SMC-TR-93-14

AEROSPACE REPORT NO
TR-0091(6945-03)-6

AD-A263 026

Lubricants for High-Vacuum Applications

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15 March 1993

Prepared for

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El Segundo, California

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This report was submitted by The Aerospace Corporation, El Segundo, CA 90245-4691, under Contract No. F04701-88-C-0089 with the Space and Missile Systems Center, P. O. Box 92960, Los Angeles, CA 90009-2960. It was reviewed and approved for The Aerospace Corporation by R. W. Fillers, Principal Director, Mechanics and Materials Technology Center. Captain Borden was the project officer for the Mission-Oriented Investigation and Experimentation (MOIE) program.

This report has been reviewed by the Public Affairs Office (PAS) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nationals.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

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UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) TR-0091(6945-03)-6	5. MONITORING ORGANIZATION REPORT NUMBER(S) SMC-TR-93-14
6a. NAME OF PERFORMING ORGANIZATION The Aerospace Corporation Technology Operations 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Space and Missile Systems Center
6c. ADDRESS (City, State, and ZIP Code) El Segundo, CA 90245-4691	7b. ADDRESS (City, State, and ZIP Code) Los Angeles Air Force Base Los Angeles, CA 90009-2960
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F04701-88-C-0089
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS PROGRAM ELEMENT NO. / PROJECT NO. / TASK NO. / WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
Lubricants for High-Vacuum Applications

12. PERSONAL AUTHOR(S)
Hilton, Michael R.; and Fleischauer, Paul D.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
	FROM ______ TO ______	15 March 1993	60

16. SUPPLEMENTARY NOTATION

17. COSATI CODES		
FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Bearings, Coatings, Greases, Lubricants, Mechanisms, MoS_2, Oils, Space Environment, Tribology, Vacuum

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report reviews the selection criteria and performance of lubricants in vacuum environments found in terrestrial equipment and in (and around) space vehicles. Vacuum, mechanical, and thermal conditions of such lubricant use are outlined. Tribology issues are defined that should be considered in initial design of systems used in terrestrial equipment or space vehicles. The types of vacuum lubricants that are available (dry or solid, liquid, or grease) are reviewed, their properties and applicability to general situations are assessed, and the option of not lubricating is discussed. Examples of specific applications and performance data for lubricants in space and on earth are presented.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL

CONTENTS

I. DEFINITION AND SCOPE OF THE PROBLEM 5

II. IDEAL TRIBOLOGICAL SITUATIONS AND CONSIDERATIONS 9

A. Low Vapor Pressure 9

B. Acceptable Lubricant Creep or Migration 10

C. Long Life 11

D. Low Friction and Wear 11

E. Temperature Insensitivity 14

F. Suitable Electrical Conductivity 14

III. TYPES OF VACUUM LUBRICANTS 15

A. Solid (Dry) Lubricants 15

B. Liquid Lubricants 28

C. Grease Lubricants 42

D. Surface Modification With and Without Lubrication 43

IV. SPECIFIC APPLICATIONS 49

A. Space Environments 49

B. Terrestrial UHV Environments 51

V. SUMMARY 55

REFERENCES 57

FIGURES

1. Friction coefficient of various types of MoS_2 as a function of cycles in pin-on-disk tests 20
2. Reduction in vapor pressure as a function of percent oil loss for three oils: (1) mineral oil [SRG 40], (2) poly-α–olefin [Nye 179], and (3) polyolester [Nye UC7] 31
3. Schematic of a bearing configuration showing a labyrinth seal 32
4. Viscosity versus temperature for a homologous series of super-refined mineral oils 35
5. Nominal molecular structure of selected fluid lubricants for space/vacuum applications 38
6. Life-test results for various lubricants investigated with a boundary lubricant screening test and an oscillatory scanner-bearing test 40

TABLES

1. Potential Solid Lubricants for Use in Vacuum 16
2. Relative Merits of Solid and Liquid Lubricants for Use in Vacuum 17
3. Plastics and Fillers for Self-Lubricating Composites 26
4. Some Self-Lubricating Composites and Their Possible Uses in Space 27
5. Properties of Selected Fluid Lubricants 30
6. Factors That Influence the Degradation of PFPE Fluids 36
7. Tribology Components: Requirements and Technology "Solutions" for Space Applications 50

