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# Tribology in the Space Environment

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Prepared for

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The environments of spacecraft—be they launch vehicles, orbiting satellites, or exploration vehicles (the moon or other planets)—are definitely extreme. While apparatus can be forced to operate in extreme heat or cold, in radiation environments, or under severe conditions of load, speed, and direction of motion, the major condition with which space tribology must be concerned is the vacuum environment, i.e., the absence of atmospheric gases that often provide protective coatings to minimize wear and reduce friction.

Moving mechanical assemblies can include rolling element bearings, sliding latches and actuators, gears (including harmonic drives), and sliding electrical contacts. The latter are limited to relatively short distances of travel, less than ten million passes for rolling or sliding contacts, and relatively low speeds.

Tribological surfaces for space applications include steels, both high carbon and corrosion resistant, other metals such as titanium and aluminum, ceramics and ceramic thin films, and polymers and composites. Surprisingly, spacecraft manufacturers in the United States and in many other countries favor the use of oil and grease lubricants, although for many applications solid films are preferred. Fluids, on the other hand, must be confined to reduce evaporative loss over long lifetimes of operation at moderate to high speeds. Some newer synthetic oils with outstanding lubricating properties have made sealing requirements less severe in recent designs.

Finally, there are a variety of performance requirements for space mechanisms, ranging from high-speed, highly loaded ball bearings in controlled moment gyroscopes to cryogenically cooled bearings in some liquid rocket engines that obviously become very hot during operation, as evidenced by discoloration of steel bearings in these devices.

In this report, numerous examples of spacecraft mechanisms will be cited with discussions of the lubricants and tribologies associated with each. Observations and opinions of the author, based on experience and laboratory studies, concerning best practices for a number of specific applications are presented.

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# 1. Introduction

The original invitation for this paper was for a presentation on tribology in extreme environments. The definition of an extreme environment is very much a function of the intended application. Thus, what is extreme for automotive applications is not necessarily extreme for space applications. This report will present information concerning tribology in the space environment, specifically concerning moving mechanical assemblies (MMAs), structural materials and surfaces of bearings and other tribological components, and lubricants for these components and MMAs. The environments of spacecraft—including launch vehicles (rockets), orbiting satellites, and exploration vehicles (for lunar or planetary surfaces)—can be extreme. Typical environmental factors considered by space vehicle manufactures include pyrotechnic shock, random (3-axis) vibration, natural and man-made radiation, thermal cycling, orientation effects (gravitational effects in ground testing), and electromagnetic interference/charging. These factors can all be of concern for the tribologist, along with variable conditions of load, speed, and direction of motion. However, the single most significant environmental factor with which space tribologists must be concerned is the vacuum environment, i.e., the absence of atmospheric gases that often provide protective coatings to minimize wear and reduce friction. These same gases can be destructive to space-qualified lubricants during ground storage and testing.

The mechanisms utilized on spacecraft encompass various sliding and rolling elements; they have surfaces of variable composition, hardness, and toughness; and they operate under grossly different conditions of speed and load. In the latter case, speeds can vary from the extremely slow rotation of a solar array on a geosynchronous, three-axis stabilized satellite (approximately one revolution per day) to moderately high-speed spin bearings in gyroscopes (up to 15,000 rpm) and momentum wheels (usually less than 6,000 rpm). For all known conditions of operation, the contact mechanics are relatively benign, so that it is safe to say that any space mechanism will operate to its requirements as long as sufficient lubricant is maintained in the contact regions.* This observation means that most designs and structural materials will meet most of the objectives of most missions, providing that the lubricant has been engineered into the system in the correct fashion.

The lubricant is the single most significant part of any spacecraft moving mechanical mechanism. Engineering cultural differences have led to different philosophies in the approach to lubricant selection, depending on which side of the Atlantic the designers and manufacturers live. Simply stated, building apparatus to operate for years in space vacuum with no servicing requires methods of confinement of lubricant to the pertinent area of contact. Europeans have exploited the advantages of solid-film lubrication for appropriate applications,[1] while in the United States much more emphasis has been on engineering systems to accommodate the use of oils and greases.[2] Both solids and fluids have their advantages, and there are tribological conditions that demand one or the other.[3] New preparations of both types of lubricant have emerged during the ten years since the above-mentioned

* One possible exception to this statement involves the turbopump bearings on rocket engines such as those used on the Space Shuttle main engine (SSME). In this case, it would probably also hold true if it were possible to have lubricant, but because of the extremes of heat and pressure, material substitution (the use of silicon nitride balls and an improved self-lubricating bearing design) was needed to improve reliability.

assessments were prepared.[1,2] Doped and multilayered $MoS_2$ thin films were developed specifically for spacecraft applications,[4,5] and synthetic hydrocarbon oils have been adopted from terrestrial industrial and automotive applications for use on spacecraft.[6,7]

This report is based on the author's experience working on research of solid and fluid lubricants and a wide variety of practical, operational problems associated with spacecraft hardware. An exhaustive review of the literature is not intended. Instead, specific examples of space-environment-related problems and our approach to their solutions is presented. After a discussion of various types of MMAs used on spacecraft (here I concentrate on orbiting satellites since my experience is in this area), I cover materials and surfaces of concern in these devices and then concentrate on lubrication. As indicated in the previous paragraph, aspects of solid and fluid lubricants are discussed with emphasis on environmental factors that can determine proper material selection and ultimate performance.

