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Preventing Spacecraft Failures Due to Tribological Problems

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ABSTRACT

Many mechanical failures that occur on spacecraft are caused by tribological problems. This publication presents a study that was conducted by the author on various preventatives, analyses, controls and tests (PACTs) that could be used to prevent spacecraft mechanical system failure. A matrix is presented that plots tribology failure modes versus various PACTs that should be preformed before a spacecraft is launched in order to insure success. A strawman matrix was constructed by the author and then was sent out to industry and government spacecraft designers, scientists and builders of spacecraft for their input. The final matrix is the result of their input. In addition to the matrix, this publication describes the various PACTs that can be performed and some fundamental knowledge on the correct usage of lubricants for spacecraft applications. Even though the work was done specifically to prevent spacecraft failures the basic methodology can be applied to other mechanical system areas.

INTRODUCTION

A wide variety of tribological components is required to operate in a space environment for long durations and at very low torque. Satellites and space vehicles have bushings and rolling contact bearings in components like hatch doors, manipulators, solar array drives, control moment gyros, antenna and camera pointing mechanisms, infrared horizon scanners, gear boxes etc. Sliding contacts are found in brakes, clutches, hinges, deployment devices, traction drives, etc. Mechanisms for extending or retracting devices often use wire cables requiring internal lubrication of the cable. Telemetry and electrical connections to moving parts require slip or roll rings whose contact resistance often must be low and unvarying. All these components involve sliding or rolling contacts and because of limited power available, they must operate with minimum friction. In addition, many of these tribological devices must operate both in air and in the vacuum of space.

Satellites and space vehicles are lubricated either by using liquid lubricants or solid lubricants. How well a lubricant functions is extremely system dependent and thus the choice of a lubricant (for any particular application) must be made consistent with the operating conditions of the system. Liquids and solids can lubricate in more than one lubrication regime and very different mechanisms can take place in each regime. Therefore the methods of evaluating and testing a lubricant depend upon which lubricating regime is operating.

This article will present different preventatives, analyses, controls and tests (PACTs) for selecting and employing lubricants for spacecraft tribological applications. Unfortunately one cannot use any one of these techniques with absolute assuredness to predict the friction coefficient, the wear, or the

endurance life of a lubricating system. The only certain way to do that is to evaluate the lubricant or lubricant system in the end use device under the actual operating conditions. It is almost impossible to do that on the ground. Two excellent books (Conley 1998, Sarafin 1995) discuss many of the problems and methodologies that can be used to prevent failures and are recommended reading.

FUNDAMENTALS OF FRICTION AND WEAR

Friction

Friction is the resistance to movement when one object moves relative to another while in contact. There are three basic laws of friction:

(1) The friction force (f) is proportional to the normal force (F), which leads to the relationship:

$f = \mu F$, where μ is defined as the coefficient of friction,

(2) The friction force is independent of the apparent area of contact, and

(3) The friction force is independent of the sliding velocity.

There are some exceptions to these laws, especially in vacuum, but for most situations they are applicable.

There are basically two reasons why friction occurs. The first is due to adhesion that occurs between the molecules of the two surfaces. The second is due to the fact that surfaces are not absolutely flat. When a hard surface slides across a softer surface, small asperities on that hard surface "plow" through the soft surface. This is known as abrasion.

For surfaces with contaminant films on them, friction is not a constant. This is because films wear off on repeated sliding which usually causes friction to increase. Also if the yield stress of one of the materials is exceeded, friction will increase due to plastic deformation of that surface.

Most metals have oxide films on them. When they are slid in air, these oxide films can be reformed as they are worn off. If the same surfaces were slid in vacuum (where there is no oxygen) they would not be reformed and friction would increase significantly.

Friction Measurement

Friction should be measured continuously during a test. Usually a test commences with high friction. This is a time where either the lubricant or the materials in contact are plastically rearranged to accommodate the sliding forces. It is called the "running-in" phase. After "running-in", the next phase is a period of time when the friction coefficient is fairly constant and reduced from the initial level. Generally, this is the value reported as the friction coefficient for this lubrication system. The final phase is a period of constantly increasing friction. Increasing friction is an indication that the lubricant is being depleted.

Depending on the type of lubricant, the type of materials, surface finish, etc. the final phase may take place over a long time or a relatively short time.

Another friction characteristic that should be noted and recorded is the "roughness" of the friction produced during a test. This "roughness" or variation of friction over a very short time span is due to the fact that at least one of the surfaces is constantly moving over a new surface on the other specimen and that the friction between the two different surfaces may not be exactly the same. The ability to pick up this difference is dependent on the time reponse of the device that is used to record the friction and the sliding speed of the rotating specimens. Often the width of a friction trace ("roughness" or variation of the trace) on a chart recorder can be quite broad. For example, the width of the trace might range from a friction value of 0.06 to 0.08. The width of this trace should always be noted. In general, the less the "roughness" (less variation of the trace), the better is the lubrication system.

Wear

Similar to friction, wear is caused by both adhesion and abrasion. In addition, corrosion, fatigue, erosion, and cavitation can cause wear. Also there is a type of wear called fretting which occurs in joints that are tightly held down and subject to vibrations. When fretting occurs the amplitude of the vibration is very small. More information can be found about these wear mechanisms in an article by Zaretsky 1997.

Friction and wear are not necessarily related. When there is low friction there is not necessarily low wear. Corrosion for example may provide a film that provides low friction, but corrosive wear can be very high. Every material combination has both friction and wear characteristics that are dependent on the conditions or environment under which they are being slid. Thus it is important to evaluated materials and lubricants in accelerated tests under conditions that they will experience in their end use application. Some of these conditions are: temperature, atmosphere (including moisture content), speed, load, geometry of parts, type of motion, etc. For more details on various aspects of vacuum tribological fundamentals see the publication by Buckley 1971.

Wear is loss of material from two surfaces in sliding contact. Archard 1980 has stated for adhesive wear that:

(1) Wear is proportional to the load (L).

(2) Wear is proportional to the distance-slid (x).

(3) Wear is inversely proportional to the hardness (p) of the surface being worn.

Thus Archard 1980 formulated an equation for the volume of material (W) worn away to be:

$W = kLx/p$, where k is the wear coefficient.

Since most wear is adhesive, this is the most common equation used to determine wear. In some instances, hardness is included as part of the wear coefficient and in this case the wear coefficient is expressed as:

$$k = W/Lx.$$

Since both load and sliding distance are known, the wear coefficient can be determined by measuring the wear volume. The most common methods of doing this are: (1) determining a weight change, (2) optical measurement of the scars and then calculating the wear volume, and (3) surface profiles of the change in shape of the surfaces and then calculating the volume of material removed.

To obtain the most accurate value for wear, several measurements of wear volume should be taken at various sliding distances. Since most surfaces experience "running-in," this will help separate running-in from steady state wear. The sections on solid lubrication and liquid lubrication testing will discuss this in more detail.

Wear Measurements

There is inherent scatter of wear test results. Therefore, multiple tests must be conducted under standard test conditions to provide a measure of the scatter. It is impractical and expensive to run large numbers of wear tests, so statistical methods sometimes must be used to analyze the data.

For example, a test that the American Society for the Testing of Materials (ASTM) recommends is called Standard G83-96 , "Standard Test Method for Wear Testing with a Crossed-Cylinder Apparatus." The standard details statistical methods and provides tables for determining the minimum number of tests. See Table 1.

Table 1.—Factors for estimating standard deviation based of sample size.

Sample Size (n)	d_2	$1/d_2$
2	1.128	0.8865
3	1.693	0.5907
4	2.059	0.4857
5	2.326	0.4299
6	2.534	0.3946
7	2.704	0.3698
8	2.847	0.3512
9	2.970	0.3367
10	3.078	0.3249

The minimum sample size for a series of wear tests can be determined from a preliminary round of tests from which the coefficient of variability can be obtained. The following parameters can be calculated from the wear results.

s' = Standard deviation (for sample size less than 10 $=R/d_2$)

R = Difference between highest and lowest test value

d_2 = Deviation factor (Varies with sample size)

v = Coefficient of variation, percent = $(s/x) \cdot 100$

s = Standard deviation

x = Arithmetic average wear for n tests

e = Allowable sampling error expressed in %.

n = Sample size

(95 percent confidence level) = $(1.96v/e)^2$

If the allowable sampling error is a given, then the minimum number of tests for 95 percent confidence level can be determined. This method has been used in round-robin tests for given material combinations run at selected conditions. The method was found useful for comparing the results from a number of different laboratories. Coefficient of variation among the labs that did this testing was reported in ASTM G83-90 as 30 percent.

PRETESTING ANALYSES

Controlling Specifications

For spacecraft design, if a proper set of specification documents are developed and then followed, many tribological problems can be eliminated. MIL-STD-961establishes a standard format for specification content. Specifications should include statements of scope and mission requirements. References to applicable documents and requirements such as mechanism function, operating environments, tribological interfaces, endurance life, materials compatibility, torque limits, etc. are also necessary. In addition, project-engineering documents with sufficient requirements specified to enable a detailed design of the mechanism and a process to be used to fabricate and assemble the mechanisms should be given. The materials to be used and a process for fabricating the mechanism should also be specified.

Material Certification/Review

Tribological materials are very system dependent. Extreme care should be taken in selecting the materials for a particular application. That not only includes the lubricants but also the materials from which the tribological components are made. Certify that these materials have functioned properly in other similar applications and review the literature for possible failures. To help in selecting the materials to use in space, NASA has written a *Space Materials Handbook* (Rittenhouse and Singletary, 1969).

Lubricant Evaporation Analysis

An analysis should be made on the liquid lubricant evaporative losses for each particular bearing system that is used on a spacecraft. The rate of loss will depend on the vapor pressure of the lubricant used, the vapor pressure of the additives used in the lubricant and the type of seal that is used to seal the system. In addition, if an active replenishment system is used, the rate of dispersal should also be figured into the calculation.

Lubricant Life Analysis

It is almost impossible to calculate an exact life for liquid lubricants because so many variables are involved. The most important criterion for life is to have enough liquid lubricant available so that the bearing does not run in a "starved" condition. If starvation occurs, wear to the bearing surfaces can take place that will cause mechanical noise (vibrations), higher torque and shortened life of the bearing. If adequate lubricant is supplied to the bearing and it is not over-loaded or run at excessive speeds, life should be dependent on the quantity of lubricant available for lubrication. In this case, the liquid lubricant evaporation analysis coupled with other loss factors (such as creep from the contact areas) should be able to give a ballpark prediction of the life of the lubricant.

Solid lubricants have a finite life. A solid lubricant film has an average life of so many passes or cycles slid over it or total distance slid. Solid lubricant composites tend to wear until the clearances between the surfaces become too large to operate effectively. In general, solid lubricant films or composites tend to wear at a constant rate if conditions remain constant. Reasonable life predictions can be made by running accelerated tests on solid film lubricants or composites under similar operating conditions to those that they will experience in the end-use application. Since life is very system dependent, it must not be assumed that wear rates given by a manufacturer are applicable for an application. The only way to obtain valid data for a particular application is to evaluate the solid lubricant under the exact conditions of an application.

Review Tolerance Stack-up

Dimensions are controlled in a spacecraft at the part or assembly level. The usual approach is to sum up the dimensions of the parts. This sum will then be considered the dimension of the assembly. This methodology is adequate as long as there are no thermal gradients. But thermal gradients do arise and must be taken into account. Heating can occur from outside thermal sources or from tribological sliding.

