Chapter 6
Nonfluid Lubrication

6-1. Solid Lubrication

a. Definition of solid lubricant. A solid lubricant is a material used as powder or thin film to provide protection from damage during relative movement and to reduce friction and wear. Other terms commonly used for solid lubrication include dry lubrication, dry-film lubrication, and solid-film lubrication. Although these terms imply that solid lubrication takes place under dry conditions, fluids are frequently used as a medium or as a lubricant with solid additives. Perhaps the most commonly used solid lubricants are the inorganic compounds graphite and molybdenum disulfide (MoS_2) and the polymer material polytetrafluoroethylene (PTFE).

b. Characteristics. The properties important in determining the suitability of a material for use as a solid lubricant are discussed below.

(1) Crystal structure. Solid lubricants such as graphite and MoS_2 possess a lamellar crystal structure with an inherently low shear strength. Although the lamellar structure is very favorable for materials such as lubricants, nonlamellar materials also provide satisfactory lubrication.

(2) Thermal stability. Thermal stability is very important since one of the most significant uses for solid lubricants is in high temperature applications not tolerated by other lubricants. Good thermal stability ensures that the solid lubricant will not undergo undesirable phase or structural changes at high or low temperature extremes.

(3) Oxidation stability. The lubricant should not undergo undesirable oxidative changes when used within the applicable temperature range.

(4) Volatility. The lubricant should have a low vapor pressure for the expected application at extreme temperatures and in low-pressure conditions.

(5) Chemical reactivity. The lubricant should form a strong, adherent film on the base material.

(6) Mobility. The life of solid films can only be maintained if the film remains intact. Mobility of adsorbates on the surfaces promotes self-healing and prolongs the endurance of films.

(7) Melting point. If the melting point is exceeded, the atomic bonds that maintain the molecular structure are destroyed, rendering the lubricant ineffective.

(8) Hardness. Some materials with suitable characteristics, such as those already noted, have failed as solid lubricants because of excessive hardness. A maximum hardness of 5 on the Mohs' scale appears to be the practical limit for solid lubricants.

(9) Electrical conductivity. Certain applications, such as sliding electric contacts, require high electrical conductivity while other applications, such as insulators making rubbing contact, require low conductivity.

c. Applications. Generally, solid lubricants are used in applications not tolerated by more conventional lubricants. The most common conditions requiring use of solid lubricants are discussed below. Specific Corps of Engineers and Bureau of Reclamation facilities where solid lubricant bearings have been used are discussed in paragraph 6-3 of this chapter.

(1) Extreme temperature and pressure conditions. These are defined as high-temperature applications up to 1926 °C (3500 °F), where other lubricants are prone to degradation or decomposition; extremely low temperatures, down to -212 °C (-350 °F), where lubricants may solidify or congeal; and high-to-full-vacuum applications, such as space, where lubricants may volatilize.

(2) As additives. Graphite, MoS_2, and zinc oxide are frequently added to fluids and greases. Surface conversion coatings are often used to supplement other lubricants.

(3) Intermittent loading conditions. When equipment is stored or is idle for prolonged periods, solids provide permanent, noncorrosive lubrication.

(4) Inaccessible locations. Where access for servicing is especially difficult, solid lubricants offer a distinct advantage, provided the lubricant is satisfactory for the intended loads and speeds.

(5) High dust and lint areas. Solids are also useful in areas where fluids may tend to pick up dust and lint with liquid lubricants; these contaminants more readily form a grinding paste, causing damage to equipment.

(6) Contamination. Because of their solid consistency, solids may be used in applications where the lubricant must not migrate to other locations and cause contamination of other equipment, parts, or products.

(7) Environmental. Solid lubricants are effective in applications where the lubricated equipment is immersed in water that may be polluted by other lubricants, such as oils and greases.

d. Advantages of solid lubricants.

(1) More effective than fluid lubricants at high loads and speeds.

(2) High resistance to deterioration in storage.

(3) Highly stable in extreme temperature, pressure, radiation, and reactive environments.

(4) Permit equipment to be lighter and simpler because lubrication distribution systems and seals are not required.

e. Disadvantages of solid lubricants.

(1) Poor self-healing properties. A broken solid film tends to shorten the useful life of the lubricant.

