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LUBRICATION OF SPACECRAFT MECHANISMS

Advancements continue to be made in the lubrication of spacecraft mechanisms. Many variables such as the environment, extent and type of movement, applied loads, construction materials, and lubrication regime must be considered in selecting the proper lubricant. In addition, a lubrication engineer must rely on past experience when choosing a lubricant for a particular application.

INTRODUCTION

The Applied Physics Laboratory has designed, built, and flown more than fifty satellites carrying over 100 scientific instruments also designed and built by APL. In addition, the Laboratory has designed, built, and flown more than eighty scientific instruments on non-APL satellites.[1,2] The instruments were designed using ball bearings, gears, pins, hinges, and other types of moving components lubricated with materials such as thin gold plate, hand-burnished molybdenum disulfide (MoS_2) or graphite, plastic cages/retainers, inorganic/organic bonded solid films, or oil and grease. For each instrument, the lubricants were selected for a specific reason; for example, electrical conductance across the bearing was needed; a short (thirty seconds) or long (twenty years) life time was required; a motor with a large torque margin was used, where wear was not a consideration; or continuous exposure to the space environment was involved. Discussions with lubrication engineers reveal that the selection of lubricants is based on various considerations as well as one's past experience. Today, lubrication engineers study tribology, the science that deals with the design, friction, wear, and lubrication of interacting surfaces in relative motion. Such study provides a better understanding of the surface conditions and chemical reactions that take place between lubricants and surfaces. This article provides a general discussion of the variables to consider in selecting lubricants.

CONSIDERATIONS IN SELECTING LUBRICANTS

Operational Lifetime of the Spacecraft

Lubricants are subject to potential degradation, depending on the amount of time they are used in various environments. Therefore, the number of days that a spacecraft will be in space, the number of duty cycles, the in-orbit altitude, and the amount of time spent in ground storage are critical elements to consider in selecting a lubricant. During ground storage, a loss of lubricant can occur, and adjacent critical surfaces can be contaminated by unwanted creep (also known as wetting and spreading) of liquid lubricants. The creep of lubricants can be reduced by using a barrier film (a very low surface tension film placed on strategic surfaces)[3,4] or by incorporating geometric designs (e.g., chevron-type baffles or flanges). A similar problem may be encountered with grease lubricants if the oil separates from the grease, resulting in creep of the oil.

The Space Environment

Lubricants are affected by the space environment. The ambient pressure can be as low as 10^{-12} torr, and the ambient temperature can be as low as -60°C, whereas the pressure and temperature inside the unit can range from 10^{-6} to 10^{-12} torr, and -50 to +20°C, respectively. This situation contributes to the loss of lubricant by outgassing and a change in creep properties because of the change in viscosity, probably resulting in a reduced life time. The temperature of operation either increases or decreases the viscosity of a liquid lubricant, causing a change in the tendency of the lubricant to flow back into place between the contacting surfaces. The effect of a small temperature difference between two close surfaces (bearing inner and outer races) increases the tendency of an oil/grease lubricant to creep toward the cooler surface. Dormant and Feurstein[5] stated that a difference of 1 to 2°C between surfaces is sufficient to cause some oils to creep. The reduction in the force of gravity in space affects the creep tendency of the liquid or mixed lubricants by changing the surface energy of the system.

Lubrication Regimes

Lubrication is usually classified into one of three regimes: solid film, mixed film, or liquid film. Holmberg[6] classified lubricants into two regimes that are more descriptive: fluid pressure and surface film (Fig. 1). Fluid pressure lubrication includes hydrostatic, hydrodynamic, elastohydrodynamic, and squeeze film lubrication and is primarily concerned with oils and greases under both low and high loads and low and high speeds. Surface film