## 2. Moving Mechanical Assemblies (MMAs)

Early satellites (Sputnik 1, 4 Oct. 1957; Explorer 1, 31 Jan 1958) were very simple by today's standards and had almost no moving parts. If they had communications antennas, they were omnidirectional so that pointing was not an issue. As time progressed, designs evolved, and the level of sophistication increased. Two basic techniques were employed for stabilizing satellites in their orbits: (1) spinning the main body of the satellite to create gyroscopic stabilization and (2) three-axis stabilization with the use of spinning fly wheels to control momentum in all directions or by means of small rocket motors (known as thrusters) to continuously adjust position. The complexity and evolution of MMAs on satellites were functions, in part, of the type of stabilization process employed. Thus, for spin-stabilized systems (mostly communications satellites), the principal moving parts consisted of the deployment latches and actuators and a device known generally as either a "despin mechanical assembly" (DMA) or a "bearing and power transfer assembly" (BAPTA). This latter device served as the interface between the spinning satellite and the despun or pointed antenna. Besides providing the structural rotation between the two parts of the satellite, this device also had to provide for conduction of power and signals across the rotating interface.

Figure 1 depicts a Defense Satellite Communications System II (DSCS II) satellite from the mid and late 1970s and early 1980s.[8] Though eventually replaced by the 3-axis stabilized DSCS III, the

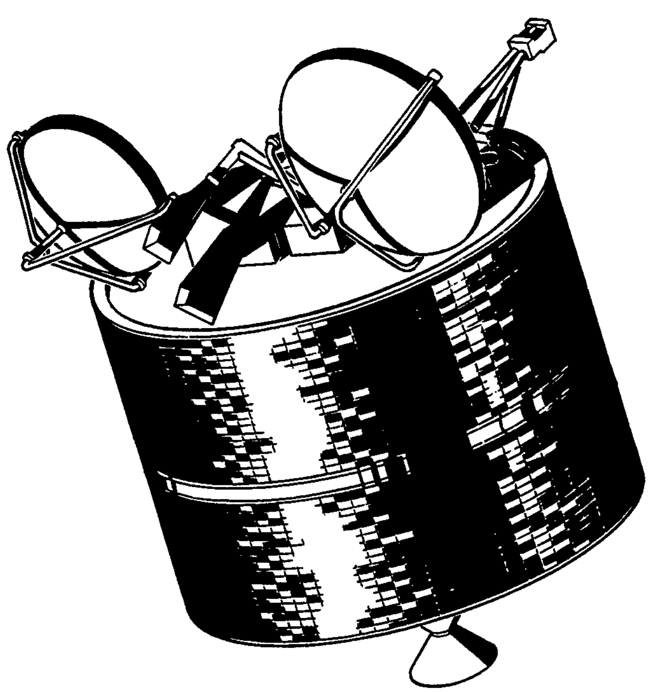


Figure 1. DSCS II Satellite showing antennas on top and solar cells around body.

DSCS II satellites had an exceptional record of success with typical operational lifetimes of eight to ten years. The DMA (BAPTA) for this satellite is characteristic of many that are used for spin-stabilized systems and for solar array drives on 3-axis systems. It contains relatively large (90 to 110 mm bore) bearings to support the rotating structures and a slip-ring assembly (also known as an "electrical contact ring assembly") consisting of gold wire "brushes" sliding against gold (plated) rings.[9] The slip-ring shaft is supported by a set of smaller ball bearings. Both sets of bearings and the sliding surfaces are lubricated with a mineral oil formulated with an antiwear additive to minimize wear in the boundary lubrication regime generated by the 60-rpm rotation rate. Two real-time life tests of the flight hardware were conducted for seven and ten years, respectively, and showed outstanding results with no evidence of abnormal or anomalous performance. The bearings and lubricants were in excellent condition after the tests, and oil migration studies indicated that lubricant remained in the regions of initial application over the entire seven-year life test.

The design philosophy embodied in DSCS II employed oil lubrication with care taken to provide labyrinth seals to prevent evaporative loss of oil during operation in the space vacuum.[10] This system worked very well; however, for the case of solar array drives involving even slower rotation rates, solid lubrication of the bearings and slip-ring surfaces also has proven to be very effective with perhaps less engineering complexity because of the absence of concern over evaporative losses. Both bonded and sputtered $MoS_2$ films have been used on the bearings.[11] The slip-ring assemblies consist of silver (85%)–$MoS_2$ (12%)–graphite (3%) composite brushes sliding against silver (plated) rings. These dry-lubricated systems are quite robust in the space environment, but the moisture in normal air (of say 50% relative humidity) can cause reactions of the $MoS_2$ and silver that result in electrical noise in signal circuits. Thus, standard atmospheric conditions constitute an "extreme environment" in this case. The degradation mechanism, during periods of storage, that leads to the generation of electrical noise is believed to be reaction of the $MoS_2$ with moisture in the ambient to liberate $H_2S$. The $H_2S$ then reacts with the silver on the ring to form $Ag_2S$ directly beneath the brush. $Ag_2S$ is a semiconductor, so the films cause electrical noise spikes when brushes pass over the affected areas of the ring. The films generally wear away in time, providing a healing or recovery of nominal behavior, but the recovery process may be rapid or may persist throughout the intended mission, depending on the rotation rate of the assembly. In extreme cases, if the bulk of the $MoS_2$ reacts to form $MoO_3$, there is no lubrication, and severe wear of the rings occurs upon operation. Consequently, it is essential that such systems be protected from the atmosphere during storage, which usually is accomplished by enclosing the hardware (in a bag or box) and then purging the enclosure with a dry, inert gas.

One other configuration, which is used for BAPTAs with relatively high spin rates (30 rpm), is to have oil-lubricated bearings with composite silver-on-silver slip-ring assemblies. In these applications, the units experience more than 150 million revolutions in a ten-year life, so dry-film lubricated bearings are impractical. In general, electrical contact lubrication for space applications has been a neglected subject. Most of the systems available today are adopted from similar ones that are used in terrestrial applications, such as in electrical motor brushes. There is very little fundamental understanding of the processes involved in slip-ring lubrication. For example, for composite lubricated systems it is not know whether lubricant transfer rates are faster or slower if speed or brush pressure are increased nor whether faster transfer rates decrease or increase brush wear rates. Systematic investigations of these contact phenomena are needed if long-life, reliable systems are to be built in the future.

