ELECTRIC POWER RESEARCH INSTITUTE

Using Environmental Solutions to Lubrication at Hydropower Plants

A Hydropower Technology Round-Up Report, Volume 1

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TR-113584-V1

Final Report, November 1999

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CITATIONS

This report was prepared by

HCI Publications
410 Archibald Street
Kansas City, Missouri 64111

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This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Using Environmental Solutions to Lubrication at Hydro Plants: A Hydropower Technology Round-Up Report, Volume 1, EPRI, Palo Alto, CA: 1999. TR-113584-V1.

REPORT SUMMARY

Hydropower owners and operators are confronted with the dual challenge of compliance with continually-developing environmental regulations and increasingly vigorous competition in the electric generation market. Managing this challenge requires consideration and selected application of new and emerging strategies and technologies. This volume of EPRI's Hydropower Technology Roundup Report presents an overview of research, practices, lessons learned, and some examples regarding the use of self-lubricating materials and environmental lubricants at hydro facilities.

Background

Hydropower owners and operators are continually investing in plants to increase the value of output, add capacity, improve reliability, reduce operating and maintenance expense, extend plant life, and comply with environmental and safety regulations or voluntarily-imposed standards. Many owners are paying particular attention to minimizing or eliminating their facilities' negative environmental effects, including reducing the risk of discharge to receiving waters, by incorporating self-lubricating materials into projects and using environmentally acceptable lubricants. This first volume of the Technology Roundup report focuses on these technologies and strategies for their implementation.

Objective

- To describe the application of self-lubricating materials in hydro rehabilitation and upgrade project components
- To discuss the availability and application of environmental lubricants
- To present "lessons learned" in these areas

Approach

The investigators assembled and reviewed recent pertinent conference reports, publications, other literature, and audiotapes of roundtable discussions on self-lubricating materials and environmental lubricants. They contacted individuals known to have significant experience in the selected areas and invited them to share additional information and perspectives. The team chose for presentation example applications and case studies involving hydro facilities of all ages, types, and sizes, located in North America and worldwide. To the extent appropriate, they made generalizations concerning the applicability and benefits of the strategies and technologies implemented in these applications

Results

Environmental enhancement is commonly an objective of improvements to hydro systems, plants, units, and individual components and frequently entails the modification of equipment to incorporate self-lubricating materials or use environmental lubricants. The topics presented in this report discuss approaches to incorporating self-lubricating materials into hydro plant components in order to improve performance. Numerous "lessons learned" gleaned from the literature or offered by contributors are presented to assist others in the consideration or application of these strategies and technologies.

EPRI Perspective

Faced with cost competition, increasing environmental standards, and on-going licensing requirements, hydropower owners need to know about the technology options available and under development to make their facilities more compliant, protective of the environment, and competitive. They need information about the benefits and costs of alternative technologies and the successful practices and strategies used for their implementation. EPRI's Hydropower Technology Roundup report series will provide a clearinghouse for worldwide information on key topics and new and emerging technologies, including case studies and contacts. This volume presents an overview of research, practices, lessons learned, and some examples regarding the use of self-lubricating materials and environmental lubricants at hydropower facilities. Technology Roundup reports are published several times a year.

TR-113584-V1

Keywords

Bearings/Bushings
Environmental Lubricants
Self-Lubricating
Upgrade (ing)

ACKNOWLEDGMENTS

Special thanks and acknowledgment is made to those individuals and organizations whose assistance and gracious input were key to the development of this report. The following contributors provided information and perspectives via personal communication:

Alfred D. Beitelman - U. S. Army Corps of Engineers, Construction Engineering Research Lab, Champaign, Illinois

Alan R. Christensen - U. S. Army Corps of Engineers, Portland, Oregon

Leslie J. Hanna - U. S. Bureau of Reclamation, Water Resources Research Laboratory, Denver, Colorado

Thomas W. Jenkins - PECO Energy, Darlington, Maryland

John A. Jones, P.E. - U. S. Army Corps of Engineers, Hydroelectric Design Center, Portland, Oregon

Rick A. Palylyk - Powertech Labs, Inc., Surrey, British Columbia

Hans Schellhase - Powertech Labs, Inc., Surrey, British Columbia

Thomas Treat - Public Utility District No. 1 of Chelan County, Wenatchee, Washington

Kerry Trottier - TransAlta Utilities, Calgary, Alberta

Randall Walter, P.E. - Public Utility District No. 1 of Chelan County, Wenatchee, Washington

The assistance of Marla Barnes and Catherine Bennett at HCI Publications for providing reference materials and permitting the use of HCI files was essential to the research for this report and is acknowledged, with appreciation.

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1 INTRODUCTION

In 1998, as part of its core program in the hydroelectric generation area, EPRI initiated the "Hydropower Technology Round-Up" project. The objective of the project is to prepare periodic "Tech Round-Up" reports to disseminate useful, world-wide information related to hydro power technological advancements.

The scope of the investigation brought to you in this report has been broad, including both U.S. domestic and international utilities and companies having international experience. This report presents an overview of research, practices, lessons learned, and some examples regarding environmental solutions to lubrication, specifically, utilizing self-lubricating materials and environmental lubricants at hydro facilities.

Situation

The onset of the competitive market for generation of electricity in North America and elsewhere has intensified interest in maximizing the economic efficiency of conventional and pumped storage hydro plants. Customer choice initiatives, the Kyoto Protocol to reduce greenhouse-gas emissions, and ever-stricter environmental regulations have increased the focus on the environmental compatibility of hydro generation. At the same time, market prices for energy and generating capacity are relatively low and are projected to remain so for the foreseeable future, as markets move to open pricing.

To sustain hydro's efficiency and competitiveness requires implementation of improved, more cost-effective maintenance and operating practices and the commitment to applying technological advancement.

Significant investment is often needed to improve many hydro plants–particularly older, conventional plants–to restore or sustain efficiency and competitiveness, and to meet environmental objectives. However, economic justification of needed investments is often very difficult. Recent improvements in technology, particularly in the areas of hydro-turbine and component design and manufacture, control equipment and instrumentation, and improved life and maintenance management, have greatly enhanced the prospects for increasing production and economic efficiency, and extending the life, of existing hydro plants.

Trends in the use of Environmentally Friendly Lubrication

A major rehabilitation project provides the best opportunity for change and improvement of plant components, particularly lubrication systems. Nearly one-third of the projects reported in a survey conducted in conjunction with the Hydro Vision 98 conference held July 1998 in Reno, Nevada [1] had been specified with environmentally superior technology for new plant equipment. Respondents also reported that 18% of the projects accomplished a reduction of environmental risk. The most commonly reported environmental practice is reducing the use of lubricants by the installation of self-lubricating or greaseless bearings and bushings, and/or the use of oil-less or low-oil governors.

Report Organization

The remainder of this report is organized as follows:

Section 2 - Using Environmental Solutions to Lubrication

Section 3 - Self-Lubricating Materials

Section 4 - Environmental Lubricants

The topics presented in this report revolve around approaches to incorporating self-lubricating materials into hydro plant components in order to improve performance. Table 1-1 lists projects that have implemented the use of self-lubricating materials; projects discussed in this report are indicated in Table 1-1 by asterisks (*).

Each section contains a "lessons learned" subsection, presenting some general guidance based on the experience of the contributors.

References are listed at the end of each report section. Lists of contacts for various owners, suppliers, and manufacturers involved in programs and projects discussed in this report are contained in Appendix A.

Reference

1. *Hydro Rehabilitation Practices: What's Working in Rehabilitation*. HCI Publications, Kansas City, MO, 1998.

Table 1-1
Projects Utilizing Self-Lubricating Materials

Project	State (U.S.), Province (Canada)	Owner
*Big Creek 8	California	Southern California Edison Company
Blenheim-Gilboa	New York	New York Power Authority
Bonneville	Washington/Oregon	U.S. Army Corps of Engineers
Buchanan	Texas	Lower Colorado River Authority
Bull Run	Oregon	Portland General Electric
Chippewa Falls	Wisconsin	Northern States Power
*Conowingo	Maryland	PECO Energy
*Dardanelle	Arkansas	U.S. Army Corps of Engineers
Deer Lake	NA	Deer Lake Power. Co. Ltd.
Forbestown	California	Oroville-Wyandotte Irrigation District
*G.M. Shrum	British Columbia	BC Hydro
Ghost GS #3 Ghost GS #4	Alberta	TransAlta Utilities
Jim Falls	Wisconsin	Northern States Power
Kamargo #1 & 2 Minetto #4	New York	Niagara Mohawk Power Corporation
Kelly Ridge	California	Oroville-Wyandotte Irrigation District
*Kootenay Canal	British Columbia	BC Hydro
Ladysmith	Wisconsin	Northern States Power
Lewiston	New York	New York Power Authority
Mc Nary Dam	Washington/Oregon	U.S. Army Corps of Engineers
*Mica GS #4	British Columbia	BC Hydro
*Mica GS #3	British Columbia	BC Hydro
*Muddy Run	Pennsylvania	PECO Energy
Pit No. 1	California	Pacific Gas & Electric
*Revelstoke	British Columbia	BC Hydro
River Mill	Oregon	Portland General Electric
Robert Moses Niagara	New York	New York Power Authority
*Rock Island #2	Washington	Chelan County PUD
*Rocky Reach	Washington	Chelan County PUD
Ross Powerhouse	Washington	Seattle City Light
White River	Wisconsin	Northern States Power

* Projects discussed in Part 1

2 USING ENVIRONMENTAL SOLUTIONS TO LUBRICATION

Hydro's long-term standing as a reliable, low cost source of power supply is challenged by the costs of rehabilitation and re-licensing, while at the same time, electric competition and utility restructuring also drive the overall sector to reduce production costs. Environmental certification and "green" energy awareness are of increasing importance in the electric generation market in the U.S. and abroad. With the advent of electricity deregulation and increased consumer awareness, producers of electricity are forced to consider both the production cost and the composition of the energy mix provided. With customer choice, the source and make-up of generation supply will become more important and visible.