I. DEFINITION AND SCOPE OF THE PROBLEM

This report reviews the selection criteria and performance of lubricants in vacuum environments found in terrestrial equipment and in (and around) space vehicles. Vacuum, mechanical, and thermal conditions of such lubricant use are outlined. Tribology issues are defined that should be considered in initial design of systems used in terrestrial equipment or space vehicles. The types of vacuum lubricants that are available (dry or solid, liquid, or grease) are reviewed, their properties and applicability to general situations are assessed, and the option of not lubricating is discussed. Examples of specific applications and performance data for lubricants in space and on earth are presented.

The pressures (vacuum) to be considered for lubricant performance range from 1.3×10^{-2} Pa to 1.3×10^{-10} Pa (1×10^{-4} to 1×10^{-12} torr) in this report. This range encompasses vacuum systems used for thin film deposition or materials processing (1.3×10^{-4} Pa [1×10^{-6} torr] base pressure or higher) and for surface science experiments (1.3×10^{-9} Pa [1×10^{-11} torr] or higher). Although deep space vacuum can reach the 10^{-12} Pa (10^{-14} torr) range, near-earth orbits have higher pressures, perhaps 1.3×10^{-6} Pa (1×10^{-8} torr). Continual outgassing within a space vehicle is estimated to expose any internal mechanism to a pressure of 1.3×10^{-5} (1×10^{-7} torr) or lower.[1] Externally exposed mechanisms in low-earth orbit (<483 km [<300 miles]) may experience atomic oxygen bombardment with an apparent flux of 10^{7} to 10^{16} cm^{-2} sec^{-1}.[2]

A potential problem created by these vacuum levels is that conventional liquid lubricants, which usually have relatively high vapor pressures ($\geq 1.3 \times 10^{-4}$ Pa [1×10^{-6} torr] at room temperature) and surface diffusion coefficients ($\geq 1 \times 10^{-8}$ cm^2 sec^{-1}) with low surface tensions (~18-30 dyne/cm), can volatilize or creep away from the area of mechanical contact. The result is high friction, wear, or mechanical seizure. The volatility problem can cause lubricant vapor pressure to limit the achievable vacuum baseline of the system. Further, this problem can cause the lubricant to migrate to and condense on (i.e., contaminate) sensitive surfaces such as solar cells, optics, or the material to be probed in a surface science experiment. However, the volatility problems of liquid lubricants can be circumvented by design features that include proper confinement geometries or the use of new synthetic oils that have extremely low vapor pressures, or both. These two solutions--the use of labyrinth seals or complete sealing geometries, and synthetic oils--will be reviewed in Section III.

Another potential tribological problem created by vacuum stems from the removal of reactive gases--particularly water vapor, oxygen, and some carbonaceous species--that are present in the atmospheric environment. Normally, these reactive gases chemically passivate the near-surface region (1-5 nm) of most materials, especially metals, significantly inhibiting the welding (adhesion) of surfaces upon contact. These passive layers are often brittle and are worn away during mechanical contact. The presence of reactive gases in the atmosphere continually repassivates the material but in vacuum such repassivation can be inhibited or eliminated. Therefore, the force of adhesion between freshly exposed metal surfaces will be quite strong upon contact. The joined areas will only separate by fracture, generally accompanied by material transfer from one surface to another. This process of adhesive wear results in the consumption of extra power to drive the mechanism (with possible total prevention of any motion) and degrades the dimensional tolerance of the mechanism components, causing mechanical noise (e.g., torque hash, vibration) in precision systems. Thus, contacting metal surfaces that might not require lubrication in atmospheric conditions may require antiseize lubricants to prevent cold-welding in vacuum. Ceramics also can be lubricated by carbon-containing reactive gases. However, along with semiconductors and polymers, ceramics are not as susceptible to the "cold-welding" phenomenon as are metals.