Figure 2 depicts other United States Air Force Satellites encompassing communications, surveillance, weather (meteorological), and navigation missions, and provides a minimal indication of significant MMAs. These satellites are all fixed in stable positions in orbit. (The surveillance satellite shown actually rotates slowly, but the entire vehicle is pointed in a given direction.) The mechanical subsystems indicated are ones for which we have provided the greatest amount of tribological consultation over the years in order to increase reliability and performance characteristics of the overall missions. Historically, operational problems with these devices have caused the greatest concern, and we have conducted laboratory tests of lubricants and surface treatment procedures to minimize torque disturbances and maximize lifetimes during operation. The types of problems encountered with these devices concerned ball bearings and sliding electrical contacts. In all cases, the problems were solved by either lubricant substitution, control over manufacturing conditions, environmental control after fabrication, or a combination of all three. Other types of tribological contacts are encountered in latches used to secure solar panels, sensors and their covers, extendible booms (for scientific measurements or probes), and any other apparatus that are stowed during launch and then deployed after reaching orbit. Typical latches are lubricated with solid films based on $MoS_2$ or perfluoropolyalkylether greases. Since the normal operational mode is for only one pass in the space-vacuum environment, there are no real lifetime considerations, except that during ground testing the devices can

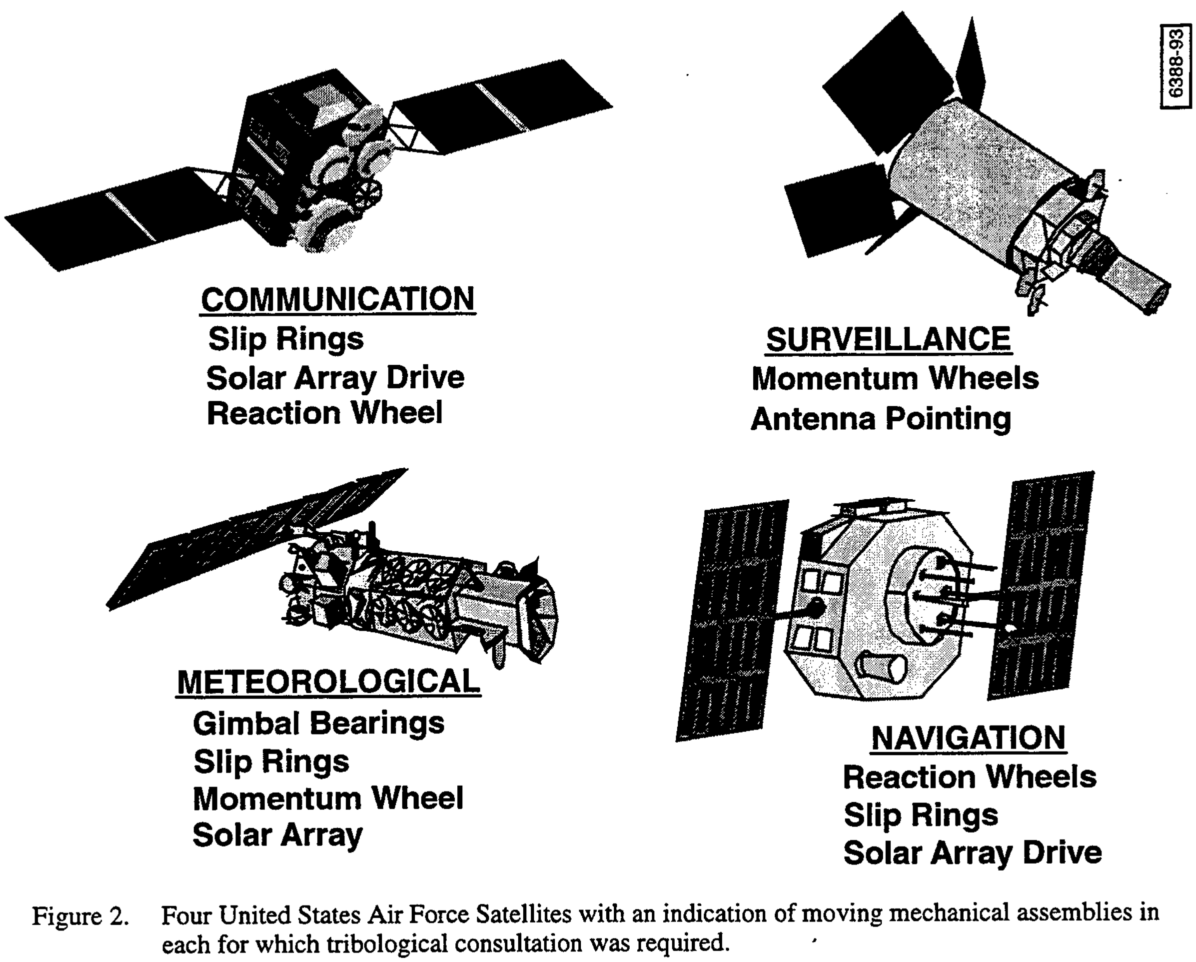



Figure 2. Four United States Air Force Satellites with an indication of moving mechanical assemblies in each for which tribological consultation was required.

be operated for 10 to 100 passes, often in air! Again, there are potential "extreme environment" problems because the lubricants are designed to perform in the absence of potentially deleterious oxygen and water. It is imperative to guarantee that the lubricant is not removed or reacted during testing so that proper function is not compromised once the satellite reaches its orbit.