(2) Poor heat dissipation. This condition is especially true with polymers due to their low thermal conductivities.

(3) Higher coefficient of friction and wear than hydrodynamically lubricated bearings.

(4) Color associated with solids may be undesirable.

f. Types of solid lubricants.

(1) Lamellar solids. The most common materials are graphite and molybdenum disulfide.

(a) Graphite. Graphite has a low friction coefficient and very high thermal stability (2000 °C [3632 °F] and above). However, practical application is limited to a range of 500 to 600 °C (932 to 1112 °F) due to oxidation. Furthermore, because graphite relies on adsorbed moisture or vapors to achieve low friction, use may be further limited. At temperatures as low as 100 °C (212 °F), the amount of water vapor adsorbed may be significantly reduced to the point that low friction cannot be maintained. In some instances sufficient vapors may be extracted from contaminants in the surrounding environment or may be deliberately introduced to maintain low friction. When necessary, additives composed of inorganic compounds may be added to enable use at temperatures to 550 °C (1022 °F). Another concern is that graphite promotes electrolysis. Graphite has a very noble potential of + 0.25V, which can lead to severe galvanic corrosion of copper alloys and stainless steels in saline waters.

(b) Molybdenum disulfide (MoS_2). Like graphite, MoS_2 has a low friction coefficient, but, unlike graphite, it does not rely on adsorbed vapors or moisture. In fact, adsorbed vapors may actually result in a slight, but insignificant, increase in friction. MoS_2 also has greater load-carrying capacity and its manufacturing quality is better controlled. Thermal stability in nonoxidizing environments is acceptable to 1100 °C (2012 °F), but in air it may be reduced to a range of 350 to 400 °C (662 to 752 °F).

(2) Soft metal films. Many soft metals such as lead, gold, silver, copper, and zinc, possess low shear strengths and can be used as lubricants by depositing them as thin films on hard substrates. Deposition methods include electroplating, evaporating, sputtering, and ion plating. These films are most useful for high temperature applications up to 1000 °C (1832 °F) and roller bearing applications where sliding is minimal.

(3) Surface treatments. Surface treatments commonly used as alternatives to surface film depositions include thermal diffusion, ion implantation, and chemical conversion coatings.

(a) Thermal diffusion. This is a process that introduces foreign atoms into a surface for various purposes such as increasing wear-resistance by increasing surface hardness; producing low shear strength to inhibit scuffing or seizure; and in combination with these to enhance corrosion-resistance.

(b) Ion implantation. This is a recently developed method that bombards a surface with ions to increase hardness, which improves wear- and fatigue-resistance.

(c) Chemical conversion coatings. Frequently, solid lubricants will not adhere to the protected metal surface. A conversion coating is a porous nonlubricating film applied to the base metal to enable adherence of the solid lubricant. The conversion coating by itself is not a suitable lubricant.

(4) Polymers. Polymers are used as thin films, as self-lubricating materials, and as binders for lamellar solids. Films are produced by a process combining spraying and sintering. Alternatively, a coating can be produced by bonding the polymer with a resin. Sputtering can also be used to produce films. The most common polymer used for solid lubrication is PTFE The main advantages of PTFE are low friction coefficient, wide application range of -200 to 250 °C (-328 to 418 °F), and lack of chemical

reactivity. Disadvantages include lower load-carrying capacity and endurance limits than other alternatives. Low thermal conductivity limits use to low speed sliding applications where MoS_2 is not satisfactory. Common applications include antistick coatings and self-lubricating composites.

g. Methods of applying solids. There are several methods for applying solid lubricants.

(1) Powdered solids. The oldest and simplest methods of applying solid lubricants are noted below.

(a) Burnishing. Burnishing is a rubbing process used to apply a thin film of dry powdered solid lubricant such as graphite, MoS_2, etc., to a metal surface. This process produces a highly polished surface that is effective where lubrication requirements and wear-life are not stringent, where clearance requirements must be maintained, and where wear debris from the lubricant must be minimized. Surface roughness of the metal substrate and particle size of the powder are critical to ensure good application.

(b) Hand rubbing. Hand rubbing is a procedure for loosely applying a thin coating of solid lubricant.