The consideration and use of environmental lubricants as part of a maintenance strategy is one approach to enhance environmental compliance. While "environmentally friendly" product use for lubrication may not provide immediate cost savings, the benefit is to improve response in the event of a spill and decrease the risk of environmental pollution.

The research and applications of incorporating self-lubricating materials into equipment, either during initial design or rehabilitation, is a recognized solution to provide long-term reduction in maintenance requirements and improve environmental operation.

Driving Factors

Why then turn to environmental solutions to lubrication? In developing a strategic plan for rehabilitation or maintenance that incorporates environmental awareness, the options become a trade-off between cost and environmental risk. The use of alternatives to traditional lubrication systems or material use may be driven by other qualitative factors in the overall electricity production process as discussed below. Environmental stewardship, embracing not only the required regulatory compliance but also voluntary extra effort, has the potential for achieving benefits. This is especially valid as deregulation, risk assessment, environmental certification, and green power marketing become more commonplace.

Maintenance Optimization in a Deregulated Industry

In the new electric generation industry, management challenges include doing more with less, producing power with ever-greater reliability, and being environmentally conscious and cost-effective. During the re-engineering of maintenance tasks, redefined goals of the generation business units change the character of operation. Dealing with these changes requires flexibility among both technicians and management.

Maintenance programs are increasingly being geared towards condition-based maintenance, with longer intervals between routine surveillance and maintenance. Major overhauls of critical components are being extended, and the "in-service" maintenance without loss of generation is also being required. Staff reductions and industry consolidations modify the expectations of the character and importance of maintenance programs. It is within this context that the opportunities for consideration and use of environmental solutions to lubricating systems are appropriate.

Risk Assessment

Traditionally, electric utilities developed oil Spill Prevention Control and Countermeasure (SPCC) plans consistent with current regulations. Proactive secondary containment and contingency plans for components and systems, particularly in high-risk areas may be more difficult to implement. The principles of risk assessment–to determine the relationship between the probability of a spill incident and the environmental sensitivity of the facility–have been used to prioritize maintenance and rehabilitation plans.

As part of BC Hydro's Oil Spill Containment program, the utility's Oil Spill Containment Working Group suggested a target acceptable risk for each facility. [1] This target risk factor was defined as the equivalent of a 10 percent probability that significant environmental damage would occur from an oil spill at a moderately sensitive site, once in 10 years. This quantitative target then allowed mangers to assess and design oil spill containment or alternatives, to cost-effectively reduce the risk to the target level at each facility, on a priority basis.

The containment or alternative measures were implemented in priority of greatest environmental risk reduction per dollar spent. This resulted in implementing measures to bring facilities outside the targeted risk within the boundaries first, with others implemented at later dates. Hydroelectric station powerhouses were reviewed first and, subsequently, associated switchyard facilities. The alternatives identified as part of this oil spill containment or reduction program were part of the impetus for the research on environmentally friendly fluids and self-lubricated bushings initiated by BC Hydro, described later in this report.

Environmental Certification ISO 14000

Another reason for potential movement to the use of environmental solutions to lubrication is the increased impetus, even in the absence of regulation, to meet voluntary environmental standards.

The International Organization for Standardization (ISO) 14000 for implementing effective environmental management systems is an international standard designed for individual companies to set their own environmental goals and commitments to environmental policy. The standard then guides the company to formulate a plan and carry out a policy to identify significant activities that affect the environment in the production of a good or service. The company then trains personnel in environmental practices, and creates an internal audit review system to ensure the program is implemented and maintained. A registration audit by a third party may be carried out, and subsequent surveillance audits may be conducted to maintain registration. An alternative method is for a company to perform an internal review and evaluate itself for conformity with the standards.

As highlighted in a 1998 EPRI Journal article, worldwide movement for accreditation in all sectors of industry is increasing. [2] The power industry is no exception. The ISO 14000 Info Center reports that 11% of the US companies registered as of June 1998 represent the power/utility sector. The framework of ISO 14000 is a flexible set of criteria, which is aimed at improving the process of environmental management, not measuring pollution. The criteria encourage setting goals and seeking ways to implement and measure progress towards achieving better environmental performance. Further information on the ISO certification process can be found on the ISO web site: www.ISO.com.

What does the consideration of either implementing environmental lubricants into maintenance or retrofitting equipment with self-lubricating materials mean within the framework of ISO 14000 certification? Clearly, as an element to an overall plant environmental management objective, any material accommodation or substitution, or equipment modification undertaken to prevent or minimize pollution, or emission risk can be included as an aspect of the plant's goals for environmental management. [3] For near-term solutions, moving towards the use of environmental lubricants in maintenance situations where equipment is not economically ready for retrofit may be appropriate. Consideration for retrofit during major overhauls may also be a longer-term goal, which also complies with the intent of the process.

While there are still many outstanding questions about market and regulatory acceptance of the standards, the implementation of environmental management goals promotes environmental stewardship and encourages alternative solutions.

"Green" Energy

As energy marketers try to ascertain the best way to capitalize on the new consumer choice in electricity generation, the definition of green energy is similarly a moving target. Perceptions of clean, green, renewable energy, and the beginnings of informational disclosure of energy labeling have, in the short run, allowed for reported premiums in green rates, using environmental advantage as a marketable quality. Qualitative packaging and certification programs have been developed to meet the informational need; power content labeling, effective in states that have customer choice, may help to validate the promotion of the product. Following principles similar to those involved with ISO 14000 certification, scientific approaches to environmental green claims are beginning to develop. While these certifications and evaluations of generation sources are under development and debate, it can be expected that a hydro owner or operator will be asked to incorporate additional environmental measures into hydropower maintenance, in order to benefit from the prospective green market advantage.

Using Environmental Solutions to Lubrication

The impetus to reduce environmental risks in the overall operation plan and increase stewardship is only beginning to become apparent in the electric industry. However, following the paradigm of other industries that have been through deregulation, cost, consumer perception, and reliability all play important roles in the success of the product or service.

The need to sustain reliability of hydro component systems may allow for improving maintenance by utilizing technology with the application of environmental lubricants or, alternatively, retrofits using self-lubricating or greaseless materials. While these practices by themselves will not enable a power producer to become more competitive, they are among the advantageous practices available to place hydropower in a position of demonstrating sound environmental stewardship.

References

1. H. Schellhase, Powertech Labs, Inc., personal communication, October 1998.
2. "Environmental Management with ISO 14000." *EPRI Journal*, March/April 1998, p. 24.
3. P. Radcliffe, EPRI, personal communication, October 1998.

3
SELF-LUBRICATING MATERIALS

Self-lubricating materials are increasingly being considered for incorporation into equipment during initial design and rehabilitation projects. Despite the traditional use of oiled systems to provide a good lubrication surface, operation and maintenance difficulties can occur over time. The incorporation of greaseless, or self-lubricating, bearings and bushings has been applied worldwide, owing to increased environmental pollution concerns and overall reductions in long term bearing-related maintenance costs.

As noted in the HydroVision 96 Operations Best Practices Survey, 53 different hydropower producers reported the following: [1]

- 76% of the respondents identified bearing oil analysis as one of the prime indicators for scheduling hydro units for overhaul (Chart 21)
- 43% of the respondents installed greaseless bushings as part of a major overhaul (Chart 22)

With the expectation for hydroelectric projects to be rehabilitated in the next 20 years perhaps exceeding 30,000 MW in the U.S. alone, the opportunity to employ this technology is significant. Moreover, with the increased emphasis on long-term performance, reliability, and environmental stewardship, evaluation of new materials for incorporation into hydroelectric rehabilitation remains in the forefront.