Another set of MMAs that have required considerable attention so that proper lubrication was provided encompasses actuators, including harmonic drives, that are used to steer antennas, solar arrays, and sensors on stabilized platforms. Typically, stepper motors drive a gear train that provides very fine adjustments to the orientation (or pointing) of the device. The gears and the associated ball bearings operate in the boundary lubrication regime and can undergo changes in direction of motion. Ideally, these devices can be lubricated with $MoS_2$-based, solid-film lubricants, as long as the gear ratios are not such that the number of revolutions or passes exceeds the limit for these films (a maximum of about 10 to 20 million revolutions). In practice, in the United States, fluorocarbon-based or, more recently, synthetic hydrocarbon-based greases are used. Both life tests and flight experience have shown that the synthetic hydrocarbon greases are superior in terms of torque stability, wear, and contamination considerations.[6] In combination with some of these actuators, position indicators, such as potentiometers, are also used. Potentiometers are another form of sliding electrical contact. The metal wipers slide against metallized polymers and are usually lubricated with a mineral or synthetic hydrocarbon oil. Fluorocarbon oils have been found to create highly resistive films and to degrade under the boundary conditions.

The mechanical devices employed on satellites that have provided some of the greatest challenges for tribologists consist of the various types of fly wheels used for momentum compensation and stabilization. By convention, such wheels are called *momentum wheels* when the rotation is in one continuous direction at a constant angular velocity; *reaction wheels* when angular velocity is changed during a mission with the possibility of reversals in direction; and *controlled moment gyroscopes* (CMGs) when the rotating wheel, also running at constant angular velocity, is gimbaled to change the direction of the momentum vector and thus the interaction with the main body of the satellite. Typically, wheels are arranged in clusters in a satellite so that, in conjunction with appropriate control systems, all axes of motion can be stabilized. Frequently, designs will include spare wheels to provide redundancy in the event of an anomaly or failure during the mission. Wheel systems, specifically the spin bearing arrangements, vary somewhat depending on the manufacturer, but normally one or more pair of very high-precision bearings supports the spinning elements. Oils lubricate the bearings during operation in either elastohydrodynamic (momentum wheels and CMGs) or boundary regimes (often for reaction wheels). Highly refined mineral oils (sometimes in grease formulations) have been used, primarily with phosphate ester additives, in practically all wheel applications. For the most part, wheel operation was very successful with lifetimes of operation in excess of ten years. However, designers have recently increased the rotation speeds of wheels to over 5,000 rpm to achieve greater moments of inertia and momentum capabilities, and numerous anomalies and failures have occurred. (Other, slower-speed systems have failed, but it has usually been because of inadequate, initial oil supplies or extended, on-the-ground storage times prior to launch.)

A schematic torque trace for a wheel in the process of exhibiting major anomalies and ultimate failure is shown in Figure 3a. This type of behavior is very characteristic of many failures that we have studied. Initial periods of high torque are followed by recovery and nominal operation for a significant time. Gradually, the periods of unstable, high torque become more frequent and increase in