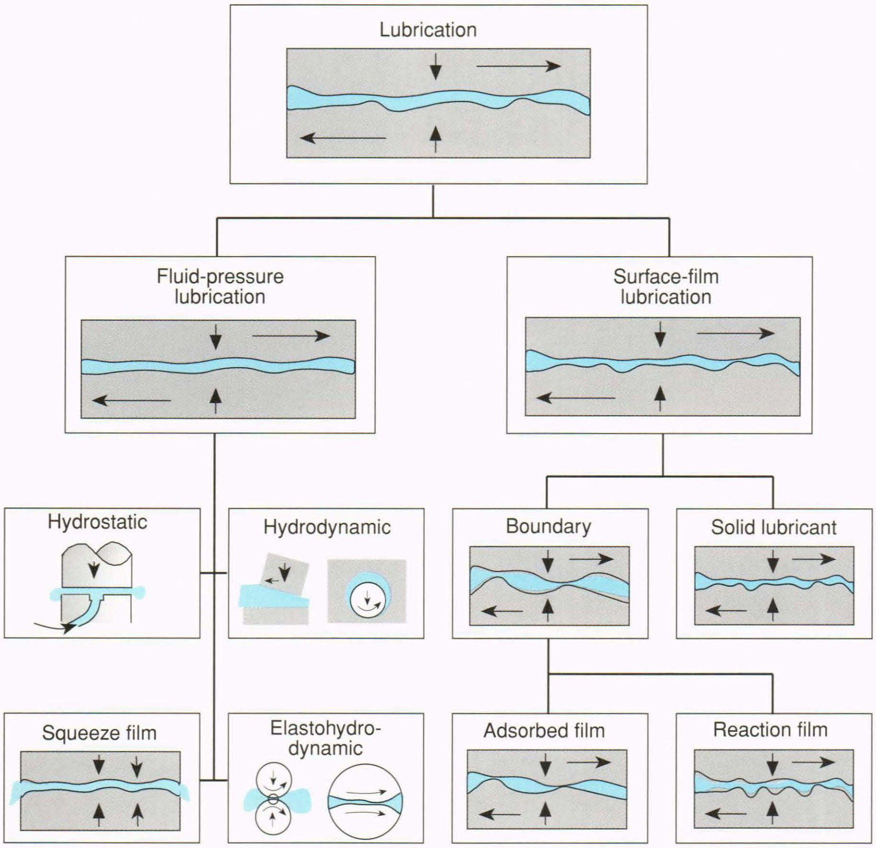


Figure 1. Classification of the lubrication regimes into two major classes and a further division into eight subclasses. (Reprinted, with permission, from Ref. 6. © 1989 The American Society of Mechanical Engineers.)

lubrication includes boundary films (mixed films), solid applied films, adsorbed films, and reaction films and is essentially concerned with high loads, slow movement, and relatively short life times. The lubricants may consist of MoS_2, graphite, Teflon, nitrided or carburized surfaces, tri-creysl phosphate, or greases with an extreme-pressure additive.

Type, Frequency, and Extent of Movement

Narrow-Angle Oscillation

In a narrow-angle oscillation mode, the movement may be such that the load is carried by one tooth in a gear or one ball in a bearing (or a portion of a tooth or ball). In either situation, the lubricant may not be replenished at the contact points, as the movement is so small that the lubricant will not flow back, be dragged back, or creep back into place between the contacting surfaces. If a liquid lubricant is recommended in this type of motion, the oil must be enhanced by the use of an extreme-pressure additive that will "put down" a boundary lubricating film during "run-in" (a run-in must be performed). Where the loads are very high and the wear could be excessive, it may be more appropriate to recommend a bonded solid-film lubricant such as MoS_2. If the gear teeth are small and flex during operation, a bonded solid-film lubricant is not applicable. Instead, it would be best to add the MoS_2 to a grease and run-in the component for a period of time. After the run-in, the grease and MoS_2 would remain on the surfaces as the designated boundary lubricant.

Partial Rotation in a Ball Bearing

For partial rotation in a ball bearing, the same situation exists as in narrow-angle oscillation, wherein the rotation of the ball may be insufficient to allow the grease to flow back or be dragged back into place between the contacting surfaces. The partial rotation component is in a boundary or mixed lubrication regime, so the discussion on the lubrication of the narrow-angle oscillation is applicable.

Complete Rotation in a Ball Bearing

For complete rotation in a ball bearing in a slow-speed application, the lubricant is replenished under each ball during rotation, as the balls "track" each other. The applied load may be such that the ball may be in a mixed-film lubrication regime. In this situation, one should use a Teflon or MoS_2-filled grease or a self-lubricating polymeric material (SLPM) ball retainer/cage that will put down a transfer-boundary lubricating film (Fig. 2). Another option is to use an oil-impregnated porous polymeric material as the ball retainer. In this system, the oil bleeds out of the retainer and lubricates the bearing (Fig. 3). An SLPM lubricates by transferring a film of the material from the ball retainer to the contacting surfaces, thereby generating a solid-film lubricant. The ball bearings of the Small Astronomy Satellite model A (SAS-A) momentum wheel are lubricated with an SLPM (Fig. 4). A problem may occur in using an SLPM in a ball bearing if the transferred film contains particles of the structural filler