Discussion of Technology

A variety of manufacturers have produced self-lubricating materials for applications in mechanical equipment. Self-lubricating materials incorporated into bearing surfaces, by their nature, negate the use of oil or grease. In the literature, the “self-lubricating” technology is interchangeable with “greaseless bearings.” These materials all have some sort of solid lubricant incorporated into their structure. This is accomplished by combining solid lubricants within the metal structure under high heat and pressure.

The key advantages of self-lubricating bearings include:

- No requirements for ancillary lubrication systems
- Reduction in operation and maintenance costs
- Elimination of environmental risk for lubricants being released into the water

This section discusses a body of recent research primarily developed by the U.S. Army Corps of Engineers, Hydroelectric Design Center, in conjunction with Powertech Labs over the period 1993-1998 entitled, "Greaseless Bushings for Use in Hydropower Applications." [2] Portions of this material, particularly the "Development of a Rating System for the Selection of Greaseless Bushings" have been presented in proceedings and publications. [3,4] However, some recent updates have been noted, including an extension of results data to three decimal places to account for minute differences in performance that affect the results of the rating system.

Applications

Bronze, the traditional material employed in linkage systems, has required an automatic lubrication system to dispense its necessary lubricants. This system, while providing successful service, is not without problems. Targeting the specific problem areas with self-lubricating materials has been the focus of the manufacturing to date. These applications have included:

- Turbine wicket gate stem bushings–upper, intermediate, and lower
- Wicket gate operating ring and linkage
- Turbine blade operating linkage
- Turbine blade trunnion bushings
- Ancillary applications such as sliding surfaces of gates, valves, etc.

Specific Benefits and Advantages

Operating temperatures within turbine-generator housings can vary widely, particularly in the generator and with the on-off cycling of the units. Excessive load can lead to deformations of malleable bronze bushings, as can water turbulence in some applications. Water in the lubricant can cause oxidation, which may contribute to wear.

In order to provide an external lubricant, the delivery system adds cost, requires maintenance, and is a source of potential malfunction. Improper wear characteristics, such as shaft galling or binding from lack of lubrication to a particular area, are difficult to detect and expensive to repair.

It is desirable to avoid using quantities of grease and oils in proximity to any waterway, particularly in remote and unattended applications.

Costs, Limitations, or Disadvantages

Data on installation costs at new plants is limited; however it can be said that some attendant reductions in grease and oil lubricant delivery systems components will be realized. In addition, savings would be realized in the costs of maintenance of lubrication systems, including monthly or quarterly testing, and costs for replacement, cleanup, and disposal would be avoided.

It appears that replacement of existing systems with greaseless bushings is most often driven by environmental concerns rather than economics. Major unit overhauls provide the greatest opportunity for retrofitting self-lubricating bearing systems, thus enabling realization of reduced maintenance requirements along with improved environmental performance.

Status of Implementation

Major rehabilitation projects often provide the opportunities for upgrading bearing lubrication systems. The recent Hydro Rehabilitation Practices: Results of Industry Benchmarking Survey, found that in nearly 20 of the 66 projects surveyed, owners employed environmentally superior technology in the specification for the new plant equipment. [5]

The most commonly reported practice for environmental considerations was in reducing the use of lubricants through installation of greaseless bushings and oil-less or low-oil governors.

Recent R&D Completed

In a recent project initiated by the Corps of Engineers and carried out by Powertech Labs, in Surrey, British Columbia, thousands of hours of laboratory testing were conducted on various greaseless bushings. [2] The intent of the testing was a major effort to replace greased or oiled bearings with self-lubricated bearings at Corps hydropower and waterways projects. The driving forces for this work were to reduce environmental pollution of waterways and to reduce the cost of maintenance of the equipment. The Corps also saw a particular opportunity for achieving these goals, since major overhaul of the Corps facilities are expected in the next several years. The characteristics and performance of various materials for bearings and bushings (terms which are used interchangeably) are the areas within a hydro turbine installation which have the most likelihood for providing environmental benefits and labor reductions.

These data from test results, comparing a variety of performance characteristics, have also been applied in a rating system that allows the appropriate selection of self-lubricating (greaseless) bushings for use in hydropower applications.

The rating system and charts developed by the Corps is contained in Appendix E, pages 7 to 17 of Reference 2*; Greaseless Bushings for Use in Hydropower Applications*. Table 3-1 is an attempt to illustrate the ratings, however, for a full understanding of the direct selection of bearing materials for specific applications, the rating charts in the Appendix should be used. These are as follows:

1. Static coefficient of friction–preferably less than greased bronze.
2. Dynamic coefficient of friction–again, preferably less than the traditional material.
3. System change in strain energy vs. bearing “stick-slip” ratio (static to dynamic).

   The concept of stick-slip ratio (static coefficient of friction divided by the dynamic coefficient of friction) was originally included in the 1997 work done by the Corps on the rating system. [3,4] Subsequent review modified the rating system to a system change in strain energy concept. [2] This modification takes into account the change in a turbine bearing system as it transitions from a static operating condition to a dynamic state of sudden motion. This modification to the rating system more accurately reflects the smooth operation of bearings/materials and changed the evaluation of certain materials from the original 1997 results.

4. Wear rate–defined as wear per 100 test hours. Less wear is desirable in comparison to bronze.
5. Damage susceptibility–three measures:
   a) Breakdown under edge loading–none is desirable/expected with bronze; detectable and apparent breakdowns with the self-lubricating materials results in a penalty.
   b) Bond breakdown from edge loading–none is the baseline; detectable breakdown is unacceptable and penalized in the rating system.
   c) Peeling from substrate–a measure as to whether the material is peelable from the substrate. There is a graduated penalty in the rating system since bronze exhibits no peeling as the base case.
6. Apparent surface damage–none desirable after loading; penalties applied if surface scoring and scratching was visible to the eye.
7. Bearing material thickness, as compared to a standard of 0.04 in. (1 mm).
8. Insurance provided by manufacturer was rated a small plus.

The testing provided a quantitative measure of a variety of commercially available products in a replicated hydro environment. The development of a process for testing a number of materials under a variety of applications, and designing a systematic approach for specification and selection of bearings for performance needs, provide a useful tool to the hydroelectric industry.

Experience and Results

A pressing need in implementing the use of any new technology is examining service life expectancy, which drives the capital cost cycle as well as the operation and maintenance requirements. Bushing design life of 15 to 25 years is often reported and, therefore, the body of knowledge available in this particular application is limited. A number of recent rehabilitation projects have incorporated self-lubricating materials, so future investigations can shed more light on this important topic. A list of known project applications is presented in Table 3-2.

Initial reports of difficulties with self-lubricating material applications spread quickly. Much of the information was anecdotal, and information exchange was hampered by a lack of formal mechanisms for sharing experience. Reports and rumors, coupled with the overall adequate performance of the traditional lubricated bearing materials–despite their environmental and maintenance costs and concerns–slowed the application of the technology. With the increase in the 1980s of new small hydro design and construction, some opportunities arose for application of self-lubricating materials. Now, with these units in service for 10-plus years, further field operating experience is evolving.

Prior to the extensive testing by the Corps of the applications of materials, claims as to length of service were generally limited to the manufacturers' published literature. In many cases the literature did include testing results, yet provided only "apples to oranges" comparisons.

Difficulty in applying the emerging technology in practical applications has been noted by several hydro producers. The Corps reports that most of the early experience with greaseless bushings was negative. This experience related to bearings that use lubricant plugs, and was attributed to the fact that these materials performed poorly in small movement applications. Testing and field verification generally pointed to the fact that most continuously loaded machines actually have only small movements. [2]

BC Hydro Experience

In the mid-1980's BC Hydro noted some developing problems with self-lubricating bushings at several of their rehabilitated hydro generating stations. [6] As a consequence of these experiences, Powertech Labs, a subsidiary of BC Hydro, began an ongoing testing program. The following four project experiences are a further application of the rating and testing methodology.

The Gordon M. Shrum Generating Station (GMS) is the largest power plant in the BC Hydro system, with 10 Francis generating units producing 2725 MW. The plant is located in the Peace River Basin at the 183-meter Bennett Dam. The dam was constructed during 1961-1967, and the first three units were commissioned by 1968. The remaining seven units were in service in 1980.

In 1986-87, after approximately 15 years of operation, Unit #6 had experienced many greasing problems such that the wicket gate bushings had worn significantly to cause gate misalignment. There was sufficient water leakage to hinder stopping the units with the brakes, thus requiring the closing of the intake gates to stop the unit. The unit was rebuilt with self-lubricating bushings (Thordon SXL) as an alternative to greased bronze bushings and, secondarily, to prevent grease entering the environment.

After Unit #6 had been in service for approximately two years, shear pins were failing on the wicket gate shafts. This was traced to increased friction from the wicket gate shafts. Control of the wicket gates became a concern to the point that it was decided to again replace the bushings. This entailed a cost of approximately C$650,000. The bushings were replaced with another manufacturer's self-lubricating bushings and have been operating satisfactorily since then. Units at GMS have also reported smaller linkage pin bushing failures due to foreign debris entering the interface, and operating ring bearing surface failures.

