blanket could help reduce the viscosity and make this pumping easier.
- A shift operator discovered a fault in the automatic grease system. When investigated, it was found that air had entered into the reservoir. This was remedied and the grease system was back on-line. Heating the grease before installation in the reservoir may help remove pockets of air.
- The shift operators reported some abnormal noise in the valve; however more recently this noise has not been noticed. It is not known if this noise had to do with the lubrication system or greased bearings. The data did not reveal any unusual spikes in pressure.
- Motor overcurrent did not occur on the tainter valve hydraulic system.

- Downloading from the data logger used during the Lower Monumental fill/drain valve continues to be problematic. Export file is proprietary software that requires U.S. Army Corps of Engineers–Information Technology (ACE-IT) approval for install. Future tests should attempt to install software before attempting to download export from data loggers.

8.2.3 Environmentally acceptable lubricant grease for hydropower applications – Technical feasibility analysis for eight hydropower facilities in Washington and Oregon

The U.S. Army Corps of Engineers (USACE) Hydroelectric Design Center (HDC) contracted with HDR to assess the technical feasibility of switching from conventional greases to EALs on certain in-water hydroelectric plant equipment (Portland District 2015). The complete report is provided in Appendix C. The report stated that:

> EALs represent a class of lubricants that have been demonstrated to meet standards for biodegradability, toxicity and bioaccumulation that minimize the potential for adverse consequences in the aquatic environment when compared to conventional lubricants. The feasibility of switching to EALs is being assessed at the following power plants: Bonneville, The Dalles, John Day, McNary, Ice Harbor, Lower Monumental, Little Goose, and Lower Granite. EALs are being evaluated for use on turbine wicket gate bushings and balance of plant lifting equipment that may become submerged such as crane hooks, lifting beams and wire rope. The study objective focused on technical feasibility and whether one or more EALs can be used without risk of damage to existing plant equipment.

HDR collected representative in-service grease from USACE powerhouses to be used to check compatibility with new candidate EAL greases and serve as a performance target for new products. Candidate EAL greases were selected based on international criteria defining an EAL. Grease already in service at the plants and candidate EAL samples were sent to independent analytical laboratories for testing and analysis.

In-service grease samples were tested for their compatibility with four candidate EAL lubricants to assess whether the greases currently in service can be mixed with the candidate EALs without development of adverse characteristics or degradation in performance. The ability to mix the EAL grease with the in-service grease is very important to prevent clogging of the grease distribution lines or separation of the base oil from the thickener. Either of these scenarios could lead to one or more bearings being starved of lubricant. Additionally, each of the candidate EALs was tested for performance metrics to determine if their performance was equal to or better than a reference in-service grease.

One of the four EAL greases tested (Panolin Biogrease EP 2) was assessed to be both compatible with existing in-service greases and achieved the stated laboratory performance metrics. Based on laboratory data alone, the study concludes that switching to EALs is technically feasible on certain in-water hydroelectric plant equipment. However, the study did not find wicket gate bushing performance history on the Panolin Biogrease EP 2, and the question of whether it can be implemented without risk of damage to equipment remains uncertain.

Based on results of laboratory testing and the absence of wicket gate performance history for Panolin Biogrease EP 2, the implementation of EALs should include a “proof of concept” before full implementation. The “proof of concept” can take various forms to fully demonstrate that the new EAL is satisfactory for long-term operation and does not pose a risk to generation assets. This may involve a defined timeline of testing or operation in one or two machines at each site or on each turbine type that is of sufficient duration to determine a successful outcome.

This study identifies several candidate greases for wire rope applications. Although these greases were not subject to testing because of the reduced sensitivity to compatibility issues in these applications, several greases have been found to qualify as EALs and have promising characteristics for wire rope protection and lubrication.

8.2.4 Environmentally acceptable lubricant wicket gate bushing proof of concept testing plan

The USACE Hydroelectric Design Center (HDC) prepared this technical report (HDC 2016) to address the feasibility of using an EAL grease without risk of damage to the wicket gate bushings and operating mechanism at the following power plants: Bonneville Second Powerhouse, The Dalles, John Day, McNary, Ice Harbor, Lower Monumental, Little Goose, and Lower Granite. The EAL grease being evaluated for proof of concept testing on the turbine wicket bushing and operating mechanism is Panolin Biogrease EP2.