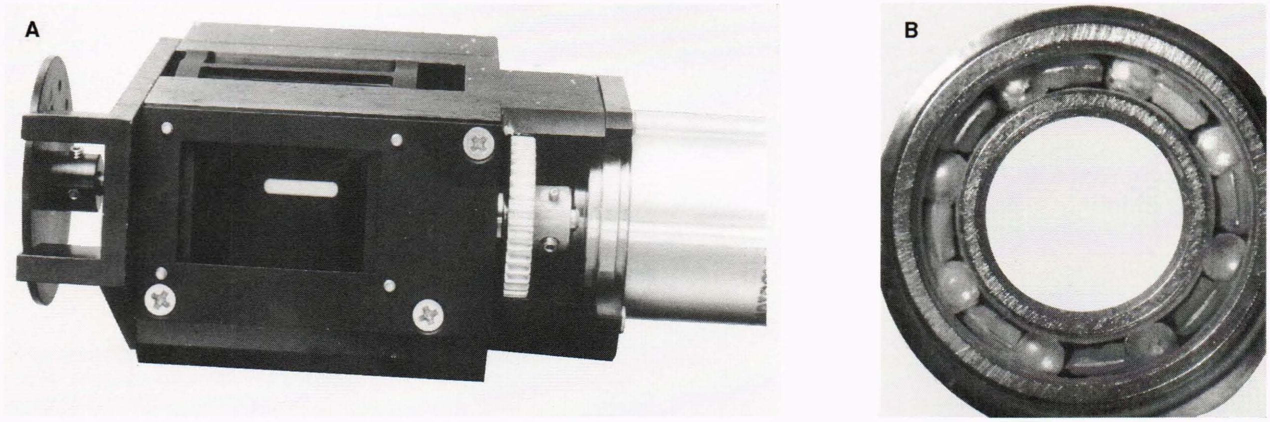


Figure 2. A. Spacecraft imager hardware. The white gear is machined from a self-lubricating polymeric material. The ball bearings and other gears (internal to the mechanism) are lubricated with a perfluorinated extreme-pressure oil grease. **B.** A properly greased ball bearing from the instrument shown in part A.

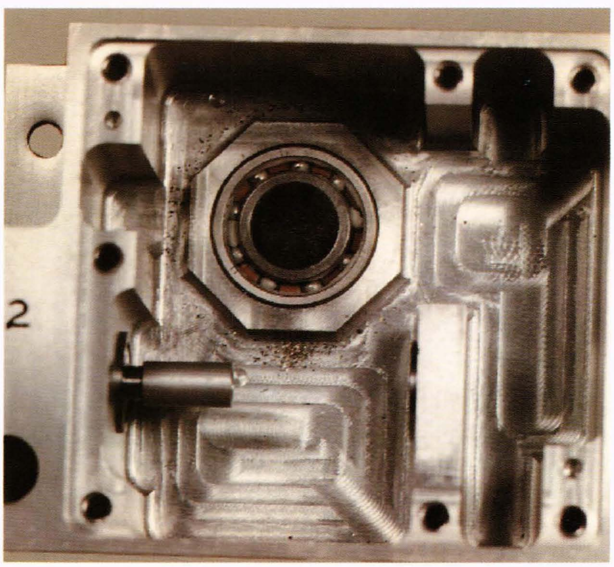


Figure 3. A ball bearing lubricated with an oil-impregnated polymeric material (red-brown material) retainer and a small quantity of a perfluorinated polyether extreme-pressure grease (white material).

(normally a fiberglass material), which may increase the torque in the bearing or cause its operation to be somewhat noisy or bumpy. It may sometimes be prudent to add a very small amount of spaceflight-acceptable grease.

For gears, sleeves, and journals, allowances must be made for wear, debris, and changes in dimension. Again, a run-in must be performed before life testing of flight hardware or equipment. Figure 5 shows the use of an SLPM-lubricated sleeve bearing on the Geosat-A scissors boom mechanism.

When a high-speed ball bearing is the component to be lubricated with oil, the balls will be in either a hydrodynamic or an elastohydrodynamic regime. Booser and Wilcock[7] defined hydrodynamic lubrication as the generation of a load-supporting pressure by a fluid located between two noncontacting surfaces in relative motion. Figure 6 illustrates the condition, and no appreciable wear is experienced. Jackson[8] defined elastohydrodynamic lubrication (Fig.7) as lubrication in the hydrody-