(c) Dusting. Powder is applied without any attempt to evenly spread the lubricant. This method results in a loose and uneven application that is generally unsatisfactory.

(d) Tumbling. Parts to be lubricated are tumbled in a powdered lubricant. Although adhesion is not very good, the method is satisfactory for noncritical parts such as small threaded fasteners and rivets.

(e) Dispersions. Dispersions are mixtures of solid lubricant in grease or fluid lubricants. The most common solids used are graphite, MoS_2 , PTFE, and Teflon®. The grease or fluid provides normal lubrication while the solid lubricant increases lubricity and provides extreme pressure protection. Addition of MoS_2 to lubricating oils can increase load-carrying capacity, reduce wear, and increase life in roller bearings, and has also been found to reduce wear and friction in automotive applications. However, caution must be exercised when using these solids with greases and lubricating fluids. Grease and oil may prevent good adhesion of the solid to the protected surface. Detergent additives in some oils can also inhibit the wear-reducing ability of MoS_2 and graphite, and some antiwear additives may actually increase wear. Solid lubricants can also affect the oxidation stability of oils and greases. Consequently, the concentration of oxidation inhibitors required must be carefully examined and controlled. Aerosol sprays are frequently used to apply solid lubricant in a volatile carrier or in an air-drying organic resin. However, this method should be limited to short-term uses or to light- or moderate-duty applications where thick films are not necessary. Specifications for solid lubricant dispersions are not included in this manual. Readers interested in specifications for solid dispersions are referred to Appendix A. Before using dispersions, users should become familiar with their applications and should obtain information in addition to that provided in this manual. The information should be based on real-world experiences with similar or comparable applications.

(2) Bonded coatings. Bonded coatings provide greater film thickness and increased wear life and are the most reliable and durable method for applying solid lubricants. Under carefully controlled conditions, coatings consisting of a solid lubricant and binding resin agent are applied to the material to be protected by spraying, dipping, or brushing. Air-cured coatings are generally limited to operating temperatures below 260 °C (500 °F) while heat-cured coatings are generally used to 370 °C (698 °F). The most commonly used lubricants are graphite, MoS_2 , and PTFE. Binders include organic resins, ceramics, and metal salts. Organic resins are usually stable below 300°C (572 °F). Inorganic binders such as metal salts or ceramics permit bonded films to be used in temperatures above 650 °C (1202 °F). The choice of binder is also influenced by mechanical properties, environmental compatibility, and facility of processing.

Air-cured coatings applied by aerosol are used for moderate-duty applications; however, thermosetting resin binders requiring heat-cure generally provide longer wear-life. The most common method of applying bonded coatings is from dispersions in a volatile solvent by spraying, brushing, or dipping. Spraying provides the most consistent cover, but dipping is frequently used because it is less expensive. Surface preparation is very important to remove contaminants and to provide good surface topography for lubricant adhesion. Other pretreatments used as alternatives or in conjunction with roughness include phosphating for steels and analogous chemical conversion treatments for other metals. Specifications for solid film bonded coating are not included in this manual. Readers interested in specifications for solid film bonded coatings are referred to the references in Appendix A.

(3) Self-lubricating composites. The primary applications for self-lubricating composites include dry bearings, gears, seals, sliding electrical contacts, and retainers in roller bearings. Composites may be polymer, metal-solid, carbon and graphite, and ceramic and cermets.

(a) Polymer. The low thermal conductivity of polymers inhibits heat dissipation, which causes premature failure due to melting. This condition is exacerbated if the counterface material has the same or similar thermal conductivity. Two polymers in sliding contact will normally operate at significantly reduced speeds than a polymer against a metal surface. The wear rate of polymer composites is highly dependent upon the surface roughness of the metal counterfaces. In the initial operating stages, wear is significant but can be reduced by providing smooth counterfaces. As the run-in period is completed, the wear rate is reduced due to polymer film transfer or by polishing action between the sliding surfaces. Environmental factors also influence wear rate. Increased relative humidity inhibits transfer film formation in polymer composites such as PTFE, which rely on transfer film formation on counterfaces. The presence of hydrocarbon lubricants may also produce similar effects. Composites such as nylons and acetals, which do not rely on transfer film formation, experience reduced wear in the presence of small amounts of hydrocarbon lubricants.