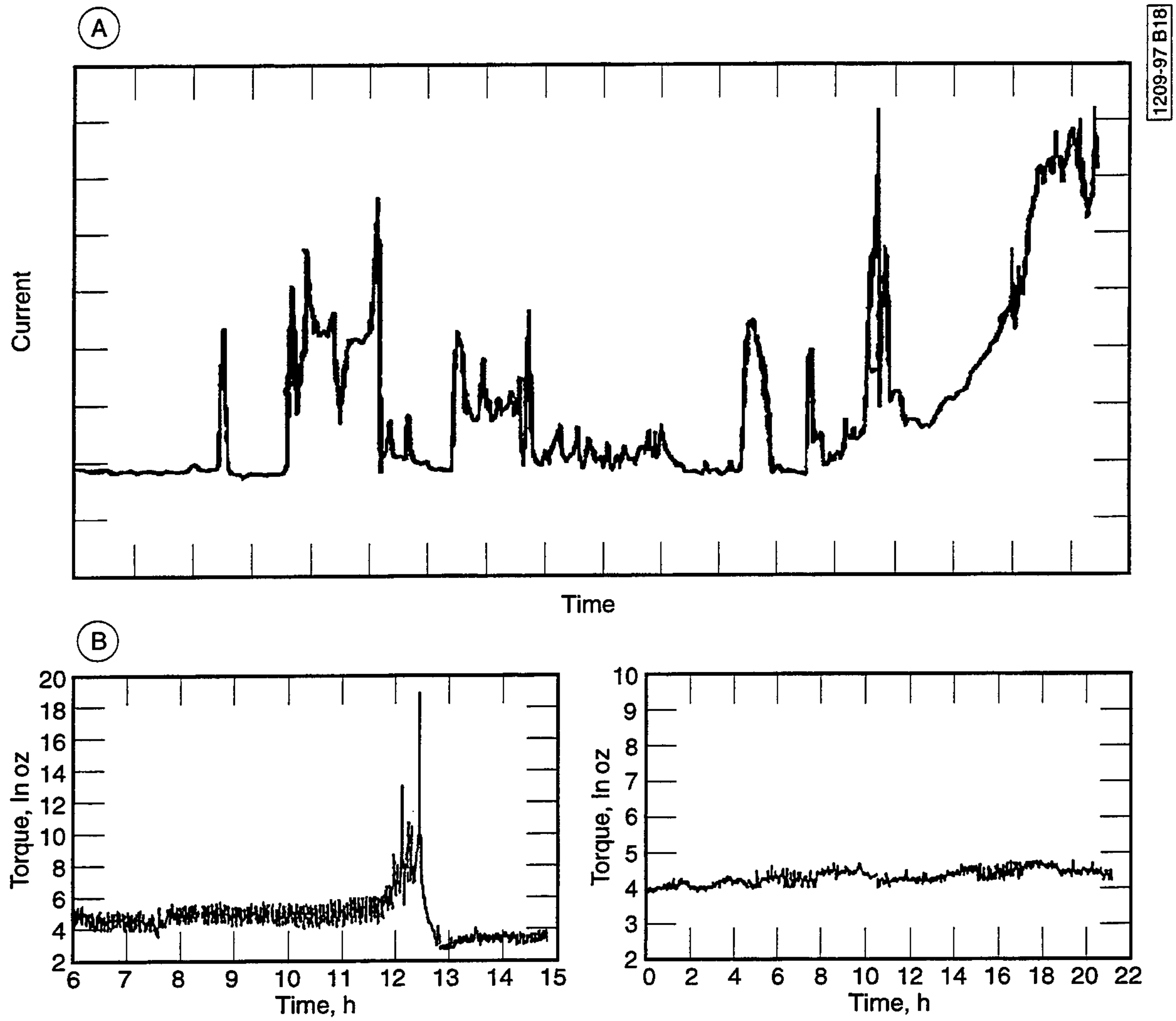



Figure 3. Torque data. (a) Schematic torque (motor current) trace for a momentum wheel experiencing bearing retainer instability and eventual failure. (b) Torque traces from bearing tests for which the initial quantity of oil was a very thin film applied from a 50:1 solvent-to-oil solution. On the left is a trace for KG-80 oil showing the onset of retainer instability, which is quieted by the injection of 100 μL of fresh oil. The right trace is for the same bearing with NYE 2001 (Pennzane) oil, showing no instability for twice the running time. A 100:1 solvent-to-oil solution treatment was necessary to obtain instability within a reasonable operating time for NYE 2001.

amplitude. Ultimately, the system torque exceeds the capability of the motor, and the system shuts down. Disassembly and analysis of ground-test systems that have experienced this type of failure have shown that the ball-retainer pockets have been "burned," and that, in general, the ball pathways and the balls are lacking in oil. The failure mechanism has been attributed to (a) loss of oil on the critical surfaces (the balls, the ball pockets, and the ball tracks on the raceways); (b) increased friction between the balls and the retainers or between the retainers and the controlling land; and (c) eventual retainer instability that exacerbates the entire cycle. Laboratory simulations (Fig. 3b) have shown that bearings lubricated with limited initial quantities of oil exhibit the same type of torque behavior, and this torque run-away is cured by the addition (injection) of oil directly into the bearing raceway. Another observation was that the use of synthetic hydrocarbon oils (poly-alpha-olefins or multiply alkylated cyclopentanes[12]) delayed the onset of instability substantially and generally provided for much smoother and longer operation.

During the investigation of these retainer instability events, exhaustive studies of retainer properties and oil absorption characteristics were conducted in The Aerospace Corporation's tribology laboratory.[13] Figure 4 depicts the type of behavior that is characteristic of the classical cotton-phenolic type of retainer. The major conclusion of this very comprehensive study was that oil is absorbed into the retainers in a two-step process, one that is rapid (within a few days), and a second that is very slow (taking months and even years). The rapid process is believed to occur via capillary action along the reinforcement threads of the composite material. The slow process probably corresponds to diffusion of oil into the phenolic matrix. Most retainers need to be immersed in oil for a minimum of seven days to complete the capillary process. It is not necessary to conduct the impregnation process in a vacuum, but it is essential to dry the retainer prior to putting it into the oil and for the environment surrounding the immersed retainer to be rigorously moisture free. Also, exposure of an impregnated retainer to moisture can force oil out of the cotton-phenolic matrix. Fully impregnated retainers