This major problem with self-lubricating bushings prompted BC Hydro to initiate a program to assess the performance of the various self-lubricating bushings on the market. The U. S. Army Corps of Engineers adopted the program and funded further testing (with enhanced test conditions) as described above. This was eventually supported by the self-lubricating bearing manufacturing industry by having their products tested under the same accelerated wear conditions.

The 1736-MW Mica Generating Station of BC Hydro, located on the Columbia River is the largest of three dams in British Columbia that were developed under the Columbia River Treaty, during 1967 to 1973. Mica Dam, a 250-meter earthfill structure, has the highest head (200 meters) and is the only installation of the three to have a powerhouse. The Mica G.S. has four Francis generating units, each rated at 434 MW, located in an underground powerhouse, commissioned in 1977. The present capacity captures most of the energy available. There is provision for two additional units which can be installed when additional capacity is required.

Mica G.S. has had two units rebuilt, Unit #3 in 1990, and Unit #4 in 1992. Both units had replacement self-lubricating bushings (Thordon SXL) in the wicket gates as part of the rebuild. On both machines, the upper wicket gate bushings were found to be breaking down and had to be replaced after five years of service. The intermediate wicket gate bushings were functioning correctly. The upper wicket gate bushings were replaced with alternative materials (Tenmat T814 for Unit #3 and Thordon HPSXL for Unit #4) which had rated higher in the testing and rating system, at a total cost of approximately C$80,000 in down-time, labor and material costs. After three years and one year respectively, the new replacements have been satisfactory.

The 548-MW Kootenay Canal Generating Station, located on the Kootenay River, in south-central British Columbia, has four Francis units, each rated at 137 MW, that were commissioned in 1975.

Starting in 1994, the units were refurbished, one unit a year, with higher efficiency turbines. After one year of service, Unit #2 wicket gate thrust washers were failing. Examination of the failures indicated the self-lubricating material (Thordon SXL) was de-bonding (peeling) from the bronze backing. The area was retrofitted with an alternate material (Karon V) that had been tested and rated more suitable for the application. The retrofit has been in service for approximately two years and appears to be performing as expected.

The Revelstoke Generating Station is located on the Columbia River, downstream of Mica Dam. The concrete gravity dam was completed in 1984. About 70% of the river flow at Revelstoke is discharge from Mica; the remaining 30% is from local inflow. The Revelstoke G.S. is the second largest power plant in the BC Hydro system, with four generating units producing 1843 MW. There is provision for two additional generation units. Revelstoke operates as a run-of-river generating station.

After 12-13 years of operation, the force required to operate the wicket gates on Unit #4 had increased to the point that gate control was difficult. The original greased-plugged bronze self-lubricating bushings were identified as being the problem affecting loss of lubrication during operation. In particular, Unit #4 was under automatic governor control (AGC) from utility system control. This resulted in many small oscillations of the gates over a long period of time. These small fluctuations following the demands of the system, did not allow for distribution of the lubricant. The other units were also suffering from the same problem, although not to the same extent as Unit #4. The unit has been removed from AGC and is operating in a block loaded mode in the hope it will extend the life of the bushings. Eventually the bushings will have to be replaced.

Dardanelle Project, U. S. Army Corps of Engineers, Little Rock District

At the U. S. Army Corps of Engineers, Dardanelle Project on the Arkansas River, the four-unit, 124-MW powerhouse, began major rehabilitation work in 1994. [4] The project was originally commissioned in 1965. The $30 million Dardanelle Rehabilitation is the first major rehabilitation project to be authorized and funded under the Corps' Major Rehabilitation Program since it was changed in fiscal 1992. [7]

The work involves replacing four turbines at Dardanelle which includes designing, manufacturing and installing new turbines. The generators at Dardanelle also will be rewound to help increase their operating efficiency. The project is the first to be managed under a partnership agreement between the District and the contractors in charge of the work.

The original units utilized a typical greased bronze system for the wicket gate linkage. As part of the retrofit, this system will be eliminated, thus reducing the cost of labor and material for maintenance. In addition, the new system will eliminate grease clean-up of the turbine pit area and prevent wicket gate bearing grease from entering the waterway.

As part of the rehabilitation project, the selection of specific bushing material, in this case Karon V, for the retrofit applications at Dardanelle was determined based on the top rated materials from the Corps testing program. These materials are being incorporated into all four units in the following locations: wicket gate stem bushings and linkage, operating wear ring, and wicket gate servomotor guide bushings.

The Dardanelle Rehabilitation Project is scheduled to be completed in September 1999. During the work, at least three units will remain operational to enable the powerhouse to continue meeting power generation needs.

This application is the first by the Corps since performing the bearing material research and development of the rating system. The first unit became operational in 1997, and will be followed by the remaining three units. The Corps intends to conduct a more in-depth, de-watered inspection of the first rehabilitated unit in 1999.

Conowingo Hydro Project and Muddy Run Pumped Storage Project, PECO Energy

The Power Generation Group (PGG) of PECO Energy is the business unit responsible for managing the fossil and hydro generating stations of PECO Energy. Hydro resources represent 28% of PECO generation and include the 512-MW Conowingo Hydroelectric project, in Maryland, and the 880-MW Muddy Run pumped storage station in Pennsylvania. [8]

In 1993, as part of a rehabilitation of one of the 60-MW conventional diagonal flow units at Conowingo, the wicket gate linkages and servo-drives were retrofitted with self-lubricating bushings. This unit, which had been in service since 1964, had previously had an auto-greasing system, which was totally eliminated. Since the retrofit, the unit has had two de-watered inspections, and no appreciable wear has been noted. The success of this retrofit has prompted PECO to make the same modification to three more units at the station.

This improvement was undertaken as part of a major overhaul of the unit. While the benefits are hard to quantify, from a maintenance perspective, the elimination of the auto greasing system has improved the overall appearance and workability of the units. It is also noted that the long-term routine maintenance requirements for that component system and attendant costs will also be decreased.

Similarly, at the 880-MW Muddy Run pumped-storage plant, commissioned in 1964, all eight 100-MW units were retrofitted in 1997-1998 with self-lubricating wicket gate linkages, eliminating an auto-greasing system.

Rocky Reach Hydro Project, Chelan County PUD

Public Utility District No. 1 of Chelan County operates the 1287-MW Rocky Reach Hydro Project in north central Washington State on the Columbia River, about seven miles upstream from the City of Wenatchee. The project generated 7.3 million MWh during 1997, and represents a major portion of power produced in the Northwest. [9]

The District is in the midst of a major upgrade of the powerhouse, as reported in the literature. The work, budgeted at $124 million, will improve the efficiency and reliability of the hydro plant and incorporate state-of-the-art, “fish friendly” turbine runners.

In 1995, the District began replacing the adjustable-blade Kaplan turbine runners for Units 1-7, along with installing new transformers, circuit breakers, and solid state excitation. Work on new Kaplan turbines and governors for Units 8-11 began in March 1997. The project is scheduled for completion in 2001.

The original seven units at the Rocky Reach Project were equipped with adjustable blade Kaplan turbines, rated at 140,000 hp (104 MW) at 92 ft (28 m) of head and 90 rpm. The rehabilitation program consists of the replacement of the turbine runners with state-of-the-art Kaplan runners with six stainless steel blades at the same diameter and setting as the originals. The governor system is being refurbished, the main pumps replaced, the volume of the oil sump and accumulator tanks increased, and the controls upgraded.

The original Units 8-11, installed in the early seventies were fixed-blade vertical propeller units rated at 177,000 hp (132 MW) at 86.5 ft (26.4 m) of head and 85.7 rpm. The runners feature five fixed-position blades, and exhibited strong vibrations at full load, severe cavitation pitting, and turbine blade cracking, necessitating the rehabilitation. Building on the experience of the design of Units 1-7, the rehabilitation modified the design to replace the carbon steel propeller runners with new Kaplan stainless steel runners with five blades at a lower centerline setting. This conversion also included a modification of the shaft system and the addition of an oil head, as well as modifications to the stay vanes to improve flow patterns. The distributors will be refurbished and new self-lubricating bushings installed. While the new design includes a significant upgrade of the governor system at a higher oil pressure to accommodate the Kaplan runner control piping, the wicket gates and linkage bushings, and the operating ring lining will be replaced with those made of greaseless materials. [10]

Rock Island Hydro Plant #2, Chelan County PUD

The Rock Island Hydro Plant #2 was commissioned in 1978. Eight horizontal bulb turbine units totaling 410 MW were installed with greaseless wicket gate bearings that have operated dependably to date. Since commissioning, the horizontal journal and thrust bearings have been replaced with an alternate self-lubricating material. The original (1978) material was a zinc-impregnated Teflon, now replaced with Karon V. It was reported that the application of greaseless technology has saved the expense of maintaining a centralized greasing system. [10]

Big Creek 8 Powerhouse Unit No, 1, Southern California Edison

An application of a water-lubricated bearing at Unit No. 1 in Southern California Edison's Big Creek 8 Powerhouse, is also described in the literature. Unit No. 1 is a 25-MW, 514-rpm vertical Francis unit with a 15.5-in. (39.4-cm) diameter shaft. Oil discharge into the tailrace from the turbine bearing during startup had been a continuing problem. In 1994, a stave-type, water-lubricated turbine bearing was installed. The bearing staves were fabricated of 5/16-in (0.8-cm) thick strips of bearing material attached to brass backings. The shaft was hard-faced with tungsten carbide in the bearing area. The bearing water system uses filtered penstock water as makeup, supplying 30 gallons per minute (gpm) (2 liters per second) to the bearing; a closed (rather than once-through) system was adopted to minimize the problem of unwanted material in the bearing water. Bearing flow is upward to ensure flooding at all times. Cooling water for the heat exchanger is supplied from the turbine wear/seal ring system.