Panolin Biogrease EP2 was selected after a series of laboratory tests were conducted by HDR in 2015 focusing on performance and compatibility with the existing in-service greases at the eight power plants (Portland District 2015), and on *Environmentally Acceptable Lubricant Grease for Hydropower Applications* (Portland District 2015) included in Appendix C. Based on laboratory testing alone, HDR found Panolin to be compatible with all but Chevron Ultra-Duty and Chevron FM ALC in-service greases. Those greases are used at McNary, Ice Harbor, Lower Monumental, Little Goose, and Lower Granite. The greases were found to have borderline compatibility with Panolin EP2. Based on laboratory testing alone, Panolin performance appears to be acceptable. However, the study was not able to locate wicket gate bushing performance history on the Panolin Biogrease EP2. Panolin has since supplied references of hydropower use in Italy. However, the duration of use or satisfactory performance was not verified and therefore concern remains as to its ability to protect the equipment.

This proof of concept test plan details the process to address the concern of equipment damage and compatibility when implementing the replacement EAL lubricant. This will be accomplished through monitoring performance and compatibility of the candidate EAL grease after being placed in service in designated test units.

The intent behind this Proof of Concept Testing Plan is to outline a 1-year test run, with the EAL grease replacing the in-service grease. HDC and the Architect-Engineer (A-E) will work collaboratively with the project personnel to install instrumentation, operate, and collect data with the in-service grease to develop a baseline for performance. With this baseline performance data for the in-service grease, the linkages will be disassembled, accessible bronze bushings (Upper Bushing or Linkage Pin Bushing) will be inspected and measured, and the in-service (non-EAL) grease will be purged and replaced with the EAL grease (Panolin). With the EAL grease in place, the unit will be periodically monitored and operated. Data will be collected at defined intervals; the current measurements include at time of install, every month for 3 months, then every 3 months until the year mark (months 0,1,2,3,6,9,12). After a year has passed, the linkages will be disassembled and the accessible bushings will be inspected again for comparison to the start of the test. HDC will be onsite with the A-E for all unit monitoring activities.

The test will be conducted on four test units, representing each unique in-service grease type. Testing will be performed on each in-service grease and allows the team to fully assess compatibility of the EAL grease after it is placed in service with the existing grease. In addition, the four test units will be selected in a manner that test units from several turbine manufacturers (Allis Chalmers, Baldwin-Lima-Hamilton, S. Morgan Smith).

Instrumentation will be installed to record wicket gate servo pressures, wicket gate journal clearance, wicket gate motion, and grease flow volumes. The instrumentation will be used to measure and record a performance baseline for the in-service lubricant. This baseline will be compared with the new lubricant throughout the test, to evaluate compatibility and performance. Also, laboratory tests will be conducted for both the used in-service grease and the used EAL grease performance characteristics on completion of the 12-month trial. This will be used to evaluate life of the lubricant after it has been placed in service and its ability to protect the equipment. From this information, it can be determined any change in friction coefficients; increase in journal clearance before and after the new grease is applied as well as compatibility issues and grease line fouling due to incompatibility.

Final bushings inspection will be used to determine if satisfactory performance is achieved with the EAL lubricant and whether the EAL can be used without risk of potential damage to the equipment.

It is unlikely that significant wear of the wicket gate bushing during this 12-month period would result in recordable dimensional change of the bushing bore. A change in surface finish would prove as indication of significant increase in wear and be deemed unacceptable.

Laboratory testing of the used in-service greases will be used to evaluate the grease's ability to protect the equipment as it ages, as well as help determine if greasing frequency is sufficient. In addition, a change in used EAL grease performance that significantly exceeds the change in performance of the used, existing in-service grease will be deemed unacceptable.

Grease meters will be used to monitor flow of grease in the line. A decreasing flow trend will be cause for concern to pumpability of EAL and compatibility issues. Fouled grease lines and excessive reduction of EAL grease performance properties will be cause to classify the EAL grease as incompatible with the existing grease.

A large differential between static and dynamic coefficient of friction will be cause for concern and indicate inadequate lubricity. Observed stalling or stick-slip (increase delta between static and dynamic frictional coefficients) of the wicket gate mechanism will require operation of the test unit to cease until further investigation of the cause.

8.2.5 EAL proof of concept plan – Ice Harbor fish pumps

This document discusses proof of concept for implementation of EALs on the fish pumps for the Portland and Walla Walla Districts (2016a). The fish pumps include those at the following projects:

- John Day Dam
- McNary Dam
- Ice Harbor Dam.