A literature review can provide expected friction coefficients needed to calculate possible thermal expansion. Thermal expansion calculations from these above mentioned sources will ensure that binding of a mechanism will not occur if there is thermal growth due to friction. Opening of clearance can also occur due to thermal cooling and this should also be considered. Sarafin 1995 discusses tolerance problems in more detail.

PHYSICAL PROPERTIES TESTING OF MATERIALS/LUBRICANTS

Quality control of lubricants can be accomplished using the physical property tests that are relative to your application. The following are some standard tests than can be conducted on liquid and solid lubricants as well as on space mechanism structural materials.

ASTM B195	Electrical resistively of metallic materials
ASTM B347	Hardness of self-lubricating composite materials
ASTM D91	Precipitation number of liquid lubricants.
ASTM D92	Flash and fire points of liquid lubricants.
ASTM D97	Pour point of liquid lubricants
ASTM D149	Dielectric breakdown and strength of solid lubricant coatings
ASTM D217	Penetration of greases
ASTM D256	Impact resistance of tribological materials
ASTM D455	Kinematic Viscosity of liquid lubricants.
ASTM D621	Deformation under load of solid film lubricants
ASTM D790	Flexural properties of materials.
ASTM D942	Oxidation stability of greases.
ASTM D972	Evaporation loss of liquid lubricants.
ASTM 1310	Flash point of solid lubricant coatings prior to application.
ASTM D1478	Low temperature torque of greases
ASTM D1743	Corrosion prevention of greases.
ASTM D2265	Dropping point of greases.
ASTM D2270	Viscosity Index of liquid lubricants.
ASTM D2510	Adhesion of solid lubricant coatings.
ASTM D2511	Thermal shock of solid lubricant coatings.
ASTM D2649	Corrosion characteristics of solid lubricant coatings.
ASTM D5949	Pour point of a liquid lubricant
ASTM E10	Standard test method for Brinell hardness of metallic materials.
ASTM E18	Standard test for Rockwell hardness and superficial hardness of metallic materials.
ASTM E228	Linear thermal expansion of solids.
ASTM E595	Material outgassing in vacuum.
ASTM 2595	Evaporation loss of greases.
ASTM F312	Particulate contamination of liquid lubricants.
MIL-L-6085	Low Temperature stability of liquid lubricants

MIL-STD-453C	Radiographic Testing.
MIL-STD-6866.	Liquid Penetrant Testing.
MSCF-SPEC-527	Materials Selection List for Space Hardware Systems.

TRIBOLOGICAL ACCELERATED BENCH TESTING

Since friction, wear and lubrication are very dependent on atmospheric conditions, it is very important to control the atmosphere when simulating conditions for the end use requirement. For the space environment, obviously the experiments should be conducted in a vacuum. However, for some initial bench screening tests, it may be possible to achieve a degree of simulation by evaluating the specimens in a very dry argon or nitrogen atmosphere. This will negate the effect that oxygen and water vapors have on the lubrication process. This section will describe a number of accelerated bench testing devices assuming that they are enclosed in a vacuum chamber or a chamber that would facilitate testing in dry argon or dry nitrogen. ASTM standards for testing would apply, but they should be adjusted appropriately for a vacuum condition.

Block-on-Ring Tribometer

A schematic of the block-on-ring test elements is shown in figure 1. The device consists of a rectangular block pressed against the periphery of a ring. The block can be flat (line contact) or it can be conforming (area contact). For area contact, the same radius of curvature is given to the contacting block face as to the ring so as to produce a large area of contact. ASTM has issued a standard testing designation for this device specified as ASTM G77. Commercial machines are built to this specification.

The block is stationary and loaded with a dead weight against the ring. The ring is attached to a rotating shaft that can rotate in one direction or oscillate. A probe attached to the block holder contacts a load transducer and measures frictional force between the block and the rotating ring. A thermocouple is imbedded near the contact area of the block to measure temperature. Also when testing a liquid lubricant, a thermocouple should be immersed in the lubricant supply cup to measure the lubricant temperature.

If liquid lubricants are tested, a lubricant reservoir (cup) should be filled up so that the ring dips into it. If a solid lubricant film is tested, the film is applied to the contact area around the diameter of the ring. The block can also be made from a composite material for testing. In all cases, the surface roughness of the ring is very important and can influence the results. Generally speaking, the smoother the ring, the lower the block wear rate. To most closely reproduce the end-use application, the roughness should closely match that of the end-use application. ASTM standard tests for this machine are: D-2714-94 for calibration and operation (with liquid lubricants) and D2981-94 for wear life of bonded solid lubricants in an oscillating motion.

Pin-on-Disk Tribometer

Schematics of two different pin-on-disk (ball-on-flat) testing devices are shown in figures 2 and 3. A hemispherically tipped pin (or a ball clamped in a holder) is pressed against a flat disk and the disk is rotated relative to the pin. The load is applied by a dead weight on a lever arm system. Wear volume of the pin is determined by measuring the weight loss or by measuring the change in diameter of a circular wear scar on the pin and then calculating the volume of material removed. Wear volume of the disk is determined by measuring the weight change or by measuring the wear track cross-sectional area using a surface profilometer and then calculating the volume removed. Wear should always be reported as a volume change (for a disk, the cross-sectional-area of the scar multiplied by the disk track length or for a ball or pin, the volume of the material removed from the tip) because as discussed previously adhesive wear has been established to be a volume phenomenon (Archard 1980). It is recommended that one relies more on optical and surface profilometry measurements rather than weight-loss measurements, since material transfer from one surface to another can provide erroneous weight change measurements. An advantage of pin-on-disk testing as compared to some other testers is that flat wear surfaces are produced which are very easy to analyze using surface analytical techniques.

For solid lubrication testing, a film or coating is applied to the disk or the disk is made from a composite material and then a metallic or ceramic pin is slid against the disk. Films are usually not applied to the pins in pin-on-disk testing, but sometimes (to approximate certain end use geometries) composite pins are slid against uncoated metallic or ceramic disks. It is important that the uncoated metal or ceramic surface be as smooth as possible since rough surfaces can abrade solid lubricants. A discussion on how to evaluate solid lubricants in a pin-on-disk tester is given in the next section and by Fusaro 1986.

For liquid lubricant testing, the disk must be dipped into a lubricant reservoir in the vertical position (figure 2) or immersed in an oil reservoir in the horizontal position (figure 3). Both pin and disk should be finished to the smoothest surface condition possible to reduce abrasive wear. A discussion of how to evaluate liquid lubricants on a pin-on-disk tester is given in a paper by Loomis and Jones 1980.

This tester is well adapted to operation in a vacuum chamber. A system designed for ultra-high vacuum friction and wear testing and surface analysis is shown in figure 4 (Miyoshi and Pepper 1992). In this configuration, the beam on which the pin is mounted is attached to a vacuum flange through a gimbal. It is sealed with a metal bellows as shown. The beam contains two flats on which strain gages are mounted. These gages measure the applied load and the frictional force between the pin and the disk. The pin load is applied by moving the beam against the disk. A 6-mm steel ball slides against the flat disk. The entire apparatus is mounted on a 15 cm (6-inch) flange, which attaches to the chamber of an XPS spectrometer. Ion sputtering can clean the flat surface and then a solid lubricant can be deposited by ion deposition without removing the specimens from the vacuum chamber.

A second type of vacuum pin-on-disk tester is shown in figure 5 (Miyoshi and Pepper 1992). This tester uses very small disks (2.0 cm diameter). The advantage of using these small disks is that the disks can easily be inserted into a scanning electron microscope for observation of the wear surfaces or they can be inserted into other surface analytical instruments for elemental and compound analysis. Large test specimens cannot be easily inserted into these instruments.

Four-Ball Tribometer

This tester is used primarily for determining the wear resistance of rubbing steel surfaces in lubricating oils. The ASTM Standard for the four-ball wear tester is ASTM D4172-94. This test should not be confused with the four-ball EP tester, which is used to determine the galling point of heavily loaded lubricated balls.

The four-ball tester uses a single ball in sliding contact with three stationary balls in a close-packed array. The three stationary balls are mounted in an assembly, which contains a lubricant reservoir and a lever arm for measuring the friction force between the rotating ball and the stationary balls. The rotating ball is held in a collet on a rotating shaft. The balls are standard size 12.7 mm (1/2-inch) bearing balls. Loads of 147 or 392 N (15 or 40 kg) are applied to the rotating shaft. The nested balls are submerged in the test lubricant. The relative size of the scars developed on the three stationary balls after a test gives a measure of the lubricant's ability to inhibit wear. The high loads and pure sliding condition result in a considerable generation of heat. This accelerates chemical reactions between the lubricant and the steel ball surfaces. Therefore, it can be considered as a very good accelerated test.

A schematic of a vacuum version of the four-ball tester is shown in figure 6 (Jones et al. 1994). The specimen configuration is the same as the conventional four-ball tester, except that 9.5-mm (3/8-inch) diameter precision balls (grade 10) are used. The apparatus is mounted in a vacuum chamber that uses a mechanical pump and then a turbo molecular pump to achieve a vacuum of approximately 10^{-4} to 10^{-6} Pa. The chamber is equipped with a hot filament ionization gage to measure chamber pressure and a mass spectrometer (residual gas analyzer) to measure vaporization products.

Spiral Orbit Tribometer (SOT)

This apparatus was designed to simulate the rolling contact in angular contact ball bearings using a planar geometry (Pepper et al. 1996). The device consists of one to three balls rolling between a stationary bottom plate and a rotating top plate. A schematic view of the SOT components is shown in figure 7 and a photograph of the SOT is shown in figure 8. To simulate a space environment, the tester is contained in a cubical vacuum chamber maintained at a pressure of about 10^{-6} Pa by a turbo-molecular pump. An external motor drives the top plate though a ferro-fluidic feed through. Load is applied upward on the bottom plate with a deadweight through a lever system that is located below the apparatus. Grade 10 precision bearing ball bearings are used.

The balls are placed between the plates. If more than one ball is used, a positioning device is used to equally space them and position them at the same radial distance from the center of the plates. After positioning, the positioning device is removed and the load is applied through the bottom plate. Movement is obtained by rotating the top plate. The balls tend to gradually spiral out to the plate periphery during rotation. Their path is eventually stopped by a bumper, which nudges the balls back to their original track orbit. This causes repositioning scrub marks on the bottom plate. The bumper assembly contains a transducer to determine the force with which each ball makes as it contacts the bumper. The length of the scrub and the bumper force indicate the degree of boundary lubrication. To determine chemical products released during the rolling and bumping interaction, a quadrupole mass spectrometer and a cold cathode ionization pressure gauge are used. Electrical resistance is used to determine the separation between the ball and the plates caused by insulating lubricant films.

Lubricants are applied by dipping the balls into a dilute solution of the desired lubricant. After removal from the lubricant solution, the solvent evaporates and leaves a thin residue of lubricant on the balls. No other lubricant is applied to the plates or balls; thus only a minimum amount of lubricant is used in this test. More details about this test device can be found in the papers by Pepper, et al. 1996, and Jones, et al. 2000.