(b) Metal-solid. Composites containing lamellar solids rely on film transfer to achieve low friction. The significant amount of solids required to improve film transfer produces a weak composite with reduced wear life. Addition of nonlamellar solids to these composites can increase strength and reduce wear. Various manufacturing techniques are used in the production of metal-solid composites. These include powder metallurgy, infiltration of porous metals, plasma spraying, and electrochemical codeposition. Another fabrication technique requires drilling holes in machine parts and packing the holes with solid lubricants. One of the most common applications for these composites is self-lubricating roller bearing retainers used in vacuum or high temperatures up to 400°C (752 °F). Another application is in fail-safe operations, where the bearing must continue to operate for a limited time following failure of the normal lubrication system.

(c) Carbon and graphites. The primary limitations of bulk carbon are low tensile strength and lack of ductility. However, their high thermal and oxidation stabilities at temperatures of 500 to 600 °C (932 to 1112 °F) (higher with additives) enable use at high temperatures and high sliding speeds. For graphitic carbons in dry conditions, the wear rate increases with temperature. This condition is exacerbated when adsorbed moisture inhibits transfer film formation. Furthermore, dusting may also cause failure at high temperatures and sliding speeds. However, additives are available to inhibit dusting.

(d) Ceramics and cermets. Ceramics and cermets can be used in applications where low wear rate is more critical than low friction. These composites can be used at temperatures up to 1000 °C (1832 °F). Cermets have a distinct advantage over ceramics in terms of toughness and ductility. However, the metal content tends to reduce the maximum temperature limit. Solid lubricant use with bulk ceramics is limited to insertion in machined holes or recesses.

6-2. Self-Lubricating Bearings

a. Self-lubricating bearing research. The Corps of Engineers Hydroelectric Design Center (HDC) has developed a standardized test specification for evaluating self-lubricating bearings for wicket gate applications in hydroelectric turbines. Although the test criteria, procedures, and equipment were established based on the requirements from hydropower applications, there is potential for other applications such as bushings for miter and tainter gates. The tests are used as benchmarks to measure and compare the performance of competing products. During the tests, bearings are subjected to accelerated wear under the worst operating conditions possible. Testing is divided into three sections: initial set and creep, accelerated wear, and edge loading.

(1) Initial set and creep. In this test the bushings and sleeves are subjected to static loads to 229.6 bar (3300 lb/in^2). The shaft is rotated at periodic intervals, and the shaft displacement wear relative to the test block is continuously monitored.

(2) Accelerated wear test. In this test a radial load of 227.6 bar (3300 lb/in^2) is superimposed by a dynamic load of 68.9 bar (1000 lb/in^2) at 2 Hz. The shaft is rotated according to established criteria, and temperatures, static load, dynamic load to rotate (friction), stroke displacement, and wear are recorded.

(3) Edge load test. This test is similar to the accelerated wear test except that the sleeve is machined to simulate shaft misalignment.

b. Application of self-lubricated bearings. Table 6-1 identifies Corps facilities using self-lubricating bearings and their specific applications.

Table 6-1
Corps of Engineers and Bureau of Reclamation Facilities Using Self-lubricating Bearings

Location	Facility	Application
Corps Facilities		
Portland, OR	Little Goose	Wicket gate, linkage bushing, operating rings
Portland, OR	Lower Monumental	Wicket gate, linkage bushing, operating rings
Portland, OR	Bonneville Lock	Swing bridge pivot bearing
Portland, OR	Bonneville Lock	Mooring rollers
Portland, OR	Bonneville Lock	Miter gate bushings
St. Paul, MN	Lock No. 10, MS River	Gate chain bushings
Louisville, KY	Cannelton Lock	Lock gate drive bushings
Little Rock, AK	Dardanelles Dam	Wicket gate, linkage bushing, operating rings
Nashville, TN	Kentucky Lock Project	Mooring rollers
Walla Walla, WA	McNary Lock and Dam	Fish screen sphericals
Rock Island, IL	Rock Island Dam	Wicket gate, linkage bushing, operating rings
Bureau of Reclamation Facilities		
Grand Coulee, WA	Grand Coulee	Linkage bearing evaluation, sole plate keys
Denver, CO	NA	Bearing evaluation