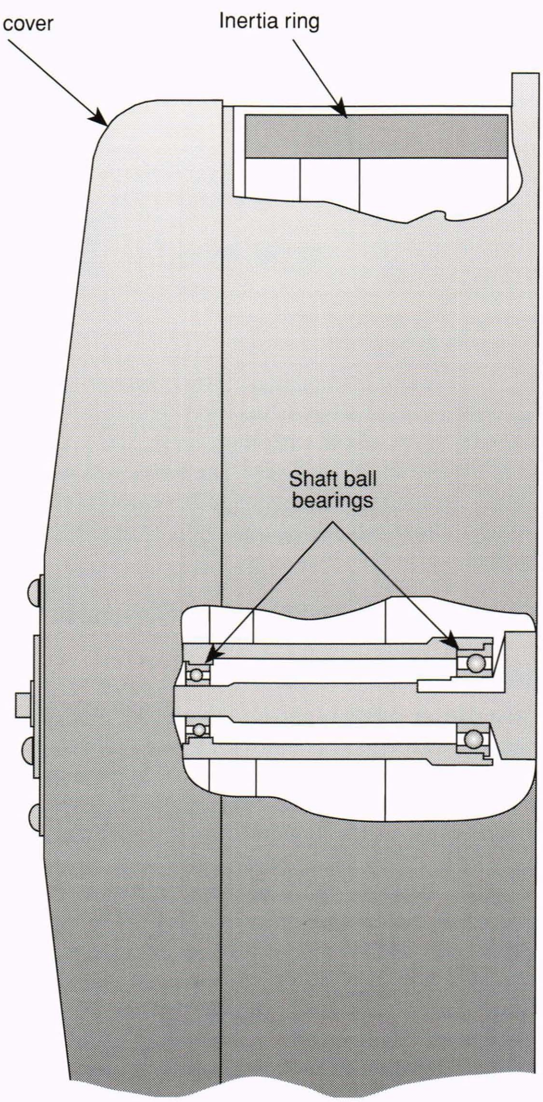


Figure 4. Sketch of a portion of the Small Astronomy Satellite model A momentum wheel showing the two shaft ball bearings that support the inertia ring. The ball bearings are lubricated with a self-lubricating polymeric material. The inertia ring, which rotates at 2000 rpm, performed successfully for almost four years before it was turned off by command.

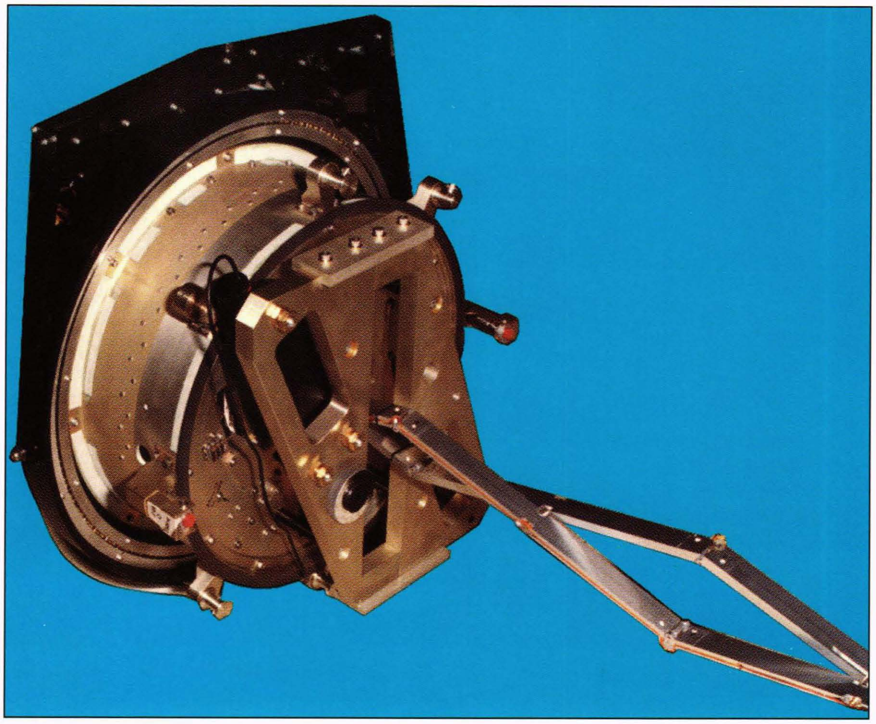
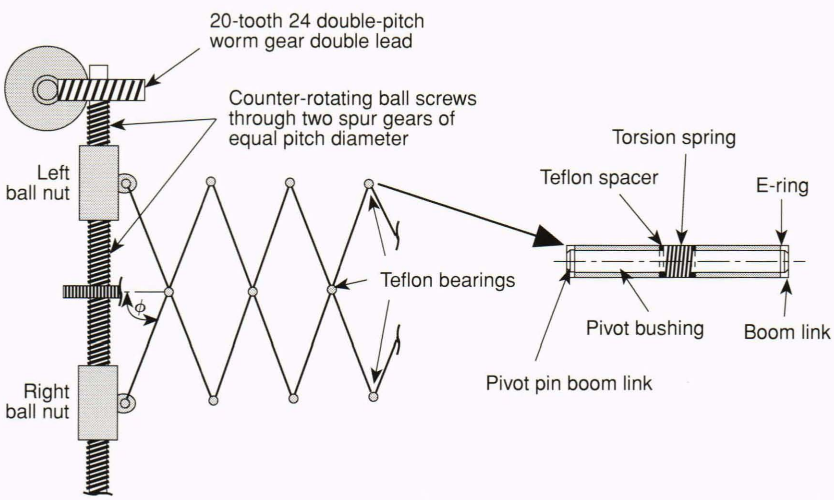