Pin and V-Block Tribometer

Another accelerated test machine that is used to evaluate lubricants is the Pin and V-Block tribometer. The test configuration consists of a pin rotating between two V-blocks (Figure 9). Generally, these tests are conducted in air or in a controlled atmosphere. The device is used to determine the life and the load carrying capacity of solid lubricant coatings. The solid lubricant coatings are applied to the pin and/or the V-blocks. The methodology for conducting these tests is specified in ASTM standard D2625-94.

This tribometer can also be used to determine the wear resistance of materials sliding in a fluid lubricant or the extreme pressure properties of fluid lubricants. The ASTM standards for conducting these tests are D2670-95 and D-3233-93, respectively.

Instrument Bearing Tester

A device has been designed and built to test angular contact instrument bearings in a simulated space environment (Jones et al. 1994). The device is shown in figure 10. The tester is contained in a cubical vacuum chamber and is driven by an external motor through a ferro-fluidic feed through. The motor is a micro-stepper that is computer controlled to provide either continuous rotation or a precise dither motion. A precision screw mechanism is used to load the bearings. Bearing torque is measured with a flex pivot assembly instrumented with micro-strain gages. The angular contact bearings to be tested (size 1219) have an O.D. of 30.16-mm, a bore of 19.05-mm, and eighteen 3.275-mm balls.

The test bearing can be electrically isolated so that the contact resistance can be measured. This helps determine if the bearing is in a starved condition at any time during a test. A mass spectrometer is also attached to the vacuum chamber to measure any out-gassing products from the lubricants or retainer materials. Test temperature range is from room temperature to 50°C. Loads can be varied from 25 to 200N. Speeds can be from 1 to 1200 rpm in a linear mode or 1Hz in a dither (oscillating) mode.

Roller Contact Tribometer

A device has been designed and built to evaluate coatings under rolling and sliding contact in a vacuum environment. A schematic of the device is shown in figure 11 and a detailed view of the test rollers is shown in figure 12. A motor drives a crowned roller that is loaded against cylindrical roller. Various solid lubricants can be applied to the cylindrical roller or to both rollers if desired. Slip between the crowned roller and the cylindrical roller is controlled by a brake applied to the cylindrical roller. Friction coefficients can be measured and traction coefficients can be calculated. Wear to the coatings can be determined either by stopping the tests at preset intervals and measuring the wear or at the end of a test. The device has been used to evaluate coatings for use in traction drives and bearings for space applications; however, to date no technical papers have been published in the literature on data from this tribometer.

Brake Tester

Brake pads are needed for some applications in space such as the remote manipulator system that will be used on the space station. In vacuum, the friction of some materials can decrease due to dehydration of the material or due to accumulation of wear debris on the conforming interface where the brake pad slides. To evaluate various materials for use in applications such as these, a tester has been constructed in Canada to test brake materials in high vacuum (Hawthorne 1990). A schematic of the tester is shown in figure 13.

In this system, the pads are driven by an electric motor through a ferro-fluidic rotating seal and slide against a metallic counterface. Loads up to 70-N can be applied to the pads by a deadweight system through a bellows seal in the vacuum chamber. Speeds up to 100 rpm can be attained in a vacuum level of 1.3×10^{-4} Pa (10^{-6} Torr).

CORRECT USE OF SOLID LUBRICANTS

Cleaning of Test Specimens

Contamination can adversely affect the performance of a solid lubricant coating. Thus, it is extremely important that the test specimens be thoroughly cleaned before coating. It is also important that after cleaning they be kept in a clean environment and that the specimens are not touched after cleaning. The hand contains oil that could affect the results of the tests.

Before coating, metallic specimens should be first cleaned with a good solvent like ethanol to remove organic deposits from the surfaces. Frequently, the solvent will leave a deposit behind when it evaporates from the surface. Evidence for this is when water is put on the surface, the water will "bead-up" and not fully wet the surface. Fusaro 1986, recommends that the surfaces be scrubbed with a water paste of levigated alumina as a final cleaning method. The very fine alumina particles will remove oxides on the surfaces and any minute traces of solvent particles. If water is applied to these surfaces (after adequately cleaning with levigated alumina), it will wet the surfaces uniformly. To remove the alumina particles, the surfaces should be scrubbed with a clean nylon bristle brush under running water and then given a final rinse with distilled water. Because some surfaces will oxidize if not dried quickly, it is advisable to use clean, dry, compressed air to blow-dry the surfaces.

After the coatings are applied, care should be taken to keep them clean. They should not be cleaned again. Solvents can absorb through the surfaces into the bulk of the coating and degrade the coating's lubricating ability. Similarly, water vapor in the atmosphere can absorb and degrade the coatings. Once coated, the specimens should be stored in a clean dry environment to prevent contamination.

There are not many good techniques to clean polymers or polymer composite materials. Many polymers (polyimides, polyamides, epoxies, etc.) have free hydrogen bonds in their molecular structures that will attract water vapor molecules. Water vapor will absorb into the surface and then hydrogen bond to the molecules and affect the tribological properties. Thus, it is recommend not to clean polymers or polymer composites with an aqueous solution. A satisfactory method for cleaning polymers (if it is deemed necessary) is to use a fast drying solvent to remove organic deposits on the surface.

Substrate Preparation for the Application of Coatings

An important consideration for the application of solid lubricant coatings is that they must be well bonded to the substrate. The first step for accomplishing this is to ensure that the surfaces are clean; that is, that they are free from oil, grease and oxide films. The surfaces should be cleaned as described in the previous section.

Cleaning is very important for achieving a good bond of the solid lubricant coating to the surface. But improved bonding can be achieved by either mechanically or chemically treating the surface to be coated. Mechanical treating means roughening the surface by such techniques as sanding, glass peening, sand blasting, etc. Chemical treating is done by reacting the surface with a chemical to promote

the formation of a thin layer of a chemical compound on the surface. For a comparison of some different surface pretreating methods see Fusaro 1984.

Mechanical treating increases the surface area and provides a reservoir for the solid-lubricant material. When this technique is used, it is important to remove any high or sharp asperities that are produced. If not removed, they can abrade the counterface of the material sliding against the coating. Lightly polishing the surfaces after mechanical treating should remove any high spots or sharp asperities created by the mechanical treating process.

Chemically treated surfaces can improve the lubricating ability of coatings in three ways. (1) They can act as a rough surface to improve bonding and to serve as a reservoir for the lubricant (similar to a mechanically treated surface. (2) They can form a conversion surface layer that can combine with the solid-lubricant coating forming a mixture that will improved bonding as well as improved lubrication. (3) The coating can improve the chemical bonding of the solid lubricant to the surface (some solid lubricants do not bond well to certain materials). For more information on surface pretreatment see Fusaro 1984 and Fusaro 1986. .

Application of Solid Lubricant Coatings

There are many methods of applying solid-lubricant coatings. The simplest method is to use a polishing cloth and manually burnish (rub) a solid-lubricant powder onto a substrate surface. A better way than burnishing by hand is to devise a mechanical method that will more vigorously rub the solid-lubricant onto the surface. For example, a brush rotating on a drill can be used. To get the best bonding of the solid lubricant to the surface with this method, the substrate must have some roughness to it. It is recommended to sandblast or glass peen the surface to a roughness of 0.90 to 1.25 micrometers (35 to 50 μm) RMS.

Another way to apply solid-lubricants is to impel them at high velocities at the substrate surface. This method will physically imbed the powders into the surface and provide a good bond. There are commercial vendors that will apply films by this method.

The most common way of applying solid-lubricant coatings for long life is to incorporate them into a binder system. The binder functions much like a paint, holding the solid-lubricant particles (and any other desired additives) and attaching them to the substrate surface. The binder can function merely as a material that attaches the particles to the surface; or, if the binder is a good lubricating material itself (like the polymer polyimide), it can mix with the solid lubricant additives to produce an even better lubricating coating. Methods for applying bonded solid lubricant coatings are dipping, painting with a brush, or spraying. Any method used to apply paint could be used to apply a bonded solid-lubricant coating. A caveat should be given for applying bonded coatings. The coating should not be applied too thick and it should be applied very uniformly to the surface. If it is not, it can be worn away very rapidly during the "running-in" process (i.e., dispersed from the contact area) and an adequate amount may not be left to provide good lubrication.

Another technique for applying coatings is called plasma spraying (Sliney 1987, Sliney 1991). In this method, a carrier gas such as argon is passed through a very high electric potential and ionized to create a plasma stream. Solid-lubricant powder is injected into the stream before it exits the plasma gun nozzle and these particles when striking the substrate surface become fused to it. A disadvantage of this method is that very high temperatures are produced in the plasma and only materials which have high thermal stability can be applied by this method. In addition, these coatings can only be applied to materials with high thermal stability. Another disadvantage is that the coatings applied by this method are often very thick and "rough." Thus, after application they must be machined (or finished by some other method) to reduce their thickness and to smooth the surfaces.

Ion plating, sputtering or chemical vapor deposition (CVD) processes can also be used to apply coatings. A vacuum system is needed for ion plating or sputtering. The advantage of these methods is that highly adherent, very dense, thin coatings of solid-lubricant materials can be applied to irregular surfaces. The disadvantage is that the methods are expensive and it is hard to coat large parts. For more information about these techniques see Spalvins 1969a, Spalvins 1969b, or Bunshah et al 1982.

Factors Which Affect Solid-Lubricant Performance

How well a particular solid lubricant performs is system dependent. Thus the solid lubricant should be evaluated as closely as possible to the same conditions and in a methodology that approximates the end-use application. Some factors that affect solid lubricant coating performance are given in Table 2. The parameters listed in the table must be considered when planning a testing sequence to evaluate solid lubricants for a particular end-use application.

Table 2.—Factors which effect solid lubricant coating performance.

• Type of materials in sliding contact.
• Surface to which a solid lubricant film is applied.
• Geometry of sliding materials.
• Contact stress or pressure.
• Substrate hardness.
• Substrate surface topography or roughness.
• Temperature.
• Sliding speed.
• Environment.
• Atmosphere.
• Fluids.
• Cleanliness or contaminants.

The material to which a solid lubricant coating is to be applied is the first factor to consider. Some metals are intrinsically hard to lubricate, such as AISI 300 Series stainless steel, aluminum and titanium. A solid lubricant applied to these materials may fail immediately. This failure is not due to the solid lubricant, but to the material that the solid lubricant was applied to. The solid lubricant and the metal it lubricates are a system. Ideally, the type of material to be lubricated should be chosen just as carefully as the solid lubricant. Unfortunately, in many instances, the type of material for a mechanical component is chosen long before the solid lubricant. When this occurs, it will limit the technologist in finding the best low friction, low wear, long life system. However, in either case, a thorough literature search should be conducted to determine which lubricant worked well with a particular metal. Literature studies, though, will only give an indication of which solid lubricants might work. You will need to test the lubricant and metal combination under your particular conditions to determine whether it will be appropriate for your application.

Applying the solid lubricant to the correct surface is also important. It is not advisable to apply a solid lubricant coating to both sliding surfaces. Generally, the coating should be applied to the surface that has the largest surface area. For example, in a pin-on-disk test, one would want to apply the coating to the disk and not the pin.

In general, hard materials can be lubricated to produce lower friction, lower wear and longer life than soft materials. A very high-contact stress applied to a coating could cause the substrate to either elastically or plastically deform. If the coating does not follow this deformation, it could either brittlely fracture or plastically deform, permitting metal-to-metal contact to occur. Thus, the hardness of the substrate relative to the applied Hertzian contact stress is a very important consideration.