6-3. Self-Lubricating Bearings for Olmsted Wicket Gates Prototype Tests

a. Introduction. Applicable to this manual is a discussion of the self-lubricating bearings used in the Olmsted Locks and Dams prototype hydraulically operated wicket gates, including lessons learned from the testing of the bearings and monitoring of the hydraulic fluid used in operating the wickets. The discussion is assembled from a report entitled *"Olmsted Prototype Hydraulically Operated Navigable Pass Wicket Dam, Final Report August 1997,"* prepared by the Corps of Engineers Louisville District. The report details project development, design, construction, testing, material evaluation, and lessons learned.

b. General.

(1) The Olmsted project has undergone numerous conceptual changes throughout its development. One approved design included 220 remotely operated, hydraulically actuated wicket gates. Each wicket was to be 2.74 m (9 ft, 2 in.) wide and 7.77 m (25 ft, 6 in.) long with a design lift of 6.7 m (22 ft). A full-scale model (prototype) was constructed with five wickets to test the design, materials, and components developed by Louisville District. New and unique materials and components were developed and tested, such as self-lubricating bearings and biodegradable hydraulic fluid.

(2) Self-lubricating bearings by five different manufacturers were tested and evaluated. The manufacturers are Merriman, Thordon, Lubron, Kamatics, and Rowend. Each wicket was installed with a complete set of bearings from one manufacturer. The size of the bearings and corresponding pins were determined based on load data collected on a 1:25 model of the wicket at the U.S. Army Engineer Waterways Experiment Station Vicksburg, MS. The contact area/diameter and length of bearings were designed to have a maximum distributed load of 552.7 bar (8000 psi). No seals were installed on any of the bearings. The manufacturers were given the option to use whatever lubrication they chose for the conditions specified. The conditions were that the bearings were to be in the Ohio River operating at slow speeds under a minimum of 6.7 m (22 ft) of head. The bearings were installed dry and each was operated approximately 50 times during the shake-down test before the site was flooded. Each set of bearings, except Wicket #1, received 400 cycles of operation. The 400 cycles corresponded to the number of operations the wickets would have been subjected to over a 25-year service life at the Olmsted facility. Because of a wicket malfunction, Wicket #1 received only 255 cycles, but was exposed to the same conditions throughout the test. The bearings were subjected to extended periods in which the wickets were left in a fixed position and the river current was allowed to flow past. Each hinge bearing on each of the wickets was subjected to the same loads and experienced the same conditions.

c. Test summary.

(1) Wicket #1, Lubron. The manufacturer of the bearings installed on Wicket #1 was Lubron Bearing Systems, Huntington Beach, CA. Lubron used a bearing manufactured with a manganese bronze housing with an inner lubricating coating of PTFE, trade name AQ100 ™. The material is a combination of PTFE, fluorocarbons and epoxy resin, hardeners, and metallic and fibrous fillers.

- Hinge sleeve bushings and pins. Evaluation of the hinge sleeve bushings after operation indicated no wear of the lubricated surface. The lubricating material inside the bushing was in good condition. The hinge pins were in good condition with no sign of wear.

- Prop spherical bearing. The spherical bearing in the prop was designed with a stainless steel ball mounted in a manganese bronze race. The race was coated with the AQ100 ™ lubricant material.

After testing, the ball and housing were in good condition with no indication of wear. The lubricant material was well coated on the ball and not worn off the race.

(2) Wicket #2, Kamatics. The manufacturer of the bearings installed on Wicket #2 was Kamatics Corporation (Kaman), Bloomfield, CT. Kamatics used a bearing manufactured with a fiberglass/epoxy housing incorporating an inner lubricating liner (Karon V™) of PTFE. Each of the bearings Kamatics provided were designed for swell caused by the inherent absorption of water into the fiberglass bushing housing.

- Hinge sleeve bushings and pins. Evaluation of the hinge sleeve bushings after operation indicated that the lubricating liner (Karon V™) material was ground and flaked off both the left and right side sleeve bushings. Kamatics sent a letter to the Corps explaining that the company believed contamination entering the bushing through unnecessarily large clearances was the reason the bushings failed. The hinge pins were in good condition with no sign of wear.