The Portland and Walla Walla Districts recently completed a study on the risk of switching to EALs on various project equipment (Portland and Walla Walla Districts 2016b). This study was prompted by a settlement agreement with Columbia Riverkeepers in 2014, which required USACE to assess if switching to EALs was feasible on certain in-water equipment. It was determined that using EAL on the fish pumps would require testing to ensure that switching to an EAL would perform similarly to a non-EAL and would not pose a risk to the equipment.

Ice Harbor was selected as the site to perform proof of concept testing on fish pumps because there are sufficient pumps such that pump performance can be monitored both with the EAL and with the existing grease. The eight fish pumps on the south shore are lubricated by an automatic grease system (Farval). The automatic greasing is separated by two grease systems that each supply grease to four of the pumps. Four of these fish pumps will be used for testing using an EAL. The remaining pumps will be monitored as well for comparison purposes with the existing grease (Chevron Ultra-Duty Grease EP NLGI 2).

The lubrication system is an automatic greasing system and consists of a reservoir, a positive displacement pump, and discharge valves that regulate the amount of grease supplied to the fish pumps. Adjustment screws are used to change the distribution of grease that is discharged each cycle. For purposes of this test, the adjustment screws shall remain in the same position as before.

The positive displacement grease pump regulates the amount of grease that is discharged to the system by a setting that changes the length of cycle time. Changes may be needed to increase or decrease the cycle time.

8.2.6 EAL proof of concept plan – Little Goose Navigation Lock – Downstream miter gate

This document discusses the proof of concept for implementation of EALs on the miter gate pintles located within navigation locks of the Portland and Walla Walla Districts (2016c). The proposed gates initially included the following lock sites:

- Bonneville (upstream and downstream)
- McNary (upstream and downstream)
- Little Goose (downstream)
- Lower Granite (downstream).

The miter gate pintle at Little Goose will be the only one investigated initially. The Portland and Walla Walla districts recently completed a study on the risk of switching to EALs on various project equipment (Portland and Walla Walla Districts 2016b). It was determined that using an EAL on the miter gate pintle bearings would require testing to ensure that switching to an EAL would perform similarly to a non-EAL and would not pose a risk to the equipment. Little Goose was selected as the site to perform proof of concept testing because the pintle bearings are being replaced in FY17, so the condition at the onset of testing will be known. The lubrication system for each miter gate serves the gudgeon, gate pin, gimbal, and the pintle bearing, although only the pintle is being replaced in FY17. Only the riverside leaf will have the EAL grease implemented. The landside leaf will be monitored with the existing grease (Chevron Ultra-Duty Grease EP NLGI 2) for comparison purposes. Note that the Project Delivery Team (PDT) considered testing at McNary since their pintle bearings are scheduled to be replaced in 2021. The new pintle bearings at Little Goose, however, provided an opportunity to assess the grease performance from a known starting condition. The pintle bearing has a sealed greased system. An O-ring seals the pintle near its base so that the grease will enter a return line that travels back up to the machinery room. Little Goose system will have a Viton (FKM, or fluorocarbon) O-ring installed with the new pintle bearing. Viton is the preferred O-ring material to ensure the best compatibility with Panolin Biogrease, as indicated by the Panolin representative. Furthermore, seal manufacturers SKF and AEGIR Marine require stern tube seals to be replaced with Viton when implementing EALs.

8.2.7 EAL proof of concept plan – Lower Granite Navigation Lock – Upstream tainter gate trunnions and wire rope blocks

This document discusses proof of concept for implementation of EALs on the trunnion bearings and wire rope blocks located on the Lower Granite navigation lock upstream tainter gate (Portland and Walla Walla Districts 2016d). This test plan will provide information to make a decision as to whether to switch to EAL grease at Lower Granite as well as on similar equipment at The Dalles, Ice Harbor, and Little Goose.

The Portland and Walla Walla districts recently completed a study on the risk of switching to EALs on various project equipment (Portland and Walla Walla Districts 2016b). It was determined that using EAL on the tainter gate trunnion bearings would require testing to ensure that switching to an EAL would perform similarly to a non-EAL and would not pose a risk to the equipment or mission. Lower Granite was selected as a site to perform proof of concept testing. Lower Granite's upstream trunnion bushings are in good operating condition with no current issues with the mechanical drive system.