In a conversion to water-lubricated bearings, a change of bearing geometry could change shaft stiffness, thus changing harmonic frequency. Bearing material must be suitable for the given bearing size and shaft speed. On these systems, an automatically activated backup system is needed. The Big Creek 8 Unit No. 1 bearing is alarmed at 15 mils shaft displacement to prevent rub of seal rings. One effect was to place more load on the generator lower guide bearing. [11]

Lessons Learned

- At a 1992 North American Hydro Research & Development Forum, development of greaseless/oil less hydraulic turbine bearings was identified as a potential research area. [12] With this battery of information in hand, and as the rehabilitation market grows, the experiences of others will add to the technology base. Competitive pressures, on design engineers as well as the manufacturers, will continue to bring these technological solutions to the forefront.

For example, it is noted that:

> "As a result of the testing program there are six new products on the market, each of which performs significantly better, for hydropower applications, than the earlier products by the same manufacturers." [13]

On the topic of self-lubricated material applications for bearings and bushings, several lessons learned were suggested.

Equipment Applications

- The sharing of case studies and research on the evaluation of in-place greaseless bushings within the industry to determine merits, demerits, and performance, clearly permits proper application of the materials for use in specific equipment locations. [4,5]
- During a rehabilitation project, in converting to greaseless bushings, wicket gate shaft surfaces should be restored to roundness and newly centered. Metal sprayed surfaces may not be effective for the application and tolerances are normally reduced. The new bushings may need to be protected with seals to prevent intrusion of abrasives. [14]

Long-Term Creep Tests

- Paraphrasing from the Corps study, some bushings have extruded under test conditions and others evidenced extrusion after being placed in-service. In order to examine the effects of long-term creep, a test which would apply maximum design load for a long period is recommended. This replicates the operational condition of units fully watered up with the wicket gates closed for months at a time. [2]

Operation/Correlation Data

- Extending the test results into hydroelectric industry practice requires several methods of verification, which are ongoing. The Corps program is described in the report "Greaseless Bushings for Use in Hydropower Applications, Appendix C - Correlation of Test Results to Actual Service Life." [2] These in-situ verifications were intended to constitute a form of machine service monitoring over a period of one year on the most active units at each of four projects; two Francis units and two Kaplan units. The scope of the original monitoring was to install transducers at the servomotors of the machines to count changes in motion of either the wicket gates or the turbine blades. The intent is to monitor the small changes, which are more consistent with the long-term operation of a hydro unit in continuous operation, rather than the greater than 15% gate movements, which are representative of unit start-up or shut down and not the steady state condition.

Unfortunately, in the Corps' report, a combination of difficulties in collecting data resulted in only data from only one Francis project for a period of 4 months. However, according to the report:

> "… the program showed conclusively that between 75% and 90% of all wicket gate motions are less than 0.2% of full gate, representing approximately 0.11 degree of rotation per motion on the monitored units."

This information concluded that the test results, representing one hundred hours on the test stand, represented approximately fourteen years of actual turbine operation.

In applying the Corps data, operation correlation data would be extremely useful to an owner in predicting actual service life. Moreover, in evaluating a retrofit opportunity and application, the same type of service information, expressed as percentage of motion, could be used to improve the selection of bearing materials for the application.

Exchange of Field Experience and Information

- As the applications of self-lubricating materials continue to expand, exchange of information and experience will be useful to the hydro industry. In addition, further research and testing of self-lubricating bearings, as well as solid field experience and reports, should result in a higher confidence level for those hydro managers facing retrofit with self-lubricated bearings. [15]

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Table 3-1
Summary[1] of Corps Rating and Performance System for Selection of Greaseless Bearings

	Applications						
	Greased Bronze	**Wicket gate (WG) Linkages (LB)**	**Upper WG Stem Bushings (UWG)**	**Operating Ring Bearings (OR)**	**Intermediate and Lower WG Stem Bushings (IWG),(LWG)**	**Turbine Hub Linkage (THL)**	**Blade Trunion Bushings (BTB)**
Comparison	NA	Greased bronze	Greased bronze	Greased bronze	Greased bronze	Oiled bronze	Oiled bronze
Performance	Dry	Dry	Dry	Dry	Wet	Wet (305)	Wet (305)
						Dry (310)	Dry (305)
Number of Materials Tested[2]	1	10	10	10	11	11	11
Rating System Points[3]	255	260->400	260->400	260->400	260->400	Wet 320-420	Wet 255-420
						Dry 270-420	Dry 295-430

[1] For a complete understanding of the applicability of the rating system, refer to Appendix E of Reference 2, pages 7 and 8.
[2] Specific Manufacturers' Materials that were tested and rated are contained in Reference 2, Appendix E, pages 6-17.
[3] Points are awarded for the following performance characteristics:

1. Static coefficient of friction
2. Dynamic coefficient of friction
3. Strain Energy Area (formerly Static/Dynamic ratio)
4. Wear rate (mil/100 test hrs)
5. Damage Susceptibility: a) edge breakdown b) bond breakdown c) peeling from substrate
6. Apparent Surface Damage
7. Bearing Material Thickness
8. Insurance

Table 3-2
Projects Utilizing Self-Lubricating Materials

Project	State (U.S.) Province (Canada)	Owner	Applications [a]	Materials	MW Capacity	No. of Units	Year	Source [b]
Big Creek 8	California	Southern California Edison Company	Water lubricated bearing	NA	25	1 Francis	1994	HCI 1994
Blenheim-Gilboa	New York	New York Power Authority	NA	Lubron AQ30	1000	4 PS	1991	HR 1998
Bonneville	Washington Oregon	U.S. Army Corps of Engineers	NA	Feroform T814	NA	NA	4/96	Manufacturer
Buchanan	Texas	Lower Colorado River Authority	WGB	NA	25	2	In progress	HR 11/98
Bull Run	Oregon	Portland General Electric	NA	NA	21	1	NA	HR 7/98
Chippewa Falls	Wisconsin	Northern States Power	WGSB GB	Replaced Bronze	24	6	1995	ASCE 93 HR 11/98
Conowingo	Maryland	PECO Energy	LB SB	NA	512 (240)	(4) 60 MW	1994-1996	Per. Com.
Dardanelle	Arkansas	U.S. Army Corps of Engineers	WGSB LB SB	Karon V Karon V Karon V	124	4	1997-1999	Per. Com.
Deer Lake	NA	Deer Lake Power. Co. Ltd.	LWG, IWG,UWG	Feroform T814	NA	NA	7/98	Manufacturer

Table 3-2
Projects Utilizing Self-Lubricating Materials (continued)

Project	State (U.S.) Province (Canada)	Owner	Applications [a]	Materials	MW Capacity	No. of Units	Year	Source [b]
Forbestown	California	Oroville-Wyandotte Irrigation District	NA	NA	36	1	1991	HR 7/98
G.M. Shrum	British Columbia	BC Hydro	WGLB	replaced in 1989	2730	10 units	1987 1989	Per. Com.
Ghost GS #3 Ghost GS #4	Alberta	TransAlta Utilities	UWG,IWG,LWG, TR,LB	Feroform T814	28 14	1 1	2/96 9/96	Manufacturer
Jim Falls	Wisconsin	Northern States Power	HMG	Feroform T814	57	NA	3/96	Manufacturer
Kamargo #1 and 2 Minetto #4	New York	Niagara Mohawk Power Corporation	UWG,IWG,LWG, LB, (OWP)	Feroform T814	NA 8	NA 5	9/97	Manufacturer
Kelly Ridge	California	Oroville-Wyandotte Irrigation District	NA	NA	10	1	NA	HR 7/98
Kootenay Canal	British Columbia	BC Hydro		replaced with Karon V	529	4 Francis	1997	Per. Com.
Ladysmith	Wisconsin	Northern States Power	UWG,LWG,LB	Feroform T814	57	NA	10/98	Manufacturer
Lewiston	New York	New York Power Authority	NA	Lubron AQ30	240	12 PS	NA	HR 1998
Mc Nary Dam	Washington Oregon	U.S. Army Corps of Engineers	Fishwater Pumps	Orkot TXM-M	NA	NA	NA	HR 1998