In addition to the substrate hardness, the roughness of the substrate is also very important. As a general rule, most burnished or bonded solid lubricant films will not adhere adequately to very smooth surfaces, so to ensure a good bond; the disk substrate surfaces should be roughened to a value of 0.90 to 1.25 micrometers (35 to 50 μin) RMS. The opposite is needed for the counterface sliding against a coating. This counterface surface must be extremely smooth or it will abrasively wear the coating.

Temperature and speed are related, the higher the speed, the higher the temperature of the sliding contact. Sometimes, higher temperatures are beneficial to a solid-lubricants performance; but, in most cases, higher temperatures decrease the endurance life of a solid-lubricant coating. One general statement that can be made is that friction, wear and endurance life are highly dependent on temperature. Thus, if possible, this factor should be controlled in an accelerated test. In addition to affecting the temperature of a coating, speed can also affect the rheological properties of a polymer coating. Flow properties of these coatings can be time dependent. Thus, if the speed of a counterface sliding over the coatings is too fast, instead of the coating flowing plastically (shearing) it will fracture brittlely.

The atmospheric environment in which a solid lubricant coating is evaluated can have a marked effect on the tribological properties. For example, the relative humidity of laboratory air (if not controlled) can vary from 80 % in the summer to 20 % in the winter. A graphite or MoS_2 film would give totally

different results evaluated under these two conditions. The graphite film would be better than the MoS_2 film in summer (humid air), while the MoS_2 film would prove to be better than the graphite film in winter (dry air). In order to determine how well a coating well perform in a certain application, the coating must be tested in whatever atmospheres the end use will experience.

Most solid lubricant bonded coatings do not function well in a liquid environment, whether it be water or oil. The oil or water will absorb into the structure and cause it to degrade. As mentioned previously, even a fingerprint can dramatically affect the tribological properties. Cleanliness in terms of dust or dirt is also important. Small hard particles can imbed in a film, a polymer or a composite and severely abrade the counterface (Fusaro 1985).

Macroscopic Mechanisms of Wear and Lubrication

To properly evaluate solid lubricant coatings, one must be aware of the macroscopic mechanisms by which solid lubricant coatings wear. There are two major mechanisms that can take place. The strength of the coating and the applied contact stress are the two main factors that determine which mechanism will occur (Fusaro 1981, Fusaro 1982). In the first mechanism, the coating has enough structural strength to support the stresses induced by the load and the sliding interface. In addition, for low wear, a very thin layer of the coating material must become "ordered" on the coating surface and the lubrication process then becomes the shear of this layer between the coating and the counterface (the surface sliding against the coating). In general, the best solid lubricants produce very thin layers. They also produce very thin transfer layers to the counterface. Thick transfer layers tend to produce stress risers and higher adhesive wear. Endurance life is determined by how long it takes the counterface to wear through the coating. Often life can be extended beyond this point because this lubricating process can transition into the second lubricating mechanism.

The second lubricating process occurs when the coating does not have enough structural strength to support the stresses due to the load and the sliding interface. In this case, the coating is rapidly worn or "spalled" away. Even though this occurs, a very thin "secondary film" can be formed at the surface of the metallic substrate and this film can provide lubrication. How well a solid lubricant will function when this mechanism occurs is determined by several factors. One is the thickness of the original coating. If the coating is too thick, most of it will be worn or "spalled" away very quickly (ejected from the contact area) and little will be left behind to form the secondary film. A thinner coating will tend to be compressed rather than to be "spalled" away and more material will tend to stay in the contact zone to form a better "secondary film."

Substrate surface roughness is also important. A properly tailored topography on the substrate will provide a reservoir for the solid lubricant and a "dump" for metallic wear particles. If this second mechanism is to function, the coating materials must have the ability to form this "secondary film." Sliding speed, load, temperature, and relative humidity will affect its formation. The formation of this film is a

"running-in" process. Often a better secondary film can be formed if the applied solid lubricant coating is "run-in" under less severe conditions rather than under actual operating conditions.

The type of wear occurring to the counterface surface is also dependent on which mechanism is operating. In the first mechanism, very little wear to the counterface occurs since only the coating material comes in contact with the metallic counterface. In the second mechanism, wear to the counterface can occur since the "secondary film" is very thin and can allow metallic asperities to protrude through the film to abrade or cause higher adhesive wear to the counterface. For more discussion on these mechanisms see Fusaro 1981, and Fusaro 1982.

Experimental Procedures for Testing Solid Lubricants

The specimens should be inserted into the apparatus and the chamber sealed. If it is a vacuum test, the chamber should be pumped down until the desired pressure is obtained and let stand until there is no measurable out-gassing. For controlled atmosphere testing, the chamber should be purged with the desired atmosphere before starting the test and continuously monitored throughout the test. The test should not be started until the atmosphere stabilizes. The time for this will depend on the size of the chamber and the flow rate of the purging gas atmosphere. Once the atmosphere is stable, the temperature should be adjusted to the correct value, if the test is not being conducted under ambient conditions. Once the temperature has stabilized, the specimens can be set in motion and the load should be gradually applied.

Two types of friction and wear testing procedures can be followed: (1) the "continuous testing method" or (2) the "interval testing method." In the continuous testing method, the test is run continuously until some maximum, predetermined friction coefficient occurs. The test is then stopped and the wear scars measured. The time to reach this value of friction coefficient is defined as the endurance life of the coating. In the "interval testing method," the specimens are removed from the test chamber at predetermined intervals of sliding and the wear scars are measured and a visual microscopic inspection of the surfaces takes place. The specimens are then put back into the chamber and the previous test procedure is repeated. Sliding continues until the predetermined friction coefficient is obtained or when enough data is obtained for wear analysis. The advantage of this method is that wear as a function of sliding distance can be determined. In continuous testing, only wear at the end of a test can be determined and run-in wear cannot be separated from steady-state wear. One caveat on the "interval testing method" is that care must be taken to replace the specimens with the same orientation and alignment that they had before they were removed. This is not a trivial task, but can be done.

Evaluation of Solid Lubricants Results

The accelerated friction and wear test will enable the evaluation of friction coefficients, coating wear, counterface wear and endurance life of the coatings. In addition, if the interval testing method is used, the wear mechanism can be determined. Coatings can be evaluated under different sliding

conditions to determine how load, speed, temperature, etc. influence the results. This is important because these are accelerated tests and the results will not necessarily directly apply to the end use application. It is most likely that friction and wear are not constant throughout the test and that there will be a running-in period with higher friction and wear, a steady-state period with constant friction and wear and a period where friction and wear increase gradually with time. However, every coating is different and these general rules may not apply. What these tests will provide is a comparison of the friction and wear characteristics of various coatings for an application. The results are only a relative indication of how well the coating will perform. The coatings may not perform as well in the end use application or it is possible they may perform better, but hopefully the relative performance of the lubricants in the final application will stay the same as that found in the accelerated test.

LIQUID LUBRICANT BENCH TESTING

Regimes of Liquid Lubrication

There are four defined regimes of liquid lubrication: (1) hydrodynamic, (2) elastohydrodynamic, (3) boundary, and (4) mixed (a combination of elastohydrodynamic and boundary) (Booser 1984, Jones 1982, and Cameron 1966). When specifying or testing a liquid lubricant, it very important to determine under which lubrication regime or combination of regimes the mechanism will be operating. The viscosity characteristics of the oil, the load, contact geometry and the speed are the main factors that determine which regime will be operating. During hydrodynamic and elastohydrodynamic lubrication, no contact takes place between the surfaces because the viscosity of the oil is high enough, the load is low enough and/or the speed is high enough to separate the moving surfaces. Thus, in the hydrodynamic and elastohydrodynamic regimes, friction is very low and no wear of the surfaces takes place. Ideally, one would always like to design a mechanism so that either of the above two lubricating mechanisms takes place, but this is not always possible.

When the other two regimes of lubrication occur (mixed and boundary lubrication), rubbing contact between the surfaces takes place. Rubbing contact causes wear. In order to provide lubrication in these two regimes, a thin layer of a boundary lubricant type material must form between the interface of the two sliding surfaces. This boundary lubricant material must adhere to at least one of the surfaces and must shear under sliding contact to mitigate the wear and provide low friction. A good boundary lubricant oil may be capable of providing for the formation of these adhered lubricant type films by itself. However, to optimize the process, chemical additives are often dissolved or suspended in the oils. In effect, the oil serves as a carrier for supplying the surfaces with material that will react with the surface to form a type of solid lubricant material.

One must be careful in formulating the oils, however. Problems have occurred in boundary lubrication situations when a boundary lubricant film which is too thick has been deposited on bearing raceways. The deposited film can cause mechanical noise (vibrations) (Kannel and Dufrane 1986,

Zaretsky 1990 and Kingsbury 1992) during unidirectional sliding or torque bumps (Zaretsky 1990, Todd 1981) during oscillating bearing motion.

Specimen Preparation

In general for liquid lubrication, the smoother the test surfaces the better. Specimens should be ground, lapped and polished to surface finishes of better than 0.1 μm (4 μin). After polishing, they should be cleaned before testing. The cleaning procedure is the same as was stated in the solid lubrication section.

Liquid lubricants for space use should also be degassed before using or testing them. Loomis and Jones 1980 used a degassing procedure of 150°C (302 °F) for one hour under a pressure of 270 N/m^2 to degas lubricants. Measurements made after degassing showed that this procedure reduced the dissolved water content in the fluid to less than 20 ppm.

Experimental Accelerated Testing Procedures

Since there is no wear and very low friction when operating in the hydrodynamic and elastohydrodynamic lubrication regimes, there is no need to do accelerated experimental testing. As long as adequate oil remains in the system and the operating conditions do not change, almost unlimited life is possible. In this case, testing needs to be conducted in the final end use device to determine if enough lubricant will be present to ensure that starvation will not take place over the projected life of the spacecraft.

For boundary lubrication however, accelerated testing is often useful. Boundary lubrication is very similar to solid lubrication and the statements made in the previous section on solid lubrication also apply here. The advantage of boundary lubrication over solid film lubrication is that the boundary lubricant film can be constantly replaced by reactions of the surfaces with the oil or additives in the oil. With dry solid lubricant films, once the films are depeted they cannot be replaced except by taking the specimens apart, refinishing the surfaces and reapplying the films.

When conducting tests to evaluate boundary lubrication, make sure that conditions are indeed in the boundary lubrication regime. As mentioned previously, oil viscosity, sliding speed, contact geometry and contact stress are the factors that determine whether or not boundary lubrication will take place. In addition, if there is not enough oil present, a "starved" condition can take place that could cause a non-lubricated condition. Care must be taken to determine what the testing conditions will be for each situation. For example, if the temperature and the oil viscosity are constant, loads and speeds should be adjusted to insure a boundary lubrication condition exists. Oil viscosity can change with temperature, thus it is important to monitor temperature to insure it remains constant.

There is a caveat, which could occur when testing in the boundary lubrication regime. After long sliding duration, sufficient wear of the specimens could take place to reduce the contact stress to the

point that mixed or even hydrodynamic lubrication could occur. If the experimenter is not aware of this, the wear results could be misinterpreted.