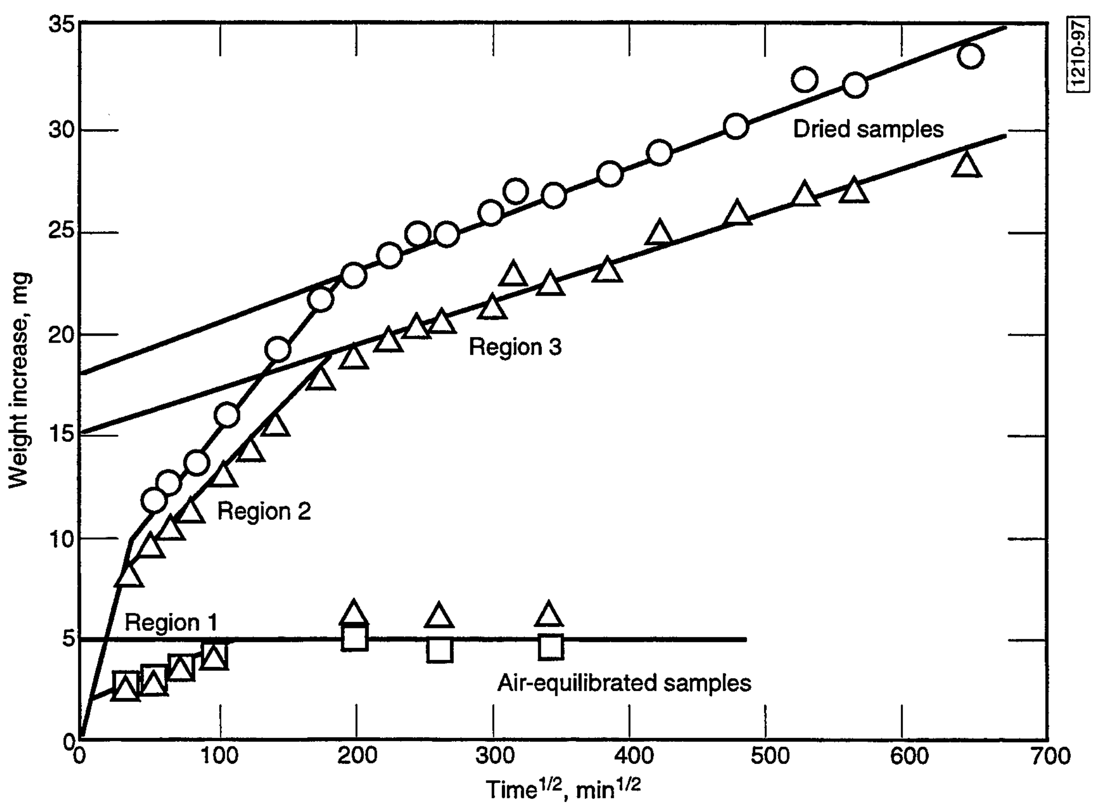



Figure 4. Oil absorption into cotton-phenolic material showing a two-step absorption mechanism and the drastic effect of ambient moisture on absorption. Regions 1 and 2 correspond to capillary fill associated with the threads and region 3 is fit by diffusion from the capillaries into the resin matrix. (Adopted from ref. 13.)

assist in maintaining oil in bearings because they do not absorb oil from the lubricated metal parts. There is no net delivery of oil from the retainer to a bearing, even if the metal is depleted (14), but impregnated retainers tend to provide lower friction surfaces for contact with metal parts and thus help minimize retainer instability events. Additional information regarding the superior performance of synthetic lubricants is presented in the section on lubricants.

## 3. Materials and Surfaces

The materials used to fabricate most spacecraft MMAs are ones adapted from terrestrial applications and are known to most tribologists. There is very little about the space environment that makes material selection, apart from lubricants, very unusual. Instead, standard criteria such as predicted loads and stresses, speeds of operation, and fatigue properties are used to select most materials. One criterion, potentially unique to space applications, concerns the outgassing properties of any material, but again this normally relates to the lubricants (see the next section) rather than to the structural materials. This lack of uniqueness is not to say that there is not a variety of different materials and surface treatments used for space applications. Selection depends entirely on the type of apparatus and the conditions of use and performance.

Standard bearing steels, mostly 52100, are used in ball bearings for space mechanisms. In some instances, because of concerns about corrosion during ground operations, stainless steels (440C) are utilized. To my knowledge, no space ball bearing has failed because of fatigue problems within the bulk material. Failures result from depletion or failure of lubrication and subsequent wear of metal or retainer parts. However, recent projections of fatigue requirements of a wheel bearing system have concluded that steel alloys with higher fatigue ratings (e.g., Rex 20) will be required for the specific application. Once the materials are selected to meet the load and stress predictions, one can expect that the ultimate determination of lifetime of operation again will be the effectiveness of the lubrication system.

The preparation of steel surfaces for ball bearing use has received renewed attention during the recent past because of the restrictions placed on chlorofluorocarbon solvents and the solvents' effects on the Earth's environment. Studies of steel surfaces have revealed that the oxide structure is complex and that cleaning can alter this structure.[15] The composition and structure of the surface of a steel is extremely important because of the effects on protective film formation and lubrication. The formation or growth of antiwear additive layers and films [i.e., tricresylphosphate (TCP)] are particularly sensitive to surface chemical compositions.[16] In the past, solvent rinsing (with Freon) of TCP-coated parts left the films intact; but the newer, environmentally friendly, detergent-based cleaners remove most of the phosphate-containing material on test surfaces. On the other hand, wear tests with The Aerospace Corporation's eccentric bearing tester have shown that TCP pretreatment of bearings is not nearly as important as having the additive formulated with the base stock[17–19] (see Figure 5). The chemical interaction(s) of the additive with the steel still determine the degree of surface protection and the overall performance, in spite of their complexity. Such interactions can be thermally induced, as with the TCP pretreatment, or they can be tribochemically induced. Data in Figure 5 show that a bearing initially run-in for approximately 10% of total normal life with formulated oil, operates 2 to 3 times longer than one pretreated with the standard thermal, TCP process. Both test were run with pure base oil after the respective pretreatments (run-in or heating).