There are two categories of systems in which ultrahigh-vacuum lubricants are needed: (1) systems in terrestrial vacuum chambers and (2) systems in space vehicles. Category 1 includes chambers used for surface science experiments, analytical instruments such as electron microscopes, thermal vacuum testing chambers, thin film deposition chambers, and other materials processing equipment primarily used in the semiconductor industry. Such systems often have manipulators to move objects within the most critical vacuum region. Contamination by the lubricant is a prime issue for terrestrial vacuum systems, whereas lifetime is a lesser concern because the lubricant can be periodically replaced by breaking vacuum. In Category 2 systems, those in space vehicles, human intervention is essentially impossible (except infrequently, when a satellite in low-earth orbit can be retrieved by a manned shuttle). Therefore, both lifetime and contamination are of great concern.

Although the conditions of mechanical contact in vacuum systems are varied, some generalizations can be made. Most mechanisms do not operate continuously, so there are periods of boundary contact (when lubricant film thickness is less than the contacting surface roughness) between component surfaces. Similarly, boundary contact also develops when oscillating mechanisms change direction. In such situations, the chemical interaction of contacting surfaces, often modified by the presence of lubricants, is critically important. Both sliding and rolling elements are designed into vacuum systems. Each element requires proper consideration of lubricant specification to prevent cold-welding, to promote low torque noise performance, and to ensure adequate service life. Other mechanical parameters that are important in the design of moving assemblies and in the selection of the proper lubricant include the expected loads and contact stresses, the geometry of the contact (the conformity of the surfaces and the possibility of lubricant confinement), and the relative velocities (rotational speed) of the contacting surfaces. Temperatures encountered by vacuum components usually range from 0 to 75°C, although mechanisms within infrared sensors are cryogenically cooled. Lubricants functioning above 200°C are beyond the scope of this text; interested readers are referred elsewhere.[3,4]

Another possible condition for lubricants in vacuum is the requirement for electrical conductivity. Some satellites maintain attitude stability by spinning the entire vehicle while the antennas and sensors are continually despun to allow them to remain pointed at fixed objects. Other satellites have rotating panels of solar cells that track the sun to maintain constant power and to keep batteries charged. Electrical signals and power must be transmitted across a rotating interface, which consists of sliding wipers having a conductive lubricant. This issue will be explored later in the text. Yet another condition is the possible use, in satellite systems, of high-speed bearings, such as those in fly wheels used for momentum stabilization and in turbomachinery (rocket motors). Because of frictional heating in such bearings, lubricants (usually oils or greases) are required that can conduct heat efficiently among rolling elements and maintain low overall operating temperatures. (The unusual case of liquid hydrogen and liquid oxygen pumps as used in the space shuttle main engines involves solid lubrication of the bearings with fluid [fuel] coolants. The involvement of the fluids in lubrication is probably minimal.)

II. IDEAL TRIBOLOGICAL SITUATIONS AND CONSIDERATIONS

When an individual or group is confronted with the task of designing and building a mechanical system to function in vacuum, tribology quite often is not given sufficient and timely consideration in the designing phase. Such inattention can convert an expensively fabricated mechanism into scrap material, increasing system cost and causing delays in schedule (which are also costly). This section will review (1) the ideal or desirable characteristics of tribological contact in vacuum and (2) the general principles involved in achieving these characteristics.

The ideal characteristics for lubricants in vacuum are:

1. Low vapor pressures.
2. Acceptable lubricant creep or migration (including little or no lubricant debris formation).
3. Long life (meeting system service life with margin).
4. Low friction (including low power consumption, low heat generation, low disturbances and low torque noise).
5. No wear/no significant deformation.
6. Temperature insensitivity.
7. Suitable electrical conductivity.

A. LOW VAPOR PRESSURE

As stated previously, low vapor pressures are desirable to prevent lubricant loss away from the region of mechanical contact, which can lead to mechanism seizure, and to prevent contamination of critical surfaces. Conventional mineral oils, even those that are "super refined" (i.e., molecularly distilled), consist of a broad distribution of molecular species. The lighter weight members of the distribution, which can be significant in number, are volatile and result in a moderately high vapor pressure ($\sim 1.3 \times 10^{-4}$ Pa [1×10^{-6} torr]) for the oil.