The same type of friction and wear testing methods as described for solid lubricant films can be used for oils. Usually one does not run life tests since life could be indefinite. A test is usually conducted for a predetermined time and then stopped. The specimens are removed and the wear measured and the boundary lubricant films on the surfaces evaluated. To separate running-in from steady-state wear, it is a advisable to conduct interval type tests.

Liquid lubricants are as a rule not as dependent on the type of atmosphere as are solid lubricants. Often a good evaluation of liquids can take place by evaluating the lubricants in a dry inert atmosphere. This involves less time and is cheaper than evaluating lubricants in a vacuum environment.

Evaluation of Results

Essentially, when applying accelerated testing methods to evaluate liquid lubricants, one lubricant formulation is being compared to another. The target is to find the lubricant formulation that provides the least amount of wear and gives the lowest friction coefficient for the conditions under which the lubricant operates. Besides friction and wear, there are other characteristics that can demonstrate a good lubricant formulation. For example, the "smoothness" or consistency of the friction force, the consistency of the wear rate, and the types of boundary lubricant films found on the wear surfaces are important characteristics. Very thin, continuous, smooth boundary lubricant films are indicative of a good lubrication condition. In addition, the chemical composition of these films can indicate the "quality" of the lubricants. Various surface analysis techniques that can be used to study the wear surfaces will be discussed in the next section.

CHEMICAL ANALYSIS AND CHARACTERIZATION TECHNIQUES OF SURFACES

This section gives a short overview of some of the surface analytical techniques available for the investigation of wear mechanisms taking place on the sliding surfaces of accelerated testing devices. The same techniques can be used for the analysis of surfaces of actual space mechanical components. The difficulty with actual space components is that they are often too large to fit into the analysis chamber. Therefore, they must be sectioned for analysis. For more detailed discussion of these surface analysis techniques see the papers by Ferrante, 1982, Ferrante 1989, Kane and Larrabee1974, and Hilton and Didziulis1993.

Visual Light Microscope

A good optical microscope can be used to measure the size of the wear scars, to determine what type of deposits are found on the wear surfaces and to observe the type of wear taking place. Low magnification (up to 100X) is used to measure the wear scar while high magnification (up to 1500X) is

used to examine the deposits and wear processes. Photography can be used to record the wear scars and the nature of wear or deposits on the surfaces. A disadvantage of this technique (especially for high magnifications) is that it is hard to focus on non-flat surfaces. Thus, an advantage of using pin-on-disk testing devices is that they produce flat wear surfaces that are much easier to keep in focus over a larger area under an optical microscope.

An advantage of the visual light microscope for looking at surfaces is that very small differences in surface irregularities can be observed. Being able to observe the surfaces in color is also an advantage. Interference fringes can sometimes be observed which can be used to calculate film thickness. Film thickness can also be determined by using the focusing micrometer to focus on the top and then the bottom of a feature and then subtracting the micrometer readings obtained. One-micrometer differences in thickness can be discerned by this method.

Surface Profilometry

A surface profilometer can be used to measure the cross sectional area of wear on the sliding surfaces. The simplest instruments use a stylus that generally is pyramidal or conical in shape. Typically a stylus cone is 60 degrees with a radius of 12.5 μm. The stylus is made from diamond and the tip can be either flat or rounded. Traversing the surfaces can cause some damage to the surfaces, but the loads are so light it is usually insignificant. If this is a concern, there are some units available that use lasers or interference methods to scan the surface, but these units are more expensive.

A surface profilometer is used to make recordable traces of the surface topography or wear surface area. By taking passes over the surface, that cover both the unworn edges of the specimen as well as the wear track, the depth of the wear scar and thereby the wear volume can be calculated. Wear volume measured over several different sliding distances can be used to determine a value of the wear rate. Very high vertical magnifications can be obtained using this instrument.

Scanning Electron Microscopy

Wear specimens can also be examined by inserting them into a scanning electron microscope (SEM). One disadvantage of this instrument is that oils must be removed from the specimens before insertion. Another disadvantage is that the instrument will not generally accommodate large specimens, although there are some that can handle specimens up to 200 mm diameter. A third disadvantage is that many well-lubricated wear surfaces are very smooth and featureless and this instrument does not give good pictures under this condition. Charging of specimens can also be a problem if the specimens are not conducting. This can be mitigated by shadowing the sample with a thin layer of conductive material such as carbon or gold. An advantage is that SEM's have better spatial resolution than optical microscopes. Another advantage is that wear features show up very well and the surfaces remain in focus to very high magnifications (10,000x or more).

Energy Dispersive Spectroscopy

An additional advantage of the SEM is that while the surfaces are being observed visually, an elemental analysis of the deposits on the surfaces can be made using electron dispersive spectroscopy (EDS). An overall analysis of the whole surface can be taken or small particles or small areas can be focused upon and their spectra taken. One disadvantage of this technique is that the analysis goes rather deep into the surface (~ 1 μm) and the substrate material under a particle may be included in the spectra. Also the technique is not good for the detection of light elements with energies less than 170 eV. In addition there is some problem in discriminating between elements whose x-ray energies are too close together, for example, Mo and S. However, more expensive modern equipment using ultra-thin windows can resolve x-rays down to carbon and can separate Mo and S. There are ways to improve detection by using wavelength diffractometers (WD) and electron probe micro-analyzers as accessories in the SEM.

Mass Spectroscopy

A residual gas analyzer (RGA) can be attached to a vacuum chamber in which a friction and wear test is being conducted. The RGA can detect out-gassing of materials that occurs when a material is exposed to vacuum or during the friction and wear experiment. By knowing the masses of atoms, the technique can be used to determine what the out-guessing products are. The analyzer can also be used to insure that there is a "clean" vacuum before starting a test.

Auger Electron Spectroscopy

Auger electron spectroscopy (AES) or scanning Auger microscopy (SAM) is used to determine the elemental composition of very thin surface layers on the wear surface (~10 nm). The technique works by bombarding the surface with electrons to generate Auger electrons with various energies. The energies can then be analyzed to determine the elements present. The chemical information obtained can be semi-quantitative. The electron beam can also be scanned over the surface to give an elemental composition map. This is called scanning auger microscopy (SAM).

The chemical composition of very thin films or deposits (~2 nm) on a wear scar can be determined by using x-ray photoelectron spectroscopy (XPS). In this technique the surface is bombarded with x-rays that cause photo-emitted core and valence electrons to be emitted. Semi-quantitative analysis of the surface composition can also be made with XPS data.

Secondary Ion Mass Spectroscopy

Another technique to determine elemental information on wear surfaces is secondary ion mass spectroscopy (SIMS). In this technique, a beam of ions is directed at the surface that sputters away charged particles, the mass of which can be analyzed. The technique is surface sensitive and both elemental and compound analysis can be conducted. The advantage of this technique is that the

sensitivity is better than AES, but the spatial resolution is not as good. The technique is also destructive because it involves the sputtering away of the surface during the analysis.

Fourier-Transform Infrared Microscopy

This technique combines optical microscopy with infrared spectroscopy to provide structural information of films or deposits on wear surfaces. The advantage of this technique over conventional infrared spectroscopy techniques is that a very small area on the contact area can be focused upon and isolated from the rest of the surface to obtain structural information.

FINAL CHECKS AND TESTS

Assemble in Class 10,000 Clean Room

Tribological surfaces can be markedly affected by contamination such as dirt, dust, water vapor, etc. As mentioned previously, even touching a surface with a "clean" hand can affect the tribological performance. Once cleaned, tribological surfaces should never be touched! When applying lubricants to a clean surface they should be applied under very clean conditions. The specimens should then be stored under very clean conditions and when ready to be assembled into the final configuration, the components should be assembled in a class 10,000 clean room. A clean room is rated by the number of pollutant particles it allows per unit volume of air. For example, a class 10,000 clean room would have to maintain a level of no more than 10,000 particles larger than 0.5 microns in diameter per cubic foot (353,000 particles per cubic meter). For more information see Sarafin 1995.

QA Assembly Inspection

A quality assurance assembly inspection is necessary to make sure that all processes that went into designing, manufacturing, testing and assembling the mechanism will deliver a product that will meet the operating objectives of the mechanism. One should verify that the mechanism meets the specifications of the engineering drawings, that the tests match the test plan, and those critical elements such as materials, parts, processes and configuration are controlled and are as was specified.

Run-in Testing

Many mechanisms need to be "run-in" before they are actually used. Liquid lubricated devices need to have "rough areas" worn off at lower loads and speeds to insure that proper elastohydrodynamic films will form and starvation of the bearing surfaces will not occur. Solid lubricated devices need to also be "run-in" at lower speeds and loads to insure that a smooth dense film is developed. Solid lubricants, which are not "run-in", can spall and not produce low friction, long life films.

Cycle or Life Testing (with Thermal Simulation)

To insure that the desired life of a spacecraft will occur, life testing with simulated thermal cycling should be conducted on either the entire spacecraft or the particular unit mechanism. This will verify whether or not binding, friction or cold welding, wear, corrosion, high torque, blocking, contamination by the lubricant, mechanical noise, or electrical noise will occur. In addition, one will be able to assess if the right type of lubricant has been applied, and if it has the right viscosity characteristics, whether there is any material, lubricant or environmental incompatibility, and whether there has been excessive lubricant depletion. MIL-STD-150B states that the unit should be tested for a time period that exceeds twice the total expected operating cycles that would be expected for both the service life and for the acceptance testing. Life tests should be done in a hard vacuum of less than 1.3×10^{-4} Pa (10^{-6} Torr) and at the temperature extremes expected for the mission.

Vibroacoustic Testing

Acoustic response can occur during launch or when a pyrotechnic device is activated. Fluctuating pressure waves are produced which can cause fretting of contacting surfaces and lead to friction welding. They can also cause liquid lubricant depletion when there is only a small amount of lubricant available for lubrication. Both of these actions can lead to a decreased life of the spacecraft. Vibroacoustic testing of tribological components coupled with post inspection can help mitigate problems caused by random acoustic responses.

Thermal Vacuum Testing

Thermal vacuum tests are conducted to verify the performance of the fully integrated spacecraft under vacuum conditions for the full spectrum of thermal conditions that the spacecraft will encounter. This testing can assess tribological problems such as binding, cold welding, liquid lubricant depletion, temperature-related lubricant viscosity changes, environmental compatibility, electrical noise and mechanical noise. Outgassing of the lubricant can also be ascertained. Methods for conducting these tests are discussed in Sarafin 1995.

Post Test Functional Testing

Post-test functional testing is conducted after an environmental test to verify that the mechanism is still operating as it did before the environmental testing and to determine if it still meets the mission requirements. The results should be compared to the results that were obtained on the mechanism before the environmental test was conducted. If the results are not similar, one should not proceed until it is understood why there is a deviation in the two sets of data. If it is determined that the deviations do not violate the specified requirements, the mechanism will be considered verified. Such tribological problems as binding, cold welding, friction welding, wear, insufficient liquid lubricant, liquid lubricant depletion, contamination of the lubricant, high torque, insufficient life, mechanical noise, electrical noise,

and incomplete application can be determined. These types of tests are discussed in more detail in the book by Serafin 1995.

Active Replenishment System

To insure and adequate supply of liquid lubricant for the life of the spacecraft, an active replenishment system should be incorporated into the bearing system. There are several different types that are available. One should be chosen that best fits the particular bearing application. Review Conley 1998 and/or Zaretsky 1997 for the best type suitable for the application.