Table 3-2
Projects Utilizing Self-Lubricating Materials (continued)

Project	State (U.S.) Province (Canada)	Owner	Applications [a]	Materials	MW Capacity	No. of Units	Year	Source [b]
Mica GS #3	British Columbia	BC Hydro	UWG	Tenmat T814	1736	4	6/96	Manufacturer Per. Com.
Mica GS #4	British Columbia	BC Hydro	UWG	Thordon HPSXL	1736	4	6/96	Manufacturer Per. Com.
Muddy Run	Pennsylvania	PECO Energy	WGLB	NA	800	8	1997-98	ASCE 97 HR 9/98
Pit No. 1	California	Pacific Gas & Electric	NA	NA	61	2	1996	HR11/98
Revelstoke	British Columbia	BC Hydro		Pending replacement	1843	4	1997	Per. Com.
River Mill		Portland General Electric	NA	NA	19	1	NA	HR 7/98
Robert Moses Niagara	New York	New York Power Authority	NA	Lubron AQ30	2200	13 PS	In progress	HR 4/98 Per. Com.
Rock Island #2	Washington	Chelan County PUD	WGB HJ/TB	NA (original) Karon V (replaced)	410	8 Horz Bulb	1978 NA	Per. Com.
Rocky Reach	Washington	Chelan County PUD	LB,OR, WGB	NA	1380	11 Kaplan	1997-ongoing	ASCE 97 HR 4/97
Ross Powerhouse	Washington	Seattle City Light	LWG	Feroform T814	360	4	7/96	Manufacturer
White River	Wisconsin	Northern States Power	NA	NA	1	NA	NA	HR 7/98

Table 3-2 Footnotes:

Note: This table is representative of some recent applications in the industry, compiled from published sources as noted

NA- Not Available

[a] The applications are as follows:

BTB-	Blade Trunnion Bushing
HJ/TB-	Horizontal Journal/Thrust Bearing
HMG-	Horizontal Main Guide
IWG-	Intermediate Wicket Gate (Bushings)
LB-	Linkage Bushing
LWG-	Lower Wicket Gate (Bushings)
OR-	Operating Ring
SB-	Servomotor Bushing
THL-	Turbine Hub Linkage
TR-	Thrust Ring
UWG-	Upper Wicket Gate (Bushings)
VMG-	Vertical Main Guide
WGB-	Wicket Gate Bushings/Bearings (location not specified)
WGSB-	Wicket Gate Stem Bushing
WGLB-	Wicket Gate Linkage Bushing

[b] The sources are as follows:

ASCE (year) - *Proceedings of the International Conference on Hydropower*

CF - *Concepts for the Future* (1994), HCI Publications

HR (month/year)- *Hydro Review*

HRW (month or issue/year) - *HRW*

HV paper - paper, HydroVision ’98 Conference, Reno, Nevada

Per. Com. - personal communication

Manufacturer - reference list provided

4
ENVIRONMENTAL LUBRICANTS

Interest in environmental lubricants for hydraulic machinery, particularly when used in civil works structures that are located near bodies of water, has been pursued at different levels and within several disciplines, since the mid-1980s.

The traditional protection method incorporated into design has been to utilize reliable hydraulic drives and prudent spill prevention and countermeasure control plans. On a day-to-day basis, O&M staffs provide periodic maintenance, observation, and inspection, with specific attention being given during extreme weather or stressful periods of operation.

Mineral-based fluids have typically been used in hydraulic machinery owing to the service characteristics. These fluids have met pressure, viscosity, and service temperature requirements as well as satisfying long-term performance needs. In particular, lubricants have been applied to hydropower equipment as:

- Lubricating oils in turbines
- Hydraulic fluids in gate lift systems, valves, and governor systems
- Greases for wicket gates and linkages
- Cable dressings for head and sluice gates, and operating cranes

Programs of periodic oil testing have been conducted to examine wear and lubricity parameters, allowing oil replacement or additions to be made on an as needed basis. However, normal discharges from operating equipment, grease from wicket gates, accidental overflows of sumps or drain waste water, or leakage from hydraulic lines, can sometimes come into contact with water in a plant’s water passages.

Recently, manufacturers and owners alike have been driven, not just by environmental regulation, but also by increased pressure to be more competitive by reducing maintenance, sustaining reliability, and avoiding risks to both equipment and the environment.

The increased movement to automation and remote monitoring, the extension of maintenance periods, and total system control without daily operator review, require dependence on the reliable functioning of equipment. While the quantities of lubricants may be small, the overall consequences of a malfunction can substantially affect the bottom line.

Discussion of Technology

A distinction between terms of products:

Lubricants–a broad term–includes fluids, meaning lubricating oils and hydraulic fluids, as well as greases. A third category of products–not addressed in this report–include solvents and cleaning solutions, which are used in industrial process work. This report discusses two bodies of research on lubricants and applications to the hydroelectric industry.

Traditional mineral-oil-based hydraulic fluids and petroleum-based greases provide the baseline for the tests and applications.

Three types of "environmentally acceptable lubricants" are commercially available, each with different properties:

- Crop oil derivatives based on natural esters–such as rapeseed oil, canola oil, and oleic acid esters–commonly used in the food industry
- Synthetic esters, made from modified animal fats and vegetable oils
- Polyglycol lubricants (the first biodegradable oils on the market) [1]

What is an Environmentally Safe Lubricant?

To date no jurisdiction has established a law or standard that clearly defines the attribute of an environmentally safe fluid. Moreover, U. S. federal regulations do not accept the term "environmentally acceptable lubricant." Therefore, the federal and state standards for implementation of a spill prevention and countermeasure control plan apply and a spill must be reported as if it were a conventional lubricant. However, it is expected that there would be some cost savings associated with clean-up of an environmentally acceptable spill, because of the characteristics of the lubricant.

Some work has been done by the American Society for Testing and Materials (ASTM) toward developing standards. However, there is only general agreement on the characteristics that an environmentally acceptable lubricant should have. These include:

Biodegradability

This is the ability of a lubricant to break down if released into the environment, as measured in percentage over time. A European standard test (CEC L-33-T82) established by the Coordinating European Council was developed to determine the biodegradability of lubricants in water. In this test, substances are ranked from zero to 100 percent in biodegradability. Another test method, administered by the U. S. Environmental Protection Agency, EPA 560/6-82-003, measures the conversion of test material carbon to CO_2 in 28 days. The results of the EPA test reportedly are more conservative than those of the CEC method. [2]

Aquatic Toxicity

The standard often applied is “food grade” meaning that small amounts may be ingested by humans without toxic effects. Effects on other organisms or effects of exposure if the quantity exceeds “small amounts” are not addressed. The guidelines of the U.S. Food and Drug Administration (FDA) regulate lubricants that are used in the food processing industry; however, results of aquatic toxicity studies do not necessarily confirm that food grade is an appropriate measure. The Canadian standard test, $LC_{50,}$ also has been utilized; this test is used by the U.S. Environmental Protection Agency (EPA) as part of the 1986 “Quality Criteria for Water” standard for oil and grease. It examines the effect on the aquatic environment by testing increasing concentrations of the lubricant–expressed as the concentration of material in parts per million–required to kill 50% of an aquatic microorganism in 48 hours. A “Microtox” testing is sometimes used as a screening test since it is much less costly. [2]

While no set of standards has been agreed upon to date, it has been suggested by the European Community that a working standard for “environmentally acceptable” is defined as:

> “A lubricant with a biodegradability of greater than 60% as measured by the EPA standard test or greater than 80% by the CEC test, and a aquatic toxicity of greater than 1000 parts per million (PPM) as tolerated by rainbow trout.” [2]

Performance Parameters

Traditional performance tests of lubricants include the same parameters as the mineral- or petroleum-based lubricant as defined by the American Society for Testing and Materials (ASTM) procedures. Table 4-1 lists these parameters and tests in detail for lubricants and greases. [2,3,4] The importance of comparing standardized tests of various lubricants to be used in applications is repeatedly mentioned in the literature.

Other Properties

Lubricants for use in the field have several other desirable properties. [2,3]

- Compatibility with mineral oil products. Utilizing field test methods, the interaction with petroleum grease residues that are replaced with the new lubricants may cause formation of undesirable gums, varnishes or other insoluble contaminants. For oils, mixing is often prohibited, but even if allowed, the biodegradability properties are substantially lowered.
- Compatibility with container vessel coatings, filters, and seals. Again, this property could affect the use of existing equipment.
- Storage stability. Often, biodegradable products may have shorter shelf life than mineral-based products.
- Cold temperature storage flow. This property as tested, assesses the performance of fluids at –22°C and –40°C for any length of time.