Generally, 20-30% of such an oil will evaporate before the vapor pressure drops significantly.[5] Conversely, synthetic hydrocarbon oils, such as poly-α-olefins, neopentyl polyolesters, and other tailored polymers, are made with very narrow distributions of molecular weights, so that both vapor pressure and viscosity are controlled to give optimum values. Less than 3% of these oils evaporates in a high vacuum chamber at elevated temperatures (pressure $\geq 1.3 \times 10^{-4}$ Pa [$\geq 1 \times 10^{-6}$ torr], 100°C). Additives contained in oils, for antiwear or antioxidation protection, usually have higher evaporation rates and vapor pressures than the base oils themselves. Such differences can cause problems, because if the additives evaporate, they can become sources of contamination and deplete the base oil of the protection that they offer. Solid lubricants generally have negligible vapor pressures relative to liquid lubricants.

B. ACCEPTABLE LUBRICANT CREEP OR MIGRATION

Another phenomenon which can cause problems similar to those of high vapor pressures is surface diffusion or creep of the liquid lubricant away from the contact region. Creep is associated with characteristically low (18-30 dyne/cm) surface tension of the lubricant on the component surface. Such low surface tension is desirable because it promotes wetting. Creep is, therefore, generally countered at the system design level by including antimigration barriers, as will be discussed in Section III. Extremely low surface tensions (~18 dyne/cm), and therefore significant creep problems, are encountered with synthetic perfluorinated polyalkylether oils. These oils have been used extensively in spacecraft because they can have even lower vapor pressures than the above-mentioned synthetic hydrocarbons. However, the hydrocarbons are preferred in many applications because problems with creep are considerably reduced and they can be formulated with additives to produce far superior lubricants.

(Although not in common use at present, another class of oils known as sila-hydrocarbons[6] offers potential advantages for vacuum uses.)

For solid lubricants, there is a similar concern about the presence and migration of particulates generated from detached film debris. This possible problem is not well documented. Therefore, line-of-sight barriers and the effects of gravity should be considered to contain particle migration. In space, particulate motion may be exacerbated by the lack of gravity. On earth, prudent designers should locate mechanisms below critical surfaces or operations, allowing gravity to pull particles away harmlessly.

C. LONG LIFE

A lubricant must have a long operational life to be considered successful. However, long life in this sense is relative to the anticipated service life of the mechanism. The point is that a lubricant should be chosen that has an adequate endurance life (including a reasonable safety margin) and not necessarily the best endurance life, since other performance properties and design issues (e.g., system complexity, system production cost) also have to be considered.

D. LOW FRICTION AND WEAR

Low friction is important for vacuum mechanisms to reduce the consumption of power, which on spacecraft is finite, since it is supplied by batteries and solar cells. Low friction also reduces heat generation. For mechanisms controlled electronically or in a feedback loop, a stable ("hash-free") friction coefficient (low noise) is particularly important to maintain proper control. In spacecraft, attitude control is maintained by either momentum transfer mechanisms (reaction wheels, momentum wheels, or control-moment gyroscopes) or by spinning most of the vehicle. Variable friction of the bearings at the despin interface can cause the vehicle to wobble or tumble.

Lubricants that promote low friction also retard wear and plastic deformation of contacting surfaces. Such wear and deformation can lead to loss of component tolerance, which, in turn, may cause increased torque noise and/or variable torque levels, or outright mechanism failure. At the atomic level, reducing friction is synonymous with minimizing chemical bonding between contacting surfaces. There is a positive relationship between friction and chemical reactivity: the friction coefficient of metals against themselves in vacuum correlates with the position of the metal on the periodic table.[7] (For example, the d-shell metals on the left side of the table, which are more reactive, have been found to have higher friction coefficients.) Thus, it is desirable for the surfaces of contacting components to have low chemical reactivity. The lubricant modifies surface composition to achieve this reduced reactivity. In unlubricated situations, low surface reactivity favors the selection of polymers or ceramics.

Ceramics are particularly interesting because their bonding properties not only yield lower surface reactivity but also higher elastic modulus and strength. The latter two properties help resist deformation and irreversible loss of tolerance. The designer should only select component materials that have elastic limits greater than the operational stresses of the mechanism to avoid plastic deformation or fracture and subsequent loss of component tolerance.