Post Test Inspection

After completing any individual test. The mechanisms should be examined closely for mechanical flaws. Sliding surfaces should be examined both visually and with an optical microscope to make sure that no excessive damage has occurred that will affect the mission. In some cases, a scanning electron microscopy or other surface analytical technique may be used to insure no damage has occurred.

FINAL REMARKS

It is important to note that to date there have been no accelerated tribological tests or bench tests developed that can absolutely predict how a lubricant will perform in an end-use application. Accelerated testing can be used to screen lubricants, to obtain an idea of what the friction and wear properties of a particular lubricant are, and to determine which one might function better; but accelerated testing will not absolutely predict how well a lubricant will perform in a particular end use application. The only certain way to do that is to test the solid lubricant or liquid lubricant formulation in the end use application under the conditions it will experience.

Also, someone skilled in the field of tribology should make the evaluation and selection of the type of lubricant to use for a particular application. Without adequate training, it is not possible to make good decisions on which lubricant to choose for a particular application. Table 3 gives a matrix of tribological failure modes versus preventions, analyses, controls and tests (PACTs) that can be used to help prevent spacecraft tribology problems.

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Table 3.—Tribology Problems Versus Preventions, Analyses, Controls and Tests (PACT's).

	Preventions, Analyses, Controls & Tests (PACTs)																		
	Physical properties testing	Performance testing	Chem analysis & characterization testing	Controlling specifications	Review tolerance stack-up	Assemble in Class 10,000 Clean Room	QA assembly inspection	Material certification/review	Post-test inspection	Bench operational test	Run-in test	Cycle or life test (thermal simulation)	Vibroacoustic tests	Thermal vacuum test	Qualification Testing	Post-test functional	Activem replenishment system	Kinematic/Release Analysis
Tribology Problems																		
Binding		x	x	x	x					x	x	x		x				x
Cold welding		x	x	x				x	x			x		x		x		
Friction welding	x	x	x	x				x	x			x	x			x		
Surface wear	x	x	x		x				x			x			x	x		
Insufficient Liquid lubricant			x				x		x			x				x	x	
Liquid lubricant depletion	x								x	x	x	x	x	x		x	x	
Liquid lubricant decomposition/degradation	x	x	x	x					x			x						
Contamination of lubricant	x	x	x			x			x		x					x		
Contamination by lubricant			x						x			x						
Temp-related viscosity change	x			x					x			x		x		x		
Incorrect lubricant	x	x		x			x	x				x						
Lubricant incompatibility	x		x	x				x	x			x						
Material incompatibility	x		x	x				x				x						
Environmental Compatibility	x		x	x				x	x			x		x				
Corrosion	x		x	x					x			x						
High torque		x		x								x			x			
Insufficient life			x	x								x						
Zero gravity effects				x														
Electrical noise	x	x	x			x						x						
Mechanical noise	x	x	x			x						x						
Blocking	x	x	x									x						
Solvent incompatibility	x		x	x				x	x									
Incorrect application	x	x		x			x	x	x	x		x				x		
Coating Adhesion	x	x	x	x		x	x			x	x	x		x		x		
Fretting			x	x		x			x	x		x				x		
Galling	x	x	x	x				x	x	x		x		x		x		
High Hertzian contact stress				x				x	x	x					x	x		
Incorrect Loads		x		x	x					x		x	x	x	x	x		
Coeffiicient of Friction Sensitivity																		x

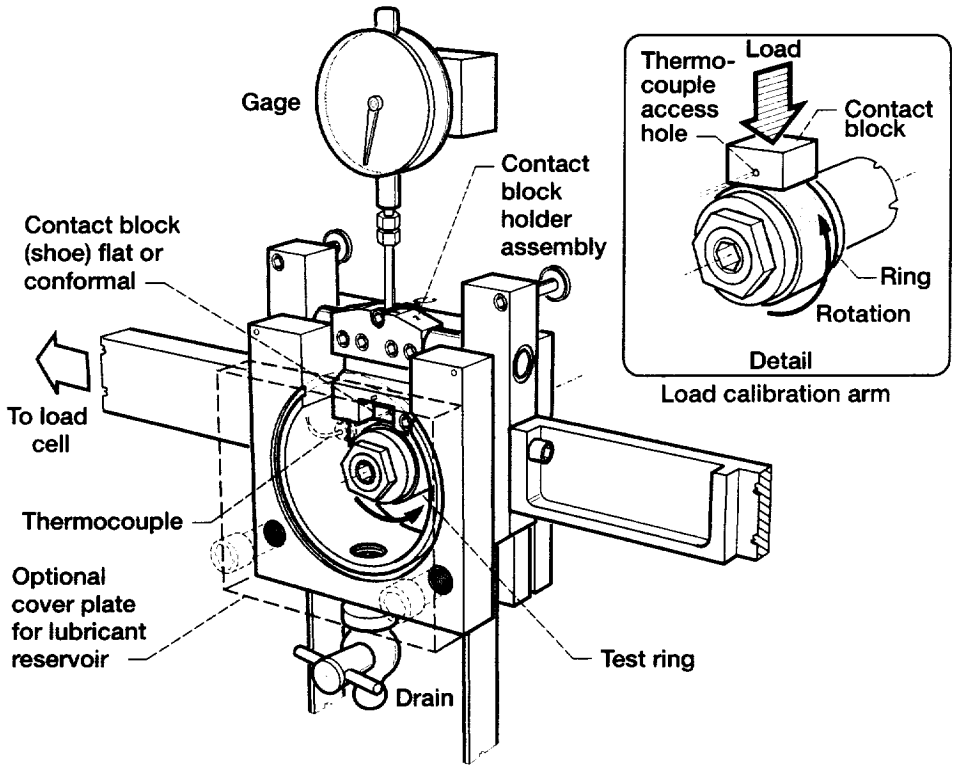

Figure 1.—Schematic view of the block-on-ring tribometer test elements.

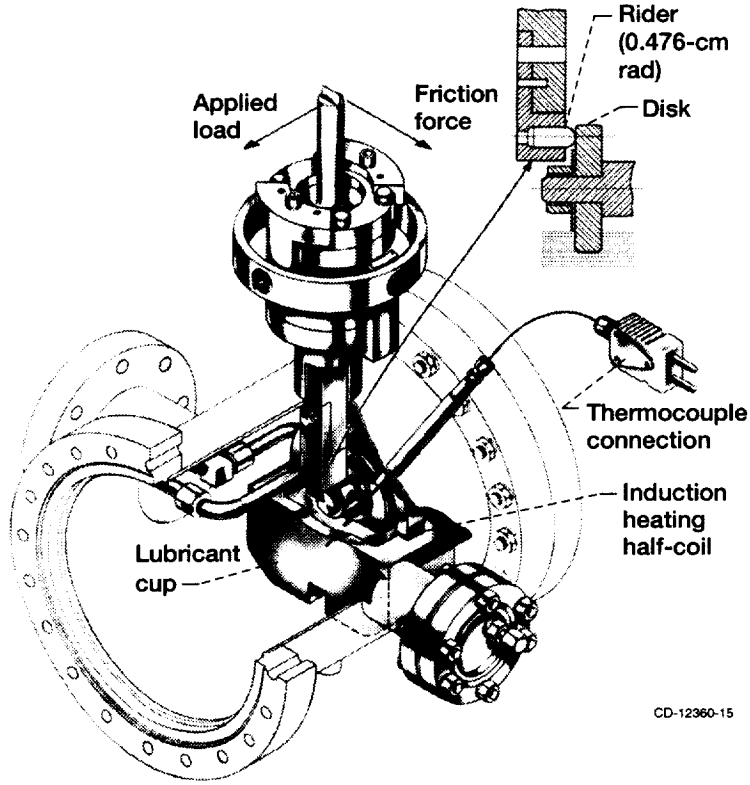

Figure 2.—Schematic view of pin-on-disk tribometer (disk in vertical position).

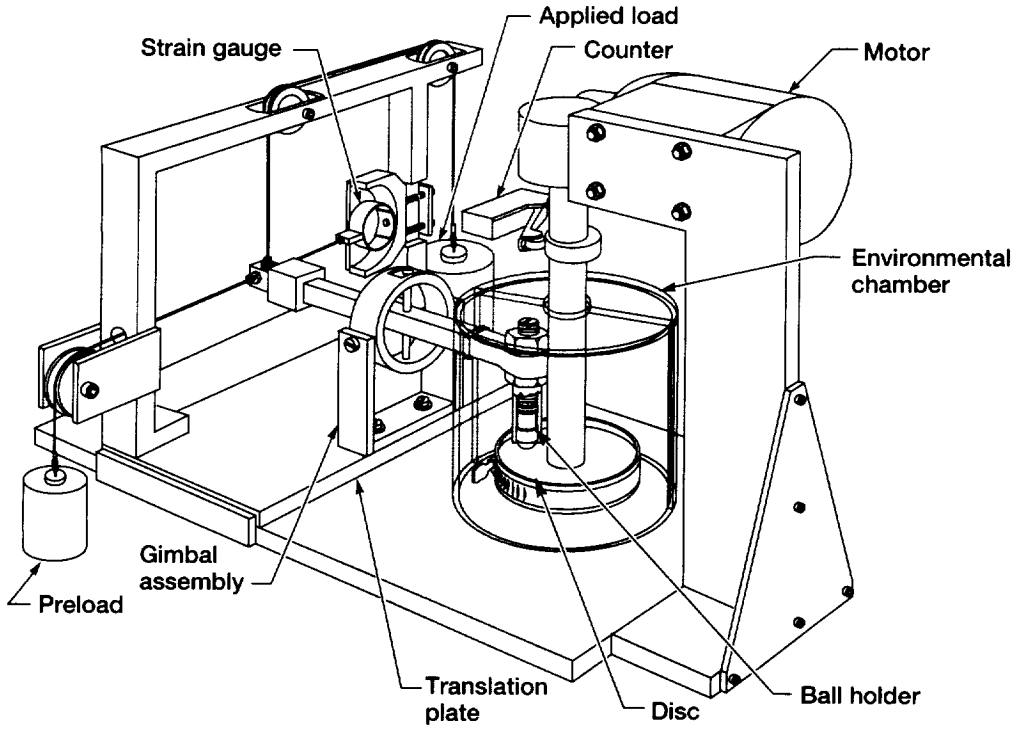

Figure 3.—Schematic view of the liquid pin-on-disk tribometer.