Status of Implementation

Hydraulic Oils

Two studies of environmentally acceptable fluids for use in hydropower applications have been conducted recently. The U.S. Army Corps of Engineers' Construction Engineering Research Laboratories conducted a review of the technology and field applications; this was reported on in *Hydro Review*. [1] Some research was also done by Powertech Labs in 1997 on eight commercially available hydraulic fluids. [2] These studies present various findings suitable for application to maintenance activities.

The Powertech analysis focused on eight fluids classified as hydraulic oils. Seven were "green" oils, including three samples of vegetable-based oils, two samples of synthetic ester-based fluid, one sample of genetically modified vegetable oil, and one sample of non-ester-based hydraulic fluid. The test program was devised to observe performance and the ability of the fluids to meet environmental expectations. The fluids were tested by seven of the methods discussed in the foregoing. The results, reported in the literature, included the following:

The vegetable oil samples all exceeded 80% biodegradability, based on the CEC test L-33-A-93. Only the baseline mineral oil sample, testing at approximately 40%, did not pass either biodegradability or toxicity tests.

The mineral oil sample passed the hydrolytic stability test (ASTM D2619) for the change in acid number and viscosity, as did the synthetic products, and two of the four-vegetable-based products.

In terms of demulsibility–the ability to shed water–two vegetable oils showed high (greater than 80%) demulsibility, while all the other oils were well within the mineral oil baseline.

The literature goes on to conclude that:

> "The use of vegetable based hydraulic oils is recommended in hydraulic systems where the temperature does not drop below -15 degrees C, where the operational temperatures are mild and contact with air and water are minimal.
>
> Some synthetic hydraulic oils have several advantages over vegetable-based oils, with broader temperature ranges for application, and corrosiveness and oxidation stability within acceptable limits, and performance better than mineral oils in terms of biodegradability and toxicity. The major drawback is the pricing differential above mineral oils.
>
> Synthetic ester based lubricants promise highly increased replacement cycle times and superior performance over vegetable oil based lubricants (not necessarily hydraulic fluids). These lubricants may be economical over the longer term due to improved maintenance. The tradeoffs are to be expected in the initial price and changeover to these products." [2]

Similar conclusions were reached in a survey and report of lubricating oils conducted by the U.S. Army Corps of Engineers. [1] This work also focused on compatibility for change-out with existing mineral-based fluid applications in civil works structures. Distinctions were made between the three types of environmentally acceptable lubricants.

Table 4-2 summarizes the general results and properties of these environmentally acceptable lubricants, in terms of biodegradability, toxicity, performance, and cost differential.

Greases

The U.S. Bureau of Reclamation's Water Resources Research Laboratory, Denver Colorado, tested greases for use in wicket gate operation. [3] The testing program focused on the replacement use of various environmentally acceptable greases for primary use in wicket gate assemblies. A test apparatus was designed to simulate conditions encountered in Reclamation's applications. A test stand within the Reclamation's Hydraulics Lab was developed to test mechanical properties of greases on a 1:4 scale prototype of a wicket gate. A second phase effort, which was planned but not carried out due to funding limitations, would have included chemical and physical analysis of the greases. These additional tests would have facilitated the evaluation of environmental effects.

Lubrication performance of standard lithium grease versus five candidate "green lubricants" was conducted using Reclamation's test apparatus. The green lubricants included three food grade (crop-based) greases and two synthetic ester-based lubricants. The greases and oils mentioned in this work are all commercially available and, again, have varying properties. The greases were tested in a 60-hour test where strain gage measurement was used during the full closing and opening stroke for wicket gate operation. The summary of this work concludes that the two synthetic ester greases performed 93 to 105% of the lubrication function as compared to the lithium- based grease, while the three food grade lubricants varied from 46 to 63% of the lubrication function.

Experience

While the above discussion focuses on some hydropower applications, the overall application of environmentally acceptable lubricants to hydraulic machinery has been more widely documented, particularly in the construction, mining, and marine operation fields. Many sources point to the use of wire rope lubricants for use on drag-lines, hoists, and cables. Additional uses in hydraulic systems on sluice gates, trash gates, head gates, and governor controls are reported.

Improving maintenance procedures and techniques, and maximizing the use of newer and better products and materials, go hand in hand with being competitive. If a particular alternative lubricant, oil, or grease does in fact lower risk exposures while maintaining high serviceability–even if costs are increased–the overall assessment of the benefits of an implementation may be positive.

As Table 4-2 shows, there is a significant cost premium–at least initially–for changing from standard lubricants to environmentally acceptable fluids.

Several hydro producers have been actively testing and implementing environmentally acceptable lubricants at both hydropower and civil works structures. At this time, replacement of existing lubricants with these alternative products is mainly considered to be an interim measure for existing stations that still have grease-lubricated bearing systems. Long-term performance rating of these products over time remains to be quantified.

TransAlta Utilities Corporation

TransAlta Utilities of Calgary, Alberta operates 13 hydro plants with a total installed capacity of approximately 800 MW, most of which are of the 1911-1972 vintage. As part of TransAlta's commitment to sustainable development, an investigation was made into environmentally friendly alternatives to petroleum lubricants. No past history of environmental incidents prompted this review of lubricating products; however, it was recognized by operations and maintenance staff that visible discharges of lubricating or hydraulic oil into the watershed was not desirable. [5]

The study, initiated in 1994, established a testing program for potential replacements for turbine lubricating oil and an alternative for hydraulic fluids at several hydro stations. The objective of the study was to review the alternative to the existing products in terms of engineering (mechanical) and environmental properties. Several applications were examined, including use of hydraulic fluids in spillway and sluice systems, sump pumps, stop log lift mechanisms, and turbine governors. Additionally, a turbine oil application in a horizontal guide bearing was also considered.

The initial investigations found that, while environmentally acceptable products for hydraulic applications were readily available, none were appropriate for turbine oil applications. The absence of tested products suitable for turbine application prompted a request for manufacturers to supply custom-formulated products for testing at two pilot sites during a six-month test period. An independent consultant reviewed the results and concluded that the technology was not yet adequate to justify a change in products for the particular turbine applications.

After considering all the information gathered by the consultant, labs, maintenance personnel, and technicians, the environmental lubricant committee made the following recommendations:

> "The utility should continue to monitor and maintain the use of environmentally acceptable hydraulic lubricants in proven applications, which may include sluice gates, trash gates, head gates, governors, and mechanical gate controls. The turbine bearing applications should revert to petroleum based lubricants. The committee should continue to monitor the progress of technology and revisit the idea of using products on a regular basis as applications and products become available." [5]

U.S. Army Corps of Engineers

The U.S. Army Corps of Engineers reports several applications at Corps of Engineers' lock and dam installations. Many are using "food grade" lubricants made from synthetic olefins or mineral oils, which are not classified as readily biodegradable. Some of the Corps Districts reported use of environmentally acceptable oils, and the longest in-use period was about five years. [1]

Rapeseed-based commercially available hydraulic fluids were being used in a variety of hydraulic power units and lock gate operating machinery, as well as pumps, and marine-based excavators, cranes, and dredges. Overall, the operators were generally satisfied with the applications and performance. Improvements were seen when heaters or coolers were installed to accommodate the limited temperature range of the rapeseed-based product. This practice resulted in increased equipment life due to reduction of stress on the pumps, because of a moderate operating temperature range.

With regard to hydropower applications, the leakage of hydraulic fluid from the blade operating mechanism of a Kaplan turbine was reported at a Corps facility. As a temporary solution, some runner blades have been welded in a fixed position to avoid leakage of fluid into the waterway. The investigation continues for an appropriate biodegradable fluid for use in these Kaplan units. [6]

The best performance of environmentally acceptable fluids was in a closed hydraulic system, with limited exposure to water which can lead to biodegradation. It was noted that failures of these hydraulic fluids occurred in cases of contamination, which caused the fluids to biodegrade while in use. [1]

Lessons Learned

Since the field experience and use of environmental lubricants is relatively recent, “lessons learned” are more appropriately termed, “observations.” Various contributors offered the following comments:

- Switching to environmentally acceptable fluids may require special measures or adaptations to the system including: very thorough draining; different coatings, filters, and seals; more frequent filter changes; and adding moisture scavengers and temperature controls. [1]
- “Selection of an environmentally safe lubricant should be based on both environmental standards, and mechanical performance, and further property tests should be conducted to determine the applicability of the products and the manufacturers claims.” [3]
- Consideration of use of lubricating oils for turbine applications should be done in conjunction with a review and testing of the properties. [5]
- One contributor recommended the development of a set of maintenance instructions and a training course that addresses the qualities and field performance characteristics of environmental lubricants, both positive and negative, for use at the field level. [7]
- Further testing is recommended particularly on the environmental and mechanical properties of greases to establish long-term performance. [3]
- Synthetic lubricants promise highly increased replacement cycle times and superior performance over vegetable-based lubricants (not necessarily hydraulic fluids). These lubricants may be economical over the longer term due to improved maintenance.