The ideal tribological contact can also be viewed from the macroscopic continuum perspective. For example, the friction coefficient between unlubricated or dry lubricated surfaces is:[8]

$$\mu = (\tau_s)(A)/W \qquad \text{(Eq 1)}$$

where μ is the friction coefficient, τ_s is shear strength of the weakest material or interface, A is the true contact area, and W is the normal contact load. τ_s is related to kinetic friction force, F_k, by:

$$F_k = (\tau_s)(A) \qquad \text{(Eq 2)}$$

For a Hertzian contact in which a smooth sphere is sliding against a flat surface, Eq 1 can be rewritten:[9]

$$\mu = (s/W)(3R/4E)^{2/3} \qquad \text{(Eq 3)}$$

where R is the radius of the contacting sphere and E is the effective modulus of the contacting materials. For a given load, the use of a lubricant or surface modification process that reduces the shear strength of the interface will reduce friction. If the lubricant film or surface modified region is thin, the load is supported primarily by the substrate. Increasing the substrate modulus decreases the contact area for a given load, which also reduces friction.

The designer can vary the surface composition of components directly or by placing lubricants on the contacting surfaces, as will be discussed in Section III. Component sliding can, in principle, occur by the shear or relative motion of atoms along only two adjacent contacting lattice planes. Thus, the above atomistic and macroscopic arguments mean that the ideal contact consists of a thin surface zone (including the lubricant, if present, and component surfaces) having low shear strength (or low reactivity), with the bulk material(s) of the components providing a high-modulus, underlying support. The ideal surface zone or lubricant film thickness has been found to be between 0.5 and 1.0 μm.[9]

E. TEMPERATURE INSENSITIVITY

Lubricants must provide acceptable friction performance within the operational temperature limits of the system. Solid lubricants generally have less temperature sensitivity than liquids and greases (Section III). Again, the designer must remember to consider all lubricants that have adequate temperature characteristics for the given application, and not necessarily to choose the lubricant with the best temperature characteristics. The thermal conductivity characteristics must also be viewed with similar criteria.

F. SUITABLE ELECTRICAL CONDUCTIVITY

For most mechanical contacts in vacuum, electrical conductivity across the contacting surfaces and through the lubricant is not an issue. However, conductive lubricants are required in sliding electrical contacts found in many space systems. These contacts transmit power and signals between different spacecraft sections that move relative to each other, i.e., motion often occurs between the main body of the spacecraft and other subsystems such as solar cell arrays, antennas, and sensors. As will be discussed in Section III, solid lubricant composites are frequently used.

III. TYPES OF VACUUM LUBRICANTS

There are three types of lubricants used in vacuum environments: solid (dry), liquid, and grease. There is also a fourth "lubricant" or approach, which is to use no lubricant at all, but to rely instead on the low reactivity of the contacting surfaces. In these cases, the component materials have to be carefully chosen and, perhaps, have their surface compositions modified to lower reactivity. Descriptions of most solid and liquid space lubricants are given, together with conditions for use, in the NASA handbook by McMurtrey.[10] This reference is a comprehensive treatise that should be consulted before choosing a vacuum lubricant. This section will define and review the lubricants available, including an assessment of their favorable and unfavorable properties. Whenever appropriate, methods of application or processing will be reviewed.

A. SOLID (DRY) LUBRICANTS

There are four types of solid or dry lubricants available for vacuum applications: soft metals, lamellar solids, polymers, or other soft solids (see Table 1). Composites of these four types of lubricants or combinations of one or more of them with matrix or support materials are also available. The major advantages of solid lubricants, as indicated in Table 2, are (1) they have negligible vapor pressures and (2) some of them are quite insensitive to temperature and therefore are the only lubricants suitable for cryogenic or high temperature applications. Accelerated testing is valid for solid lubricants, if the same wear mechanism is operative at different test speeds (which can be verified by microscopy). Since space missions often extend beyond 5 years, accelerated ground testing becomes essential for qualification of new lubricants. Generally, solid lubricants have lower friction coefficients in vacuum than greases and can have lower friction coefficients than liquids.