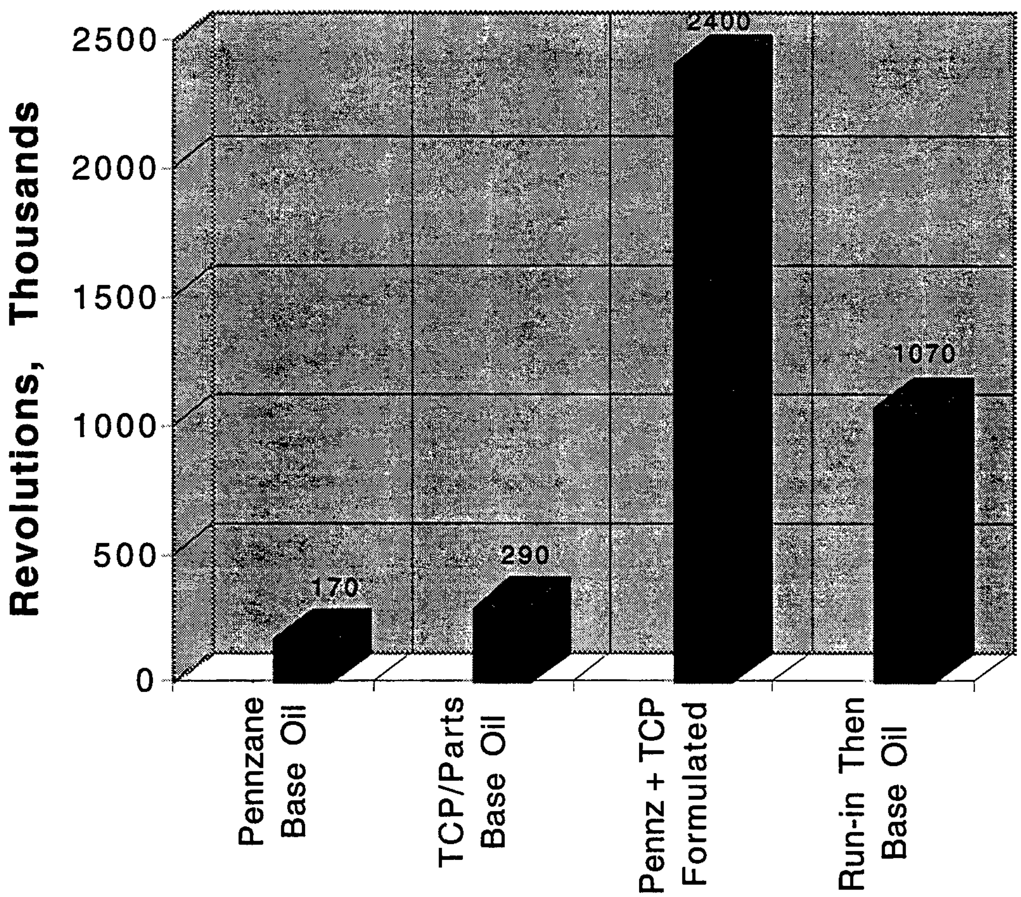


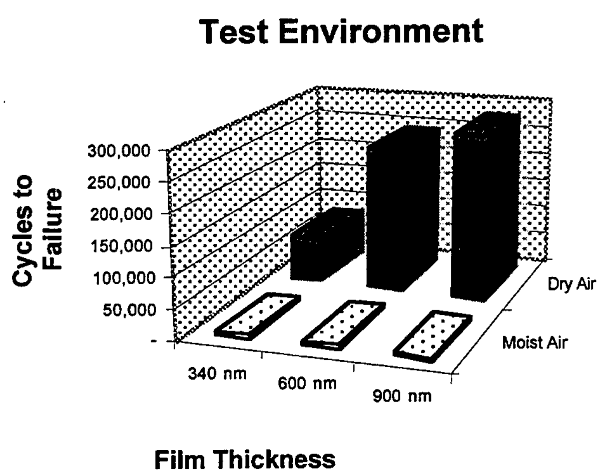

Figure 5. Wear-test results of The Aerospace Corporation eccentric bearing tester. The formulated oil ran nearly 20 times longer than the base oil and almost 10 times longer than the pretreated sample with base oil. When the bearing was run-in for 180,000 revolutions and then rinsed and run with base oil, it lasted 3 times longer than the pretreated sample with base oil.

The coating of ball and raceway surfaces with hard, thin films has gained significant popularity with the designers of European space hardware but is only just beginning to be explored in the United States space business.[20,21] TiC-coated balls have been used with great success in BAPTA and momentum wheel bearings and in gyroscope bearings for aircraft applications. Tests of such bearings have run for more than twice the life of uncoated bearings with identical lubrication and shown no evidence of degradation.[22] Though all of these results are very supportive of hard-coated surfaces, it is important to realize that the surface compositions of such parts are grossly different from those of standard steel bearings, and that these differences could significantly impact the reactions and performance of friction-reducing additives in lubricants. So far, the evidence seems to indicate that surface chemical differences are of little consequence, but investigations are in progress to better understand possible implications for other device applications and for the development of more space (vacuum) friendly additives.

The materials and surfaces of other MMAs present some variations as, for example, with the use of polymers in some latches and in potentiometers. Also, titanium is a material of choice for as many parts as possible because of its light weight. Care is required with titanium surfaces, however, because of its tendency to gall, so that coatings or surface oxidation and minimization of contact stresses are essential. In general, various steels are used for most devices, including latches, actuators, and gears. TiN coating of gears has been considered, but is not widely used at present. Finally, as mentioned previously, gold and silver are used for slip-ring assemblies to provide good electrical conductivity and relative chemical inertness.

# 4. Lubricants

The selection of a solid or fluid lubricant for a particular space application depends primarily on the conditions of load and speed (life) of the contacting surfaces. Solid lubricants provide many advantages in terms of the lack of susceptibility to space vacuum and radiation, but they are limited to applications involving relatively benign stress and low number of passes (rotations). The most common solid-film lubricants are based on $MoS_2$ or Teflon. They are applied to the critical surfaces in the form of bonded, burnished, or sputtered films.[11] Sputter-deposited $MoS_2$-lubricated ball bearings have obtained a maximum of 20 million rotations before failure[5] and should not be designated for contact stresses in excess of approximately 1 GPa. Sputter-deposited $MoS_2$ films are particularly sensitive to moisture in the operating and storage environments.[23] Figure 6 shows data for sliding tests of rf sputter-deposited films of $MoS_2$ of different thicknesses in moist [50% relative humidity (RH)] and dry air and for doped (Ni) and undoped films after storage in humid (85% RH) and dry environments. The most obvious observation is that the life in moist air is a small fraction of that in dry air. These data are for older films made in our laboratories, and some improvements for multilayered materials have been observed, but the basic conclusion that moisture threatens lifetime remains. Storage conditions can also have a dramatic effect on the ultimate life of $MoS_2$ films. It is imperative that ground testing and storage of devices lubricated with $MoS_2$ films be effected in a protected environment, either vacuum or inert gas. [There is some concern that inert gas does not reproduce the operational environment of space vacuum, but there is no disagreement that moisture is extremely detrimental.[24]]