- Manufacturers generally recommend the use of their synthetic biodegradable series over their vegetable oil (rapeseed) products in critical applications which demand a high temperature range. All manufacturers caution against the mixing with conventional oils, since biodegradability will be reduced. Moisture contamination can lead to unintended biodegradation.
- Manufacturers offer customized formulations for specific applications, and include additives for anti-foam performance and for improved temperature range application.
- Some applications of synthetic oils may result in energy savings and increased equipment life. This may deserve evaluation to quantify benefits.
- The use of polyglycols should be excluded for the time being because of negative interactions with residual mineral oils and other components. [7]
- In the absence of a consistent set of tests and criteria for environmental lubricants, widespread use will not be achieved. Awareness within the environmental community may ultimately recognize efforts to reduce risks of industrial contamination. Reward of users who incorporate environmental lubricants into their regular practice may lead to further applications and better lubricants.
- Exchange of information among manufacturers, equipment suppliers, and end users to standardize performance parameters for various applications of environmental lubricants will promote their use. This exchange, especially if coupled with a reduction in the cost component, could improve both the performance and the more wide-spread use of environmentally acceptable lubricants.

References

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Table 4-1
Standard Tests for Lubricants and Greases

ASTM Standard Test Method	Description
(ASTM D130- 94) Standard Test Method for Copper Strip Corrosion	This test gives an indication of corrosiveness to the copper, which may be found in bearings, oil coolers, and other equipment.
(ASTM D445-97) Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids	This test method specifies a procedure for the determination of the kinematic viscosity of liquid petroleum products, both transparent and opaque, by measuring the time for a volume of liquid to flow under gravity through a calibrated glass capillary viscometer. The dynamic viscosity can be obtained by multiply the measured kinematic viscosity by the density of the liquid.
(ASTM D5185- 97) Standard Test Method for Determination of Additive Elements, Wear Metals, and Contaminants of Selected Elements in Base Oils (Element Scan)	This test method covers the determination of additive elements, wear metals, and contaminants in used lubricating oils.
(ASTM D892-97) Standard Test Method for Foaming Characteristics of Lubricating Oils.	This test method covers the determination of the foaming characteristics of lubricating oils at 24 °C and 93.5 °C. Means of empirically rating the foaming frequency and the stability of the foam are included. This parameter needs to be considered in sizing hydraulic system reservoirs.
(ASTM D2619-95) Standard Test Method for Hydrolytic Stability of Hydraulic Fluids (Beverage Bottle Method)	This test method covers the determination of the hydrolytic stability of petroleum or synthetic-base hydraulic fluids. Hydrolytic unstable fluids form acidic and insoluble contaminants which can cause hydraulic system malfunction as a result of corrosion, valve sticking or change in the viscosity of the fluid.
(ASTM D665-95) Standard Test Method for Rust-Preventing Characteristic of Inhibited Mineral Oil in the Presence of Water.	This test method is used to evaluate the ability of mineral oils, to aid in preventing the rusting of ferrous parts should water become mixed with the oil. This parameter of greases indicates the rust preventative characteristics from additives for long term performance.
(ASTM D1401-96) Standard Test Method for Water Separability of Petroleum Oils and Synthetic Fluids.	This test measures the ability of petroleum oils or synthetic fluids to separate from water. This property indicates that oils with poor demulsibility, will retain water and degrade and form sludge, as well as promote corrosion in the presence of water.
(ASTM D4172-91) Standard Test Method for Wear Preventative Characteristic of Lubricating Oils (Four-Ball Method)	This test method covers the determination of the wear preventative characteristics of greases in sliding steel-on-steel applications.

Table 4-1
Standard Tests for Lubricants and Greases (continued)

ASTM Standard Test Method	Description
(ASTM D6046-98) Standard Classification of Hydraulic Fluids for Environmental Impact	This classification establishes categories for the impact of hydraulic fluids on different environmental compartments; fresh water, marine, soil, and anaerobic, for categories of environmental impact. (P) environmental persistence, and (T) ecotoxicity . This classification addresses releases to the environment which are incidental to the use of a hydraulic fluid. It does not address bioaccumulation, or performance properties of the hydraulic fluid.
(ASTM D5864-95) Standard Test Method for determining Aerobic Aquatic Biodegradation of Lubricants or their components	This method covers the determination of the degree of aerobic aquatic biodegradation of fully formulated lubricants or their components on exposure to an inoculum under laboratory conditions. This method is based on the Organization for Economic Cooperation and Development (OECD) method 301B.
(ASTM D4048- 97 Standard Test Method for Copper Strip Corrosion from Lubricating Grease	This test method covers the determination of the wear preventative characteristics of greases in sliding steel-on-steel applications.
(ASTM D4951- 96) Standard Test Method for Determination of Additive Elements in Lubricating Oils	This test method covers the quantitative determination of elements in unused lubricating oils and additive packages.
(ASTM D2266-91) Standard Test Method for Wear Preventative Characteristic of Lubricating Grease (Four-Ball Method)	Water Solubility (grease) this test can determine whether the grease absorbs water. Greater affinity to absorb water results in dilution, potential change in lubricating properties and possible premature breakdown of the grease.
(ASTM D2509-93) Standard Test Method for Measurement of Load –Carrying Capacity of Lubricating Grease (Timken Method)	This test method covers the determination of the load-carrying capacity of lubricating greases by means of the Timken Extreme Pressure Tester. This test determines the extreme pressure (EP) characteristics of the grease, which are classified with a Timken load rating. EP additive control, rather than prevent wear, acting as a protective, chemical layer preventing scoring and damage. Under extreme pressure, the layer wears away and the EP additive acts to form a new layer. The In order to prevent excessive build-up the EP additives react only at temperatures associated with heat from extreme pressure, not at ambient temperatures.

References: [2,4]

Table 4-2
Performance Characteristics of Environmentally Acceptable Lubricants, Compared to Mineral Oil

	Lubricant			
Characteristic	**Mineral Oils**	**Vegetable-Based Oils**	**Polyglycol Oils**	**Synthetic Ester Oils**
Reported Biodegradability CEC-33-T-82	20-50%	>80 %	>80%	>60%
Reported Biodegradability EPA 560/6-82-003	42-49%	72-80%	6-38%	55-84%
Toxicity LC50 EPA 560/6-82-003	389->5000	633->5000	80->5000	>5000
Price Basis (compared to Mineral Oil)	1	2-3	2-4	>5
Compatibility with Mineral Oil	Possible	Possible	Not Possible	Possible
Low Temperature Limits ° C	-20 to -30	-25	-30	-30 to -40
Cold Temperature Flow at -20 °C	Flow	Flow	Flow	Flow
Seven-day Storage Flow at -40 °C	Flow	No flow	NA	Flow
Solubility	Low	Low	Soluble	Low

References: [1,2,3]

A
CONTACT LIST

Owners

BC Hydro	Burnaby, British Columbia	604-528-1600
PECO Energy	Darlington, Maryland	410-457-2700
Powertech Labs, Inc	Surrey, British Columbia	604-590-7447
Public Utility District No. 1 of Chelan County	Wenatchee, Washington	509-663-8121
TransAlta Utilities	Calgary, Alberta	403-267-7110
U.S. Army Corps of Engineers, Hydroelectric Design Center	Portland, Oregon	503-808-4200
U.S. Army Corps of Engineers, Construction Engineering Research Laboratory	Champaign, Illinois	217-352-6511
U.S. Bureau of Reclamation, Water Resources Research Laboratory	Denver, Colorado	303-445-2300

Suppliers - Self-Lubricating Materials

Federal Mogul-Deva	Union Town, Ohio	330-454-3382
HMI Wearing & Bearing Products (formerly Tenmat Inc.)	Oakville, Ontario	905-337-3230
Kamatics Corporation	Bloomfield, Connecticut	860-769-3277
Lubron Bearing Systems	Huntington Beach, California	714-841-3007
Oiles America Corporation	Novi, Michigan	248-449-5800
Orkot Composites	Eugene, Oregon	541-688-5529
Thordon Bearings, Inc.	Burlington, Ontario	905-335-1440

Suppliers - Lubricants

Cor-Tek	Missussauga, Ontario	416-274-7871
Greenland Corporation	Lethbridge, Alberta	403-328-3111
Husk-Itt Corporation	Norco, California	909-340-4000
Lubrication Engineers, Inc	Fort Worth, Texas	NA
Mobil Oil Company		800-662-4525
Permatex Industrial	Avon, Ct	NA
Templex Sales Inc.	Thornwood, NY	914-769-6676
Texaco Lubricants		800-STAR-TLC