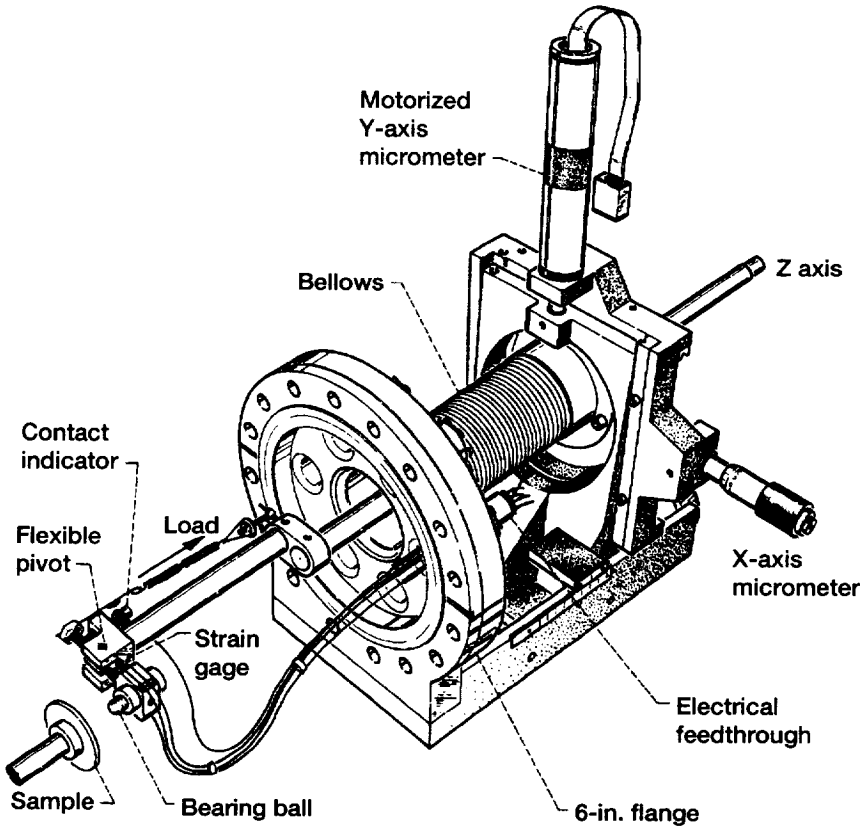

Figure 4.—Schematic view of the ultra-high-vacuum pin-on-disk tribometer.

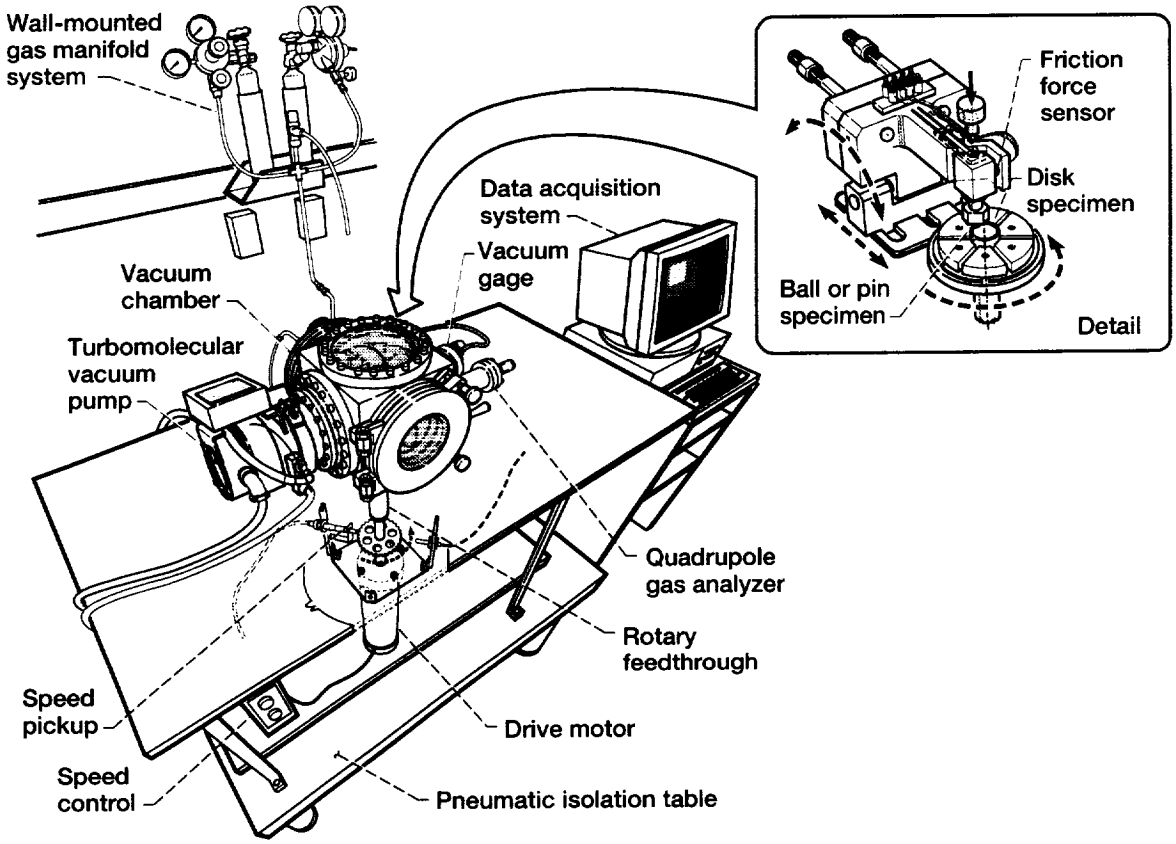

Figure 5.—Schematic view of the small specimen vacuum pin-on-disk tribometer.

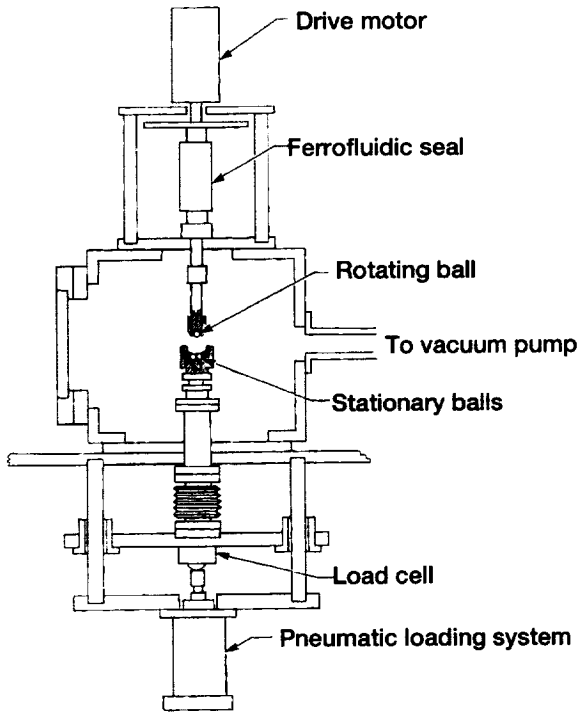

Figure 6.—Schematic view of vacuum four-ball tribometer.

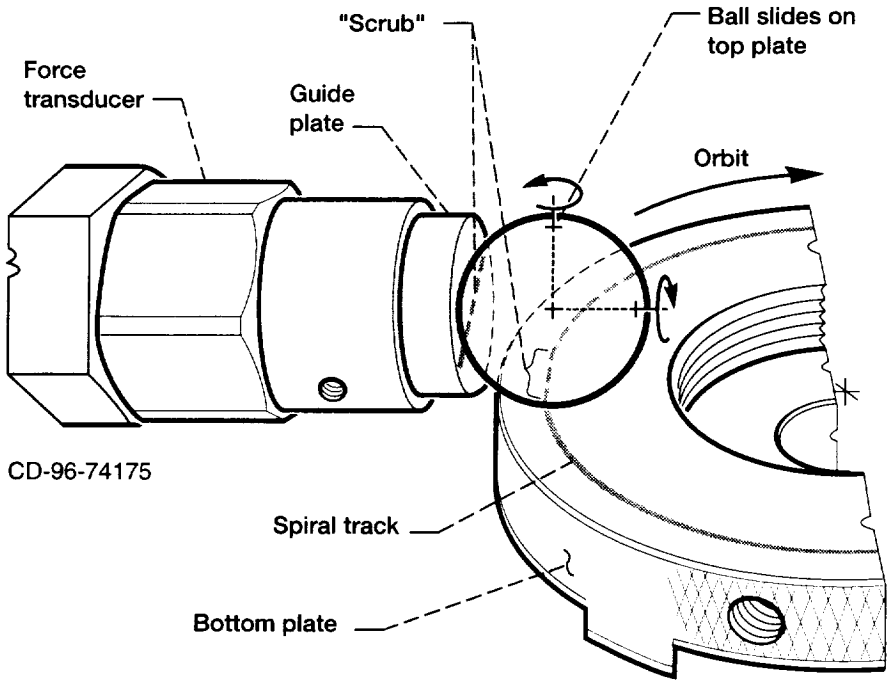

Figure 7.—Schematic view of the Spiral Orbit tribometer (SOT) components.

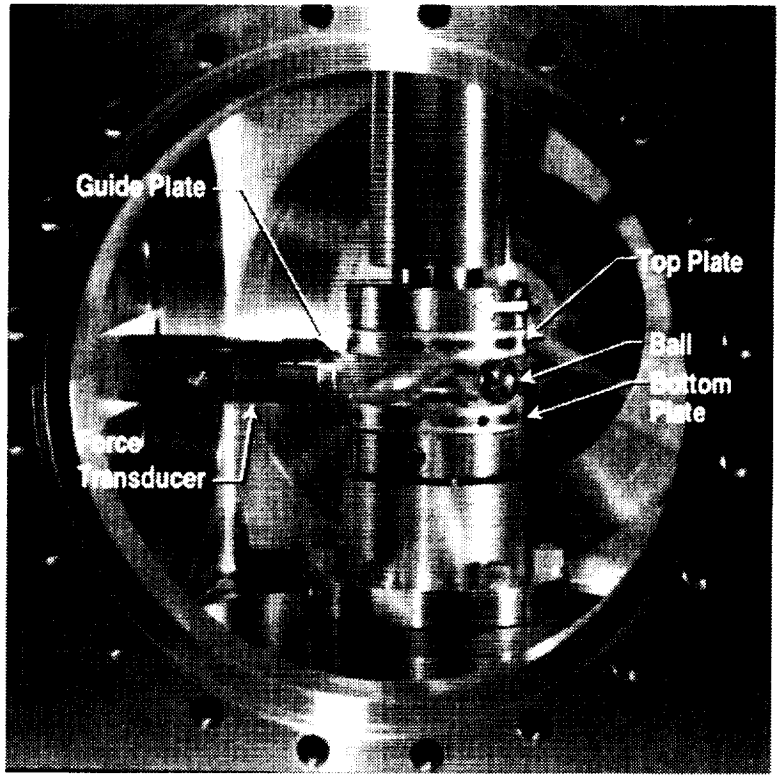

Figure 8.—Schematic view of the ultra-high-vacuum pin-on-disk tribometer.

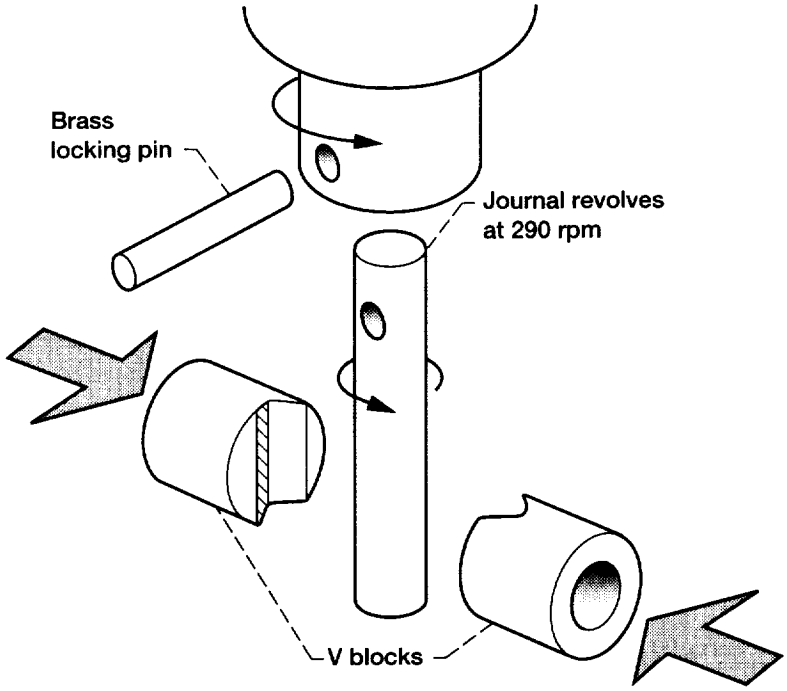

Figure 9.—Schematic view of the V-block tribometer components.