Figure 5. Geosat-A scissors boom erecting mechanism showing a hinged sleeve bearing and a ball nut/ball screw. The sleeve bearing is lubricated with a self-lubricating polymeric material, and the ball nut/ball screw is lubricated with a thin hand-burnished film of dry MoS_2.



namic regime, where the elastic properties of the material and the lubricant play a combined roll in the system. The balls do not contact the races, and significant wear of the surfaces does not occur. Where the total number of cycles and the total operational time are significantly large, and where the temperature is elevated to an usually high value, the oil may have a tendency to polymerize and become more viscous (may form a hard coating). As this happens, the torque in the bearing may increase to the point where the designated motor does not rotate the bearing, thereby causing failure. Although this is a long-term phenomenon, it has occurred, but it can be prevented by the use of sealed units or heaters.

Sliding Motion

In almost every practical application, sliding motion is a boundary lubrication situation and is typical of mechanisms such as gears, sleeve bearings, pins, and hinges. Figures 5, 8, and 9 show APL mechanisms using this type of motion. Typically, the loads are somewhat high, and wear of contacting surfaces is a definite problem (Fig. 10). In this type of application, a high-load-carrying grease with an extreme-pressure additive or a solid-film lubricant must be used. Such greases are formulated so that they will put down a very tenacious and high-load-carrying solid film between the rubbing surfaces. These films may be materials such as Teflon, MoS_2, graphite, or tri-creysl phosphate. The materials work themselves into the pores or surface depressions (tool and grinding marks, pores, pits, and other micro surface imperfections) and form a tightly bonded solid-film coating (Fig. 11).[9] One of the greases commonly used in spaceflight today is a stable perfluorinated polyether linear polymer with a tetrafluoroethylene telomer (Teflon-like) thickener/fill-

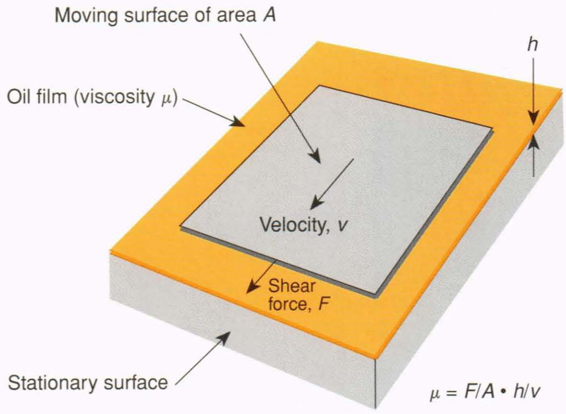


Figure 6. Sketch of hydrostatic lubrication. The two surfaces do not contact because of the quantity and viscosity of the fluid, the contour of the surface, and the velocity of movement, so no appreciable wear occurs. (Reprinted, with permission, from Ref. 7.)

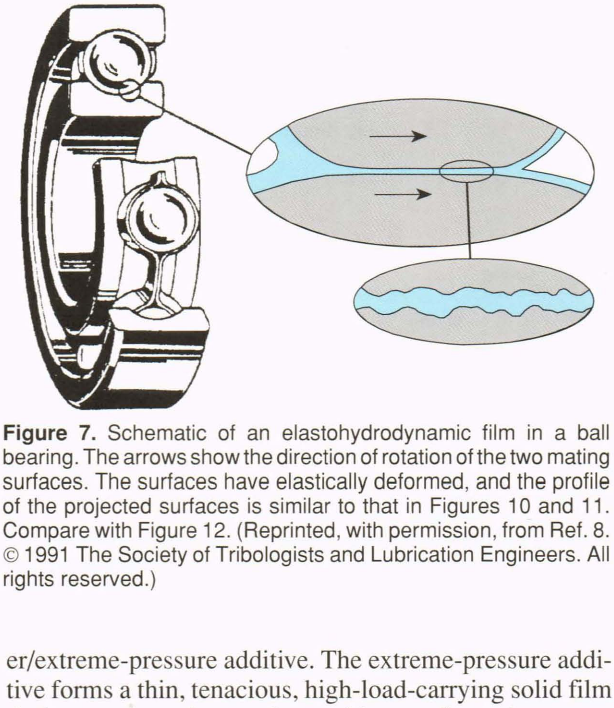


Figure 7. Schematic of an elastohydrodynamic film in a ball bearing. The arrows show the direction of rotation of the two mating surfaces. The surfaces have elastically deformed, and the profile of the projected surfaces is similar to that in Figures 10 and 11. Compare with Figure 12. (Reprinted, with permission, from Ref. 8.)

er/extreme-pressure additive. The extreme-pressure additive forms a thin, tenacious, high-load-carrying solid film during run-in and operation and has performed successfully for several years (run-in is absolutely necessary). In some instances, a hard surface film such as a hard anodized, carburized, or nitrided alloy has been used successfully.