- Prop spherical bearing. The spherical bearing on the prop was designed with a stainless steel ball mounted in a stainless steel race. Observation of the prop after testing revealed the bearing applied side loads on the cover plate caused bolts to shear off. Wear marks were evident on the stainless steel ball where contact had been made between the ball and the stainless steel race. The Karon V™ lubricating liner material was removed along the contact area of the race. Wear marks were evident on the race where the ball and race had been rubbing steel-on-steel. Kamatics sent a letter to the Corps explaining that improper location of the split of the outer race resulted in nonuniform contact between ball and liner which caused chipping of the liner. The Kamatics letter stated that with a properly located split line for the outer race, the Karon V™ lined spherical bearing would function without difficulty.

- Direct-connect cylinder to gate connection pin. Wicket #2 was a direct-connected cylinder. Therefore, the connection between the piston rod and the gate used two sleeve bushings. Evaluation of the bushings after operation indicated the lubricating liner (Karon V™) material was worn away from the nonload side of the bushing. Material from the Kamatics lubricant used in the bushing was present on the stainless steel pin. No scoring was present on the pin.

- Cylinder trunnion bushings. Evaluation of the bushings after operation indicated the lubricating liner (Karon V™) material was in good condition, with minor wear on the load-bearing surface of the bushing. Lubricant material from the Kamatics bushings was deposited on the stainless steel pins and from the thrust surface of the bushing on the side of the trunnion. The area where contact was made between the cylinder trunnion pins and the bushings could be seen, but the pins were not damaged.

(3) Wicket #3, Merriman. The manufacturer of the bearings installed on Wicket #3 was Merriman, Hingham, MA. Merriman's product, Lubrite™, used a bushing machined from manganese bronze. A series of 6.35×10^{-3} m (1/4-in.) holes were drilled in a designated pattern in the housings and filled with Merriman G12 lubricant. The inner lubricating liner used in the housings was G12 lubricant. G12 is an epoxy-based graphite-free lubricant.

- Hinge sleeve bushings and pins. Evaluation of the bushings after operation indicated the final inner surface coating layer of Gl2 was removed and the G12 plugs were exposed. On the inside of the left bushing, a couple of the plugs had begun to wear or wash out. Approximately 250 microns (10 mils) of material was removed from the plugs and the manganese bronze had begun to show wear in a 13-cm^2 (2-$in.^2$) area of the bushing. The pins were in good condition with no sign of wear. There was little to no lubricant material present on the pins.

- Prop spherical bearing. The spherical ball of the bearing was machined from manganese bronze. Lubrite™ lubricant G12 was added to the ball by means of a series of machined rings and holes and by inserting the lubricant into the voids. A 175-micron (7-mil) layer of G12 lubricant was applied over the face of the ball for break-in purposes. The surface of the ball was rough with pits where the G12 lubricant had worn or washed out. Observation of the ball indicated galvanic corrosive action between the lubricant material and stainless steel could have caused the pitting of the material. The noncontact surface of the ball still had signs of the initial break-in surface coat of G12 lubricant on it. The race was in good condition.

- Cylinder trunnion bushing. Evaluation of the bushings after operation indicated the 200-micron (8-mil) thick inner break-in surface layer of G12 was removed on the bottom, along the load area of the bushings. The stainless steel trunnion pins had G12 lubricant deposited on the pins. The load areas where the bushing contacted the pins showed no signs of wear. The pins were in good condition with no signs of wear.

(4) Wicket #4, Thordon. The manufacturer of the bearings installed on Wicket #4 was Thordon Bearings, Inc., of Burlington, Ontario, Canada. Thordon used a bushing machined from bronze. The inner lubricating liner used in the bushing was Thordon SXL TRAXL™. SXL is a polyurethane-based material with multiple proprietary additives that the manufacturer will not disclose.

- Hinge sleeve bushings and pins. Evaluation of the bushings after operation indicated that the final inner surface coating was in good condition, with minor deposits of black debris impregnated into the material. The stainless steel hinge pins were in good condition with no signs of wear.