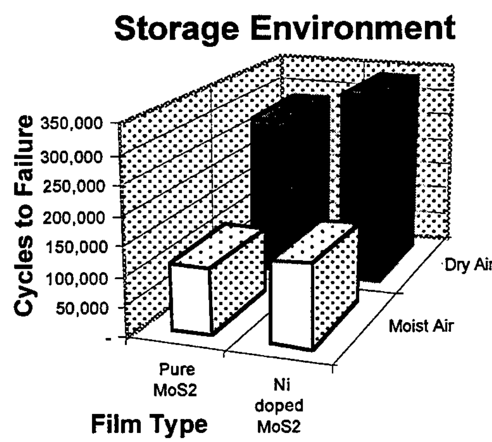




Figure 6. Sliding wear-test results showing the negative effects of moisture during testing and storage of sputter-deposited $MoS_2$ films. Test life in 50% humid air was barely measurable. Life increased with increasing film thickness but seemed to reach a maximum value. Nine-months storage in 85%-RH air reduced wear life by about a factor of 3 compared to storage in 0%-RH air; Ni doping had little effect on life or resistance to moisture.

Certain doped and ion-irradiated $MoS_2$ sputter-deposited films and multilayered materials have provided increased resistance to severe environmental conditions and are much more durable in conventional sliding and rolling wear tests.[5,25,26] The significant structural attribute of these films seems to be that they have a parallel, layered configuration; the basal planes of $MoS_2$ are aligned with the plane of the substrate surface.[27] Measurements of the susceptibility of parallel and perpendicular films to storage-induced oxidation indicated that the parallel films have considerably greater resistance.[28] Controlled methods of production of films with parallel orientation should provide some measure of control over the critical sensitivity of sputter-deposited $MoS_2$ films to the "extreme" Earth environment. $MoS_2$ films prepared under ultra-high vacuum conditions have exhibited extremely low friction coefficients, but when exposed to laboratory air they incorporate oxygen, which is believed to raise the friction.[29] An obvious conclusion with respect to the preceding rhetoric is that for sputter-deposited $MoS_2$ films and $MoS_2$ lubricants, in general, air is an extreme environment!

Fluid lubricants (oils and greases) are employed in most spacecraft devices that require millions of cycles of operation. These materials require special design and engineering procedures to minimize loss to space vacuum. Labyrinth (also known as molecular) seals are fabricated into the devices so that oil molecules have to follow a torturous pathway to escape the bearing cartridges.[2,10] The useful lifetimes of spin-bearing systems are normally estimated by calculating the free molecular loss (pumping) of oil through the labyrinths[10,30] and then incorporating at least 2 times the total quantity of oil needed for the respective mission. Manufacturers installed porous reservoirs within the bearing cavities in an attempt to provide replacement oil to the bearings during operation. These reservoirs do provide vapor within the cavity that can exit the labyrinth and therefore reduce the rate of loss from the bearings, but they do not add oil to the bearings because the latter have the highest-temperature surfaces in the closed system. Recently, various schemes for adding oil to operating bearings have been developed and tested. Some are operating successfully in orbiting satellites. However, the most significant development to impact the design and lifetimes of spin bearing systems for space applications has been the development of synthetic hydrocarbon oils to replace the standard mineral oils.[12,31,32]

The implementation of synthetic hydrocarbon oils, in general, was slowed by the infrastructure surrounding the refining of crude oil and the tremendous economic impact of oil products. Arguments against synthetics, such as that they are not better lubricants but they do have excellent volatility and viscosity properties,[31] were exactly what the space industry needed. Both viscosities and viscosity indexes can be tailored by selection of appropriate synthesis conditions, and synthetic materials are pure compounds that have low reactivities and measurable vapor pressures,[12] two facts that make them ideal for use in spacecraft devices. No claim is made that synthetic oils were developed for the space industry; the market could not support the costs. However, their availability and exceptional fit (specifically their low volatilities) to the needs of space mechanisms is very fortunate. Formulated synthetic oils, be they poly-alpha-olefins or multiply alkylated cyclopentanes, have outperformed analogous mineral oils in all tests performed in our laboratories[6,33] and in most other studies know to us.[7,34] The low evaporation rates of synthetic oils make the need for effective resupply systems less severe, though such systems are preferred for maximum reliability. The next challenge is to provide antiwear and antifriction additives with comparable low volatilities. A U. S. Air Force, Wright Laboratory study to develop and test such materials is in progress and should produce results in the very near future.

# 5. Summary

The space environment actually poses few unusual challenges for the tribologist, except for the most obvious factor, the low pressure (vacuum) of the surroundings of any spacecraft. In specialized cases, very low or high temperatures are experienced, and specific designs must be developed. Shock and vibration associated with launch must be considered in any MMA design to avoid denting of contacting surfaces. Natural or man-made radiation can impinge on exposed tribological surfaces, such as some latches and actuators, but most devices are shielded by the materials of construction and housings surrounding the moving parts. For those devices that can be exposed to radiation, solid-films of $MoS_2$ or perfluoropolyalkylether greases are quite robust. Gravitational effects during ground storage or testing can cause oils to migrate out of bearings or other contact areas, but normally orientations that mitigate such losses can be employed. Electromagnetic interferences or charging events rarely compromise tribological surfaces unless, for example, currents flow through oil lubricated bearings for long periods of operation. For space-qualified $MoS_2$ solid lubricants, exposure to humid air prior to launch can be one of the most severe environments of all. Proper care must be taken to minimize quiescent exposure and eliminate exposure during operation (testing). New developments in synthetic hydrocarbon oils and additives are providing the satellite designer with much greater latitude than ever before. The low volatilities of the oils and acceptable viscosities are making significantly longer missions possible. In the case of existing programs, this life extension is often possible with no hardware changes, a condition that is very easy to justify to skeptical program managers.

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