Types of Contacting Moving Components

The following are some of the types of contacting moving components available: ball bearings (pre-loaded pair, radial loaded, or thrust loaded), roller bearings, sleeve bearings (e.g., pins or hinges), worm and spur gears, harmonic drive with a flexible gear/ball-bearing mating system, motor brushes, and flex pivots. Of these types, roller bearings are not normally used in spaceflight applications. Small sleeve bearings are used in some places and are commonly lubricated with oil, grease, solid-bonded films, porous metals impregnated with oil lubricants, or SLPM's. The shaft sleeve bearing of the SAS-A solar array erection mechanism was lubricated with an SLPM (Fig. 9). Lubricant selection is based on the applied load and/or the design of the bearing. Does the bearing have a geometric device (lip/flange) designed into it for retention of the oil? Are the loads light or heavy? With

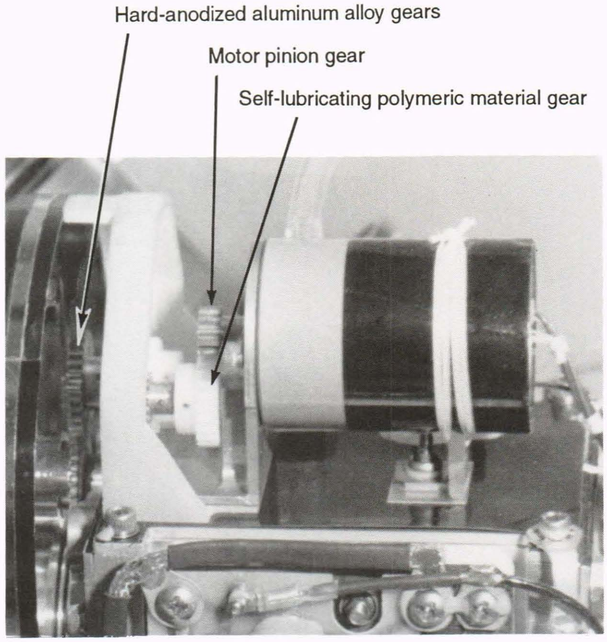


Figure 8. Galileo release mechanism showing two sets of gears exposed to the space environment. The stainless steel motor pinion gear meshes with a gear made from a self-lubricating polymeric material that rotates two mating, hard-anodized aluminum alloy gears. All mating surfaces are in the boundary lubrication regime.

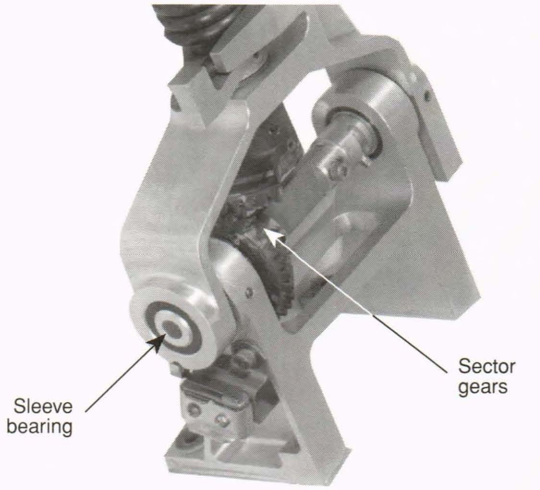


Figure 9. Section of the Small Astronomy Satellite model A solar array erection mechanism showing the hard-anodized aluminum alloy sector gears with a thin coating of a perfluorinated extreme-pressure oil grease and the shaft sleeve bearing lubricated with a self-lubricating polymeric material.

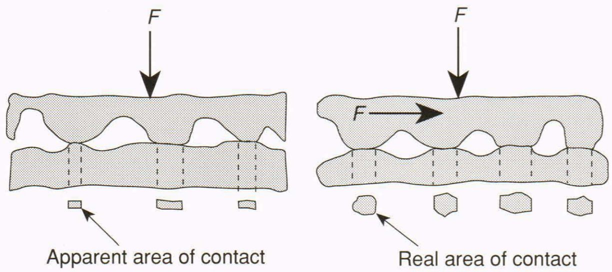


Figure 10. Diagram showing the apparent and real areas of contact under static (left) and sliding (right) conditions (*F* denotes force). This diagram represents the actual conditions of a surface and accounts for initial wear in bearings and gears. (Reprinted, with permission, from Ref. 11. © 1987 Elsevier Science Publishers.)