- Cylinder trunnion bushing. Evaluation of the bushings after operation indicated that the loads caused the lubricating material to compress approximately 125 to 250 microns (5 to10 mils).

The manufacturer of the bushings provided the Corps of Engineers an overview of their interpretation of the cause of dark areas observed in the bushing. They stated the discoloration most probably was iron oxide from mild steel that was trapped between the bottom of the shaft and the bearing, subsequently pressed into the bearing surface. The stainless steel trunnion pins showed no signs of wear and were in good condition.

(5) Wicket #5, Rowend. The manufacturer of the bearings installed on Wicket #5 was Rowend, Liberty Center, OH. Rowend used a bushing machined from manganese bronze. A series of 6.3-mm (1/4-in.) holes were drilled in the bushing and filled with R-8 lubricant in a designated pattern around the bushing. The inner lubricating material used was R-8™, a proprietary material.

- Hinge sleeve bushings and pins. Evaluation of the bushings after operation indicated that galvanic corrosion occurred between the manganese bronze bushing and the stainless steel pin. The noncontact surface of the left hinge bushings had pits. The thrust surface of the left hinge bearing also had pitting and the R-8™ lubricant was beginning to wash out of the plug area. The right hinge bushing side thrust surface experienced the majority of the side loading and was grooved and worn from the rotation. The R-8 lubricant washed out of the plug area as much as 0.79 mm

(1/32 in.) on the thrust surface. Pitting was not present on the load side of the right hinge bushing. There were no indications of galvanic action found on the stainless steel hinge pins.

- Direct-connect cylinder to gate connection pin. Wicket #5 was a direct-connected cylinder; therefore, the connection between the piston rod and the gate used two sleeve bushings. Evaluation of the bushings after operation indicated the lubricating material fully coated the bushing surface as required. There were minor traces of galvanic corrosion in the manganese bronze material. Overall, the bushings were in good condition. Lubricant material used in the bushing was on the pin. No scoring was present on the pin.

- Cylinder trunnion bushings. Evaluation of the bushings indicated that foreign material had gotten into the bushing and damaged the manganese housing. Some grooves were in the base metal. The R-8™ material was distributed around the bushing, as is normal.

d. Lessons learned. Lessons learned in this study were.

(1) Bearing materials. Of the five self-lubricating bearing materials tested, each performed differently. Four of the manufacturers made the housings of the bearings from manganese bronze into which a specific lubricant was applied. The fifth manufacturer, Kamatics, used a fiberglass housing onto which a lubricant was applied. Rowend used lubricant plugs with no break-in surface, and pitting occurred in the manganese bronze. It is believed that galvanic action between the material and the stainless steel pin caused the pitting. Merriman and Lubron used a break-in layer of lubricant which seemed to protect the bronze from the galvanic action. Thordon used a material that was laminated to the bronze and absorbed fine debris into the material. Kamatics used a PTFE-based lubricant that delaminated and flaked off the housing of the bearings. Based on the testing conducted, the Lousville District rated the products in the following order: Lubron and Thordon (equal) > Merriman > Rowend > Kamatics. The reason for the low rating of the Kamatics bearing was the observed damage.

(2) Biodegradable hydraulic fluid. The fluid performed well once the proper size filters were determined. Originally a 10-micron- (3.28×10^{-5} ft) filter was installed in the return line from the cylinders and on the supply line. In October and November, when the site was not in use, the cylinders were exposed to cold weather. The cold fluid would not pass through the 10-micron filter fast enough, activating an alarm in the control system. To correct the problem, the 10-micron filter in the return line was replaced with a 20-micron (6.56×10^{-5} ft) filter, and the heater inside the reservoir was turned on. These actions solved the problem.

(3) Hydraulic fluid filters. It is important to position the filters on the reservoir in a location where they are easily accessible for routine maintenance.

(4) Cleaning of hydraulic system. Initial cleaning of the system was performed by the mechanical contractor. After operating the hydraulic system for a period of time, metal shavings were discovered in the return filter. It was determined that the shavings came from the manifolds. It was believed that the shock to the piping system from engaging of the alignment cylinder solenoids dislodged the shavings from the manifold. Each manifold was removed and recleaned, and the problem no longer occurred.