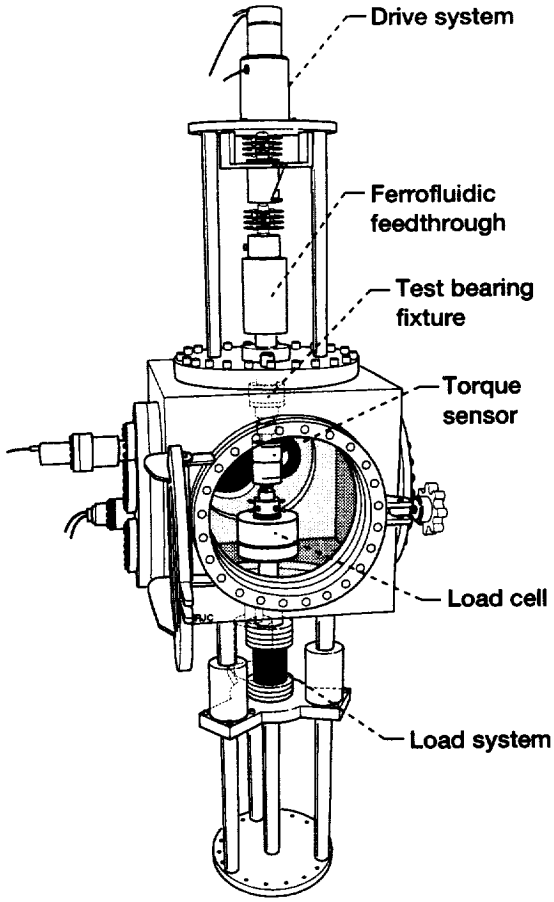

Figure 10.—Schematic view of the angular contact instrument-bearing tester.

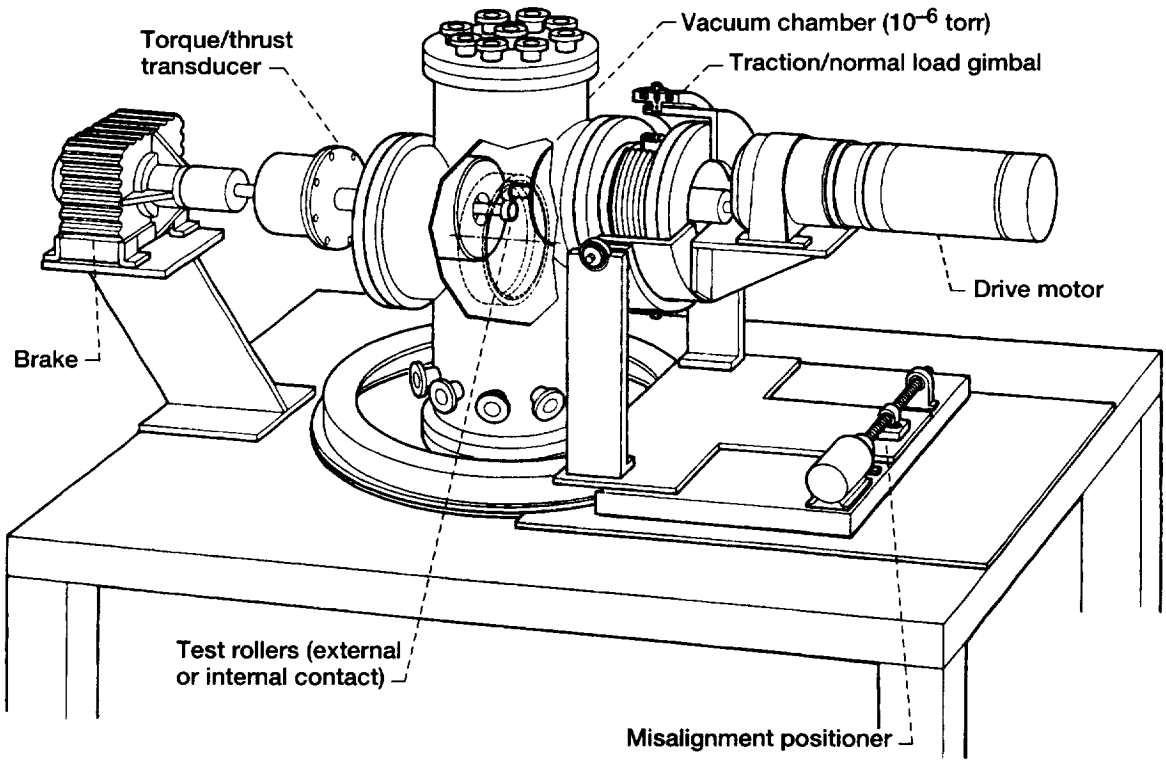

Figure 11.—Schematic view of vacuum roller contact tribometer.

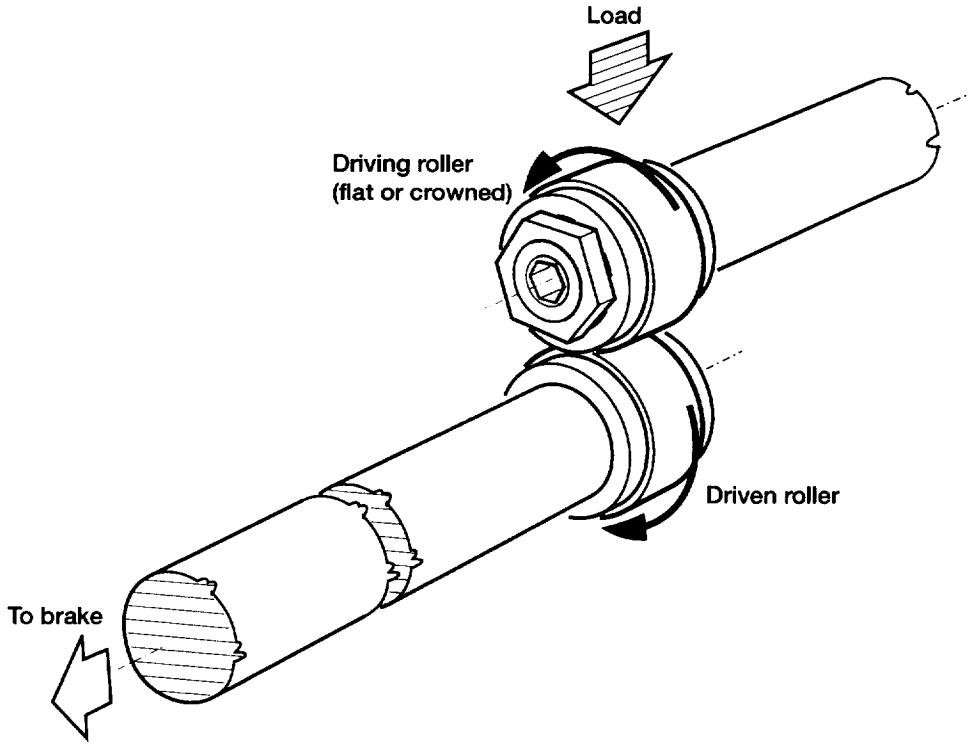

Figure 12.—Schematic view of vacuum roller contact tribometer test specimens.

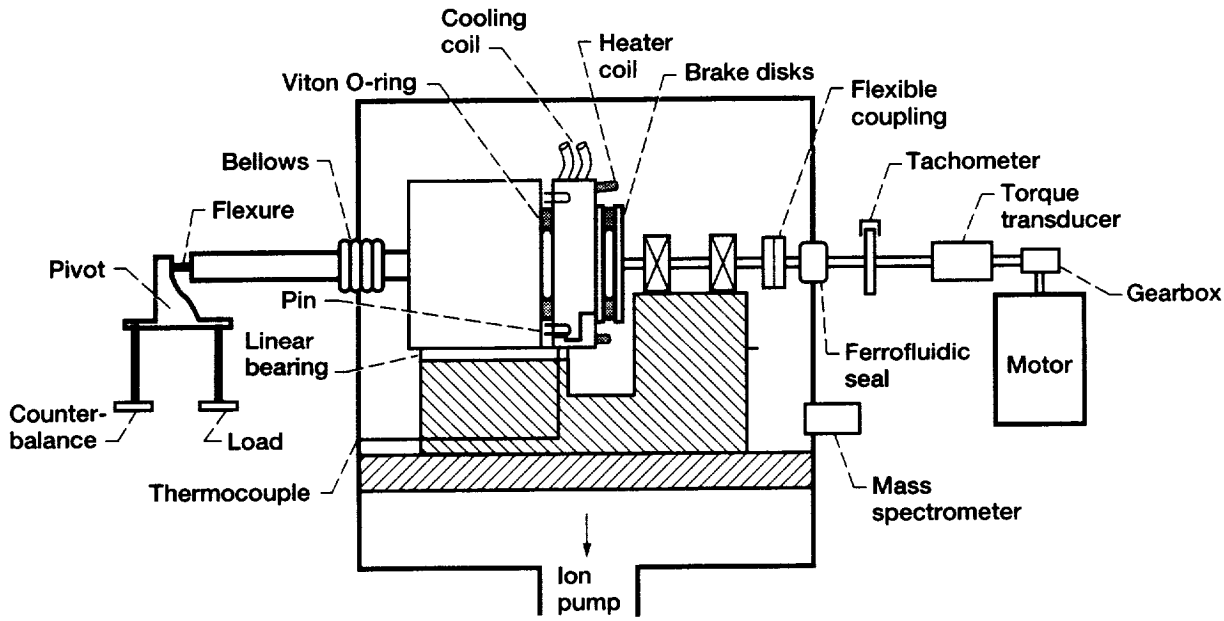

Figure 13.—Schematic view of view of vacuum brake tester.

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13. ABSTRACT (Maximum 200 words)

Many mechanical failures that occur on spacecraft are caused by tribological problems. This publication presents a study that was conducted by the author on various preventatives, analyses, controls and tests (PACTs) that could be used to prevent spacecraft mechanical system failure. A matrix is presented in the paper that plots tribology failure modes versus various PACTs that should be performed before a spacecraft is launched in order to insure success. A strawman matrix was constructed by the author and then was sent out to industry and government spacecraft designers, scientists and builders of spacecraft for their input. The final matrix is the result of their input. In addition to the matrix, this publication describes the various PACTs that can be performed and some fundamental knowledge on the correct usage of lubricants for spacecraft applications. Even though the work was done specifically to prevent spacecraft failures the basic methodology can be applied to other mechanical system areas.

14. SUBJECT TERMS

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