The lubrication system for the tainter gate serves the trunnion bearings and the wire rope blocks. Both the riverside leaf and the landside leaf bearing grease will be replaced with the EAL in lieu of the existing grease (Chevron Ultra-Duty Grease EP NLGI 2), as will the wire rope blocks. The lubrication system is a manual greasing system and consists of two ½-in. outer diameter hoses (likely 5/16-in. inner diameter) delivering grease to the trunnion bushing and wire rope block. The hoses have button head disconnects to accept a manual grease gun operated by maintenance personnel. Both the landside and riverside bearing and wire rope block are greased bi-weekly (twice per month). Each lockage has up to two cycles — one for closing and one for opening the gate.

Monitoring the effects of EAL installation will be limited to checking the hoist motor current, and a general visual and auditory inspection of gate operation. Visual inspections of the bearing will not be possible without removal of the trunnion pin, which could be done under the annual FY18 lock outage, but is not likely due to the large level of effort required. Visual inspection of the trunnion may be done via ladder with fall protection or by man basket although these methods have a high level of effort and require multiple personnel with specialized training and equipment. Work also needs to be coordinated with lock operations because the lock cannot be used while personnel are accessing the trunnions and wire rope blocks. Optics may be used to view the trunnions and rope blocks from a safe location if access is not feasible.

9 Conclusion and Recommendations

9.1 General

This report recommends that:

- All USACE civil works projects should evaluate the use of EALs and self-lubricated materials as applicable. A follow-up to this work will be to encourage HQUSACE to mandate this evaluation of EALs and SLMs on USACE civil works projects. It should be clear that the use of EALs and SLMs will ***not*** be mandated, only their evaluation and consideration.
- Formal adoption of Tier 1 and Tier 2 definitions of EALs should be developed throughout USACE civil works.
- Lubricant selection should be standardized within Districts. Lubricant selection should be standardized within waterways to the extent possible (for example on the Upper Mississippi River and Illinois Waterway). This will require Districts to establish Standard Operating Procedures for their lubricant selection and testing and replacement.
- All USACE civil works field sites should establish a lubricant sampling and testing program per the requirements in USACE EM 1110-2-1424.
- To help with standardization, USACE districts and field sites should investigate different means of purchasing lubricants including through the DLA, through IDIQ contracts, and through bulk purchases.
- An official guide specification for EAL grease should be developed and incorporated into a Unified Facilities Guide Specification (UFGS). The current draft version can be a starting point.
- An official guide specification for EA hydraulic fluid should be developed and incorporated into an UFGS. Alternatively, the existing UFGS on hydraulic systems: Section 35 05 40.14 10, *Hydraulic Power Systems for Civil Works Structures*, should be modified.
- It should be determined conclusively whether the AOAP testing laboratories can or cannot be used for USACE civil works.
- An ERDC Statement of Need should be initiated and a survey taken of EALs and self-lubricating materials throughout USACE civil works.
- ERDC reports concerning the Powertech Self Lubricated Bearing tests (Jones 1999; Race, Kumar, and Stephenson 2004) should be updated. The original Powertech test dates back to 1999. Manufacturers have since marketed new products and enhancements to their existing product lines. New and updated reports will provide much needed test data for the latest manufacturer product lines.

- A comprehensive listing of all USACE civil works sites that are using self-lubricated materials and the application for which they are used, should be developed. In addition, the performance of these materials needs to be documented to clarify whether these materials are working properly, and whether there been any failures. This is especially critical for pintle bearings on miter gates and sector gates.
- Pilot studies should be initiated (see Section 9.3) for EAL greases and EA hydraulic fluid.

9.2 Operation and maintenance and risk considerations

Several factors need to be considered when converting to EALs or synthetic lubricants or self-lubricated materials on drive machinery. Mineral oil lubricants should always be considered a baseline for any comparison. Related to costs, the most important item to cover with field sites and end users is equipment lifetime costs. The initial cost of the lubricant or SLM is often the driving factor, but life cycle costs also need to be considered. Variables include initial fluid price, any changeover or conversion costs, reduction or increase in energy consumption from the machine, and increased or decreased efficiency of the equipment. Any lubricants or SLMs that extend the life of the equipment also need consideration and need to be rated accordingly. Other factors include potential reduced labor for maintenance (if lubricant life can be extended), reduced maintenance parts costs, reduced fluid replacement intervals, reduced or alleviated environmental costs, and improved image costs. The New Cumberland study illustrated several of these considerations (see Table 15). Many times switching to an EAL can introduce risk of damage to equipment if not selected correctly. EALs should have the same performance requirements as mineral oil based lubricants.