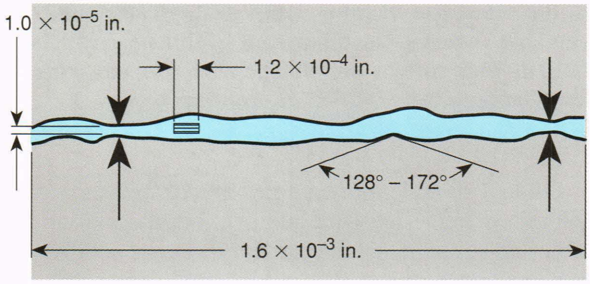


Figure 11. An expanded representation of the surface contour of a ground finish of 8 x 10^{-6} in. rms. Compare with Figure 12. The section shows the typical angle of the peaks and valleys in the ground surface, which in turn can be related to the ability of an oil lubricant to feed into the valleys, thereby contributing to a film of lubricant on the surfaces. A similar situation exists with an extreme-pressure grease (fills up the valleys with a boundary film). (Reprinted from Ref. 9.)

a heavy load, a grease with a Teflon or MoS_2 extreme-pressure additive should be used. A harmonic drive has a flexing gear/flexing ball-bearing system and a regular gear; it is highly recommended that all three components be lubricated with a grease that contains an extreme-pressure additive. Motor brushes must also be lubricated with a material that does not critically increase the resistance across the contact but that does reduce the wear of the brushes to an insignificant value. The decision of whether or not to lubricate flex pivots depends on the design, construction materials, and application. In any event, a "touch" of lubricant will not hurt.

Applied Loads

The higher the load, the more likely it is that a boundary/surface-film lubricant will be required. In every application, however, the applied load must be considered along with the type of motion and the results of a critical life test before a lubricant is selected. For example, gears have applied loads that are concentrated on a small area, and their motions are of a rolling/sliding nature. Thus, the selected lubricant must be appropriate for both of these characteristics.

Materials of Construction

The contacting surfaces of the components must be compatible with themselves and with the environment. The following is a list of requirements for materials that must be considered when selecting a lubricant for a particular application.

1. The materials should not set up a corrosion cell.[10]
2. The materials should have the proper surface hardness to withstand the expected wear.
3. The surface finish should be compatible with the type of lubricant and the overall environment (see Figs. 11 and 12 and Ref. 11 for examples of surface finishes).

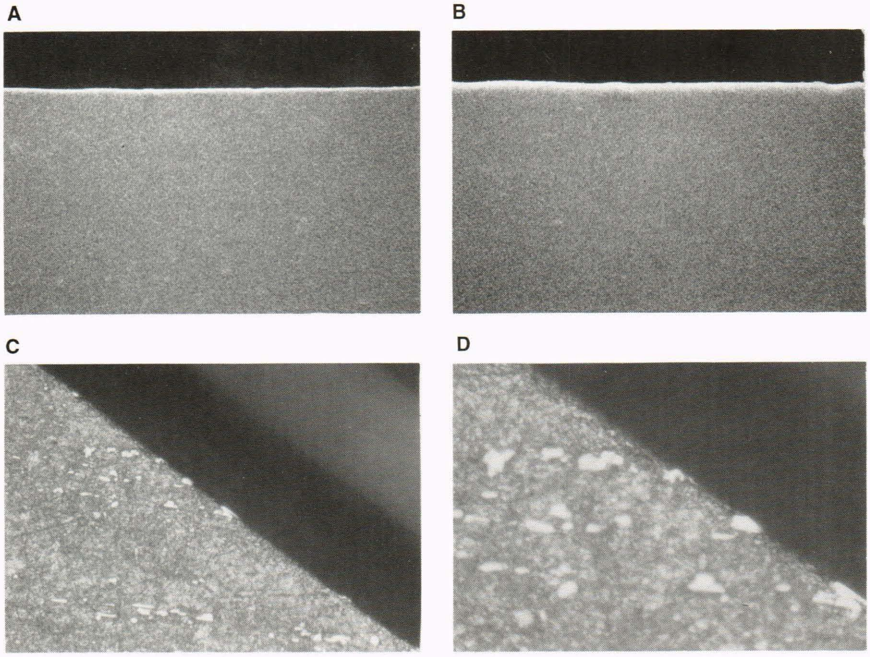


Figure 12. Scanning electron microscope (SEM) and light optical microscope (OM) photographs of a mounted and polished cross section of the inner race (ball track) of a 52100 steel ball bearing. **A.** SEM at 315×. **B.** SEM at 630×. **C.** OM at 315×. **D.** OM at 630×. Note the uniformity of the surface and the micro extensions of the white, hard, carbide precipitates out of the surface. Compare with Figures 10 and 11.

4. The materials should be amenable to the manufacturing process.

5. The materials should have the proper mechanical properties for the application.

6. The materials should not cold weld in space; if such a material must be used because of a specific material property, a protective coating such as a hard anodized aluminum alloy should be applied.

Properties of the Lubricant

Outgassing

Outgassing is a property of a material that expresses its weight loss and tendency to condense onto a colder surface when tested at an elevated temperature. The standard outgassing test for materials for space applications is ASTM E595-77/84; the test data are listed in NASA Reference Publication 1124.[12] The test is performed with the sample at 125°C, and the condensable material is collected at 25°C. Because most spacecraft mechanisms operate well below these temperatures, it is preferred that a second test be performed with the test temperature as close as possible to the temperature of operation of the specific instrument.

Vapor Pressure

Vapor pressure is a property used in determining the outgassing rate (weight loss) during operation and depends on the temperature and chemistry of the material. It is essential to know the values at the actual temperatures of operation, and to consider this information when determining the quantity of lubricant required and the potential contamination of adjacent critical surfaces such as optics.

Viscosity

Viscosity is one of the properties of liquid lubricants necessary to determine the torque requirements of the system as well as the creep/wettability of the fluid, specifically with a change of temperature. Viscosity increases as temperature decreases; a material can become very viscous at -35 to -60°C.

Surface Tension

Surface tension is associated with determining the creep properties of a fluid lubricant. As the surface energy of the fluid decreases, its tendency to creep increases. This effect contributes to a greater inclination to creep back under the ball in a bearing and/or out of a ball bearing, results that can be either favorable or unfavorable, depending on the application.

Temperature Range

The operating temperature range for a fluid lubricant will alter several of its room-temperature physical properties including vapor pressure, viscosity, and surface tension. As the temperature varies in the component, the torque in an oil/grease-lubricated device will change because of the change in viscosity of the lubricant. The temperature range for solid-film boundary lubricants must be known because temperature changes may degrade the adhesion of the film to the substrates; precipitate cracking of the film, thereby causing it to spall (differential thermal expansion); and increase its wear. These effects create unwanted debris, contributing to an increase in the wear rate and the torque of the system.

Type and Quantity of Lubricant

The following lubricants are commonly used in spacecraft applications: oils; greases with extreme-pressure additives; solid films (burnished and vapor deposited) such as MoS_2, Teflon, tri-cresyl phosphate, and SLPM's; and hardened surfaces (e.g., case hardened, thermal sprayed, deep oxidized, or nitrided). The quantity of lubricant used depends on several variables such as time, torque margin, operating temperature, total environment, and construction materials. It is essential that sufficient lubricant be used, but not too much or too little. At times in the same-size bearing, 1 mg of lubricant may be acceptable, whereas at other times, 100 mg may be required. The correct amount depends on the particular application.

RUN-IN OF THE UNIT

Often a suitable lubricant is applied, such as a grease with an extreme-pressure additive, but the motion is so slow and so small that the extreme-pressure additive does not function properly. In such an application, the components should be run-in under specific loads, types of motion, speed, and time so that the extreme-pressure additive is put down, generating a surface/boundary film on the contacting surfaces.

LIFE TEST INSPECTION AND TEST PROCEDURES

After a lubricant has been selected for a specific application, a life test should be performed (at least a life test of the most critical components) to "prove out" the system. In addition to the life test, a pre-life test and post-life test should be performed.

Pre-Life Test

A pre-life test includes examination of all components (both macroscopic and microscopic), the assembled unit, and all documentation. All specifications must be met, or appropriate waivers must be prepared and approved with all discrepancies noted and corrected. Further, all test parameters must be evaluated and appropriate suggestions made (conditions should be sufficient to put down a surface/boundary film). Fixturing and setup must also be reviewed and approved.

Post-Life Test

The post-life test includes a review of the test data, inspection of the mechanism in the test configuration and after removal and disassembly, macroscopic and microscopic inspection of the wearing surfaces of each component to determine wear or lubricant degradation, and documentation of all results. After the tests are complete, recommendations should be made as to the acceptability of the lubricant and the test procedure.

SUMMARY

The lubrication of moving components in mechanisms operated in space must be studied thoroughly and tested adequately. For each application, detailed life testing and examination of the individual components before and after such testing must be carefully performed. If such an effort is carried out with care, the necessary lubrication of the mechanism and its successful operation in space should follow.

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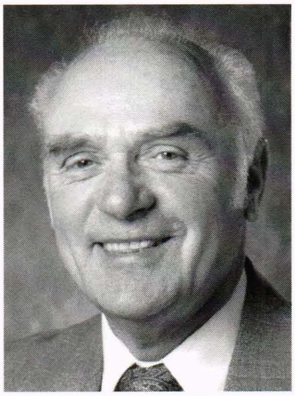

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