9.3 Pilot studies

A pilot study or multiple pilot studies at USACE lock and dam sites could give critical data for the assessment of sustainable and standardization practices in navigational structures. Essentially, these studies would provide a “proof of concept” for either EALs or SLMs. This work is already being done in NWD for in-water greases as described in Chapter 8 of this report and a pilot study could be a follow-on to that work. The plan would be to test specific EAL greases on a miter gate pintle, a sector gear and pinion, and a tainter gate trunnion bearing. At Troy Lock in New York State, an EAL grease is currently being evaluated for the miter gate pintle. However, it is proving difficult to find a suitable EAL grease. This is but one example of the difficulties in selecting an EAL grease over a mineral oil grease. There is limited guidance and direction.

It is recommended to initiate three pilot studies for EAL grease on lock and dam pintle bearings. This work is already being done in the Northwest Division at Little Goose, McNary, Bonneville, and Lower Granite Locks and Dams (Portland and Walla Walla Districts 2016c). As such, this pilot study would be a follow on to the work in NWD. One site could be the Chicago Lock, one site on the Upper Mississippi River, and one site on the Illinois Waterway. The Chicago Lock has already been using “food grade” grease for the sector gate pintle bearings. In addition, there should be a study evaluating EAL grease for tainter gate trunnion bearings. This work is also being done in NWD at Lower Granite Lock and Dam (Portland and Walla Walla Districts 2016d). So the pilot study would be a follow on to that work. This pilot study could be done on both the Upper Mississippi River and Illinois Waterway.

A pilot study is recommended to include a hydraulic system for a miter gate and tainter valve drive system at one or several USACE locks and/or dams. This would be an opportunity to evaluate and assess the performance of various synthetic hydraulic fluids, biobased hydraulic fluids, and EALs. The study could also look at the performance of any current hydraulic systems in use that are using non-mineral oil based hydraulic fluids such as Folsom Dam. The Illinois Waterway and the Ohio River both have multiple lock sites that use hydraulic drives. As such, this pilot study could be conducted at one of these sites.

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Appendix A: U.S. Coast Guard Technical Report 262

This Coast Guard technical standard provides the general information, requirements, and guidance necessary for the use, testing, and analysis of lubricating oils and systems. The standard covers a wide range of topics including lubrication fundamentals, properties of lubricants, and lubricant types and applications. Although the standard is focused on floating plant, many of the topics in the standard are directly applicable to USACE civil works.

The standard includes a detailed lubricant sampling guideline and discussion of lubricant testing. The standard also provides a detailed oil analysis program.

Appendix B: REMR EM-MM-1-1 and EM-5

These reports, which dates back to 1989, includes a discussion of lubrication fundamentals. The report EM-5 includes a lubricant survey of USACE field sites and selection criteria for a range of mechanical equipment

Appendix C: Environmentally Acceptable Lubricant Grease for Hydropower – U.S. Army Corps of Engineers Portland District – July 2015

Sub-Title: Technical Feasibility Analysis for Eight Hydropower Facilities in Washington and Oregon

The U.S. Army Corps of Engineers (USACE) Hydroelectric Design Center (HDC) contracted with HDR Engineering, Inc. (HDR) to assess the technical feasibility of switching from conventional greases to EALs) on certain in-water hydroelectric plant equipment. The feasibility of switching to EALs was assessed at the following power plants: Bonneville, The Dalles, John Day, McNary, Ice Harbor, Lower Monumental, Little Goose, and Lower Granite. EALs are being evaluated for use on turbine wicket gate bushings and powerhouse balance of plant lifting equipment that may become submerged such as crane hooks, lifting beams and wire rope. The study objective focused on technical feasibility and whether one or more EALs can be used without risk of damage to existing plant equipment.

Appendix D: Bureau of Reclamation FIST 2-4, Lubrication of Hydropower Equipment

Although this is Bureau of Reclamation technical report focuses on hydropower, it is also directly applicable to all USACE civil works. The proper selection and use of lubricants, as well as the care and operation of lubricating systems, is an essential part of any powerplant maintenance program. Any piece of equipment with moving parts depends on some type of lubricant to reduce friction and wear and to extend its life. This document discusses lubrication fundamentals, lubricant characteristics, additives, maintenance of lubrication systems, and the selection of lubricants for common powerplant equipment. The report provides a lubricant selection guide for turbine oil, wicket gates, gears, wire rope, and radial gates (tainter gates). The content of this report can provide a basic understanding of lubrication theory and the characteristics of lubricants essential to choose an appropriate lubricant for a particular application, and to maintain the lubricant's effectiveness.

Appendix E: Memorandum on Clean Water Act Compliance at USACE Hydropower Facilities

This memorandum provides guidance on the operation and maintenance of USACE hydropower facilities, in accordance with Engineer Regulation (ER) 200-2-3 (Environmental Compliance Policies), Chapter 11-1, specifically regarding compliance with the Clean Water Act (CWA). This guidance identifies management practices that should be considered, where economically practicable and technically feasible, for implementation at USACE hydropower facilities. This guidance refers to normal operations and does not address actions that may be required to respond to a spill of regulated substances.

Appendix F: Defense Logistics Agency (DLA) National Stock Numbers for Lubricants

This spreadsheet provides the National Stock Numbers (NSN) and military standards for fuels and lubricants provided by DLA.

Appendix G: ERDC - Evaluation of Environmentally Acceptable Lubricants at non-Hydro Facilities for NWD and NWW Dams – August 2015

This report focuses on two questions:

1. Are EAL greases available for use at multipurpose facilities (dams) for non-hydropower application? And,
2. Do these EALs meet performance needs?

A separate study was conducted evaluating candidate greases for hydropower applications (HDR 2015). Although applicable to all U.S. Army Corps of Engineers (USACE) dams, this project particularly focused on dams in the Columbia and Snake Rivers, which are under the management of the Portland and Walla Walla Districts (NWP and NWW respectively), and which are both part of the Northwest Division of the U.S. Army Corps of Engineers.

Appendix H: ERDC DOTS 16-1 - Understanding, Classifying, and Selecting Environmentally Acceptable Hydraulic Fluids – August 2016

The objective of this technical note is to educate USACE end users (boat operators, plant managers, lock and dam operators, project managers, supervisors, etc.) about the use of environmentally acceptable hydraulic fluids. This document presents the USACE definition and classification criteria for an environmentally acceptable hydraulic fluid, along with considerations for selecting an environmentally acceptable hydraulic fluid. This technical note is intended to provide basic knowledge and understanding for end users considering the use of environmentally acceptable hydraulic fluids.

Appendix I: Draft Guide Specification for an EAL Grease

This appendix provides a guide specification for purchasing EAL grease. It is emphasized the specification is only in draft format. One consideration is the viscosity of EAL grease for gate trunnion applications and miter gate and sector gate pintles. Recent investigations have shown the difficulty of finding an appropriate EAL grease that meets the target viscosity requirement.

Appendix J: Army Oil Analysis Program AOAP TB 43 -0211 – 1 December 2004

The Army Oil Analysis Program (AOAP) is part of a Department of Defense program to detect impending equipment component failures and determine lubricant condition through on-line and laboratory evaluation of oil samples. The application of laboratory non-destructive analytical techniques allows flight safety to be improved, equipment readiness to be enhanced, and resources to be conserved. Program Manager (PM) AOAP provides operational management of the oil analysis program. Army Regulation (AR) 750-1, *Army Materiel Maintenance Policy* prescribes the objectives, policies, and the responsibilities of commands participating in the AOAP. This technical bulletin must not be interpreted to imply that AOAP minimizes the need to employ good maintenance practices and strong maintenance discipline. AOAP is an effective maintenance diagnostic tool and not a maintenance substitute.

This technical bulletin identifies equipment enrolled in the AOAP, provides instructions on taking oil samples, and provides guidance for installation and unit management of AOAP operations. This publication also gives the equipment maintainer needed information regarding what supplies to obtain, how to prepare forms, where AOAP laboratories are located, and where to seek assistance when unusual situations are encountered and appropriate information is not contained herein.

Tables list data on the sampling frequency for a variety of equipment, some of which is applicable to USACE civil works.

Appendix K: Bureau of Reclamation FIST 4-1A

This appendix provides the Bureau of Reclamation document FIST 4-1A that establishes minimum recommended practices for maintenance of mechanical equipment in Bureau of Reclamation hydroelectric power and large pumping plants. Included in this document are recommended maintenance activities, maintenance interval, and references.

Appendix L: EAL Survey

This appendix provides the results of the EAL survey among USACE civil works.

Appendix M: USACE St. Paul District Lubrication List

This appendix provides a listing of the lubricants used on the St. Paul District Locks and Dams.

Appendix N: Test Report for a Miter Gate Gearbox at Lock and Dam 4

A test report is provided for the gearbox oil at Lock and Dam 4 on Mississippi River.