Table 1. Potential Solid Lubricants for Use in Vacuum

Soft Metal Films	-	Au, Ag, Pb, In, Ba
Lamellar Solids	-	Dichalcogenides (MoS_2, WS_2, $MoSe_2$)
	-	Pthalocyanines
	-	$CdCl_2$, $PbCl_2$
	-	Intercalated graphite
	-	Boron nitride
Polymers	-	PTFE, FEP, polyacetal, polyimide PEEK, UHWPE
	-	Phenolic and epoxy resins
Other Low Shear Strength Solids	-	Oxides: Cd, Co, Zn
	-	Sulfides: Bi, Cd
	-	Fluorides: Ca, Li, Ba, rare earths

Table 2. Relative Merits of Solid and Liquid Lubricants for Use in Vacuum

Dry Lubricants	Wet Lubricants
Negligible Vapor Pressure	Finite Vapor Pressure
Wide Operating Temperature	Viscosity, Creep, and Vapor Pressure All Temperature Dependent
Negligible Surface Migration (Debris can float free)	Seals Required
Valid Accelerated Testing	Invalid Accelerated Testing
Short Life in Laboratory Air*	Insensitive to Air or Vacuum
Debris Causes Frictional Noise	Low Frictional Noise
Friction Speed Independent	Friction Speed Dependent
Life Determined by Lubricant Wear	Life Determined by Lubricant Degradation
Poor Thermal Characteristics	"High" Thermal Conductance
Electrically Conductive	Electrically Insulating

*Depends on type and matrix; e.g., some polymers and bonded solids, especially graphite, behave well in air.

For example, MoS_2 films have been developed with friction coefficients lower than 0.01. (Although Guiness[11] lists Teflon as the material with the lowest friction coefficient known, at 0.02, MoS_2 films can have considerably lower values, being as low as 0.007 under the right conditions.[9])

The major disadvantage of solid lubricants is their shorter lifetime relative to liquids or greases. Once a solid lubricant is pushed out of the contact zone, lubricant resupply generally does not occur (except for transfer film schemes, as described shortly), as it does for liquids or greases. Also, failure is quite abrupt (i.e., catastrophic as compared to graceful failure observed for most fluid lubricants), often with no prior performance degradation seen by the system operators. The solid lubricant pushed out of the contact zone forms debris, which can form bumps and lead to torque disturbances in precision bearings, or can become unwanted particulate material.

Solid lubricants can be applied either by rubbing (burnishing) a powder or a solid block of lubricant against a component surface, resulting in transfer of the lubricant to the critical surface, or by applying the lubricant as a thin film to the component prior to mechanism use. The rubbing approach can be used to develop a source of lubricant resupply if some portion of the mechanism is fabricated from the lubricant. Ball bearing cages (retainers) made of polymer-based composites or of leaded bronze have been used in this way. The disadvantage of the rubbing approach is that lubricant transfer can be sporadic or uneven (nonuniform), yielding lubricant bumps or bare regions on the contacting surfaces. For precision mechanisms, unacceptable torque noise can result.

Solid lubricant films can be applied by rubbing or burnishing, although careful procedures have to be followed to maximize even coverage. Another alternative, for lamellar compounds, is to mix the lubricant with a binder and a solvent, and apply the mixture by dipping, painting, or spraying. The resulting bonded films often require air or heat curing after application. Bonded films are generally several micrometers thick, which often does not allow for the lowest possible friction of low-shear materials, and which is dimensionally unsuitable (too thick) for many precision components. However, the bonded film technology is well established and is quite effective and appropriate for many low-cycle applications, such as release mechanisms, journals, clamps, etc., that cannot tolerate seizure.[10,12]

Another approach to applying thin films of dry lubricants is to use vacuum deposition techniques for uniform coverage of components in precision systems. When film thickness is less than 1 μm, low and steady friction has been obtained, as shown in Figure 1. For precision mechanisms, the films can be applied by sputtering, ion plating, or other ion-beam assisted techniques to obtain even, controlled lubricant coverage. Ion cleaning of the substrates prior to deposition can be used to improve film adhesion to the components. A major disadvantage of solid lubricant thin films is that there is no means of lubricant resupply. Therefore, lubricant endurance life relative to system service life is of prime importance when considering solid lubricants.

1. Soft Metals

Soft metals, including lead, gold, silver, and indium, have all been used as lubricants in vacuum applications.[13] Of these metals, lead has had the most success and use. To apply lead, burnishing or electroplating has been used; however, deposition by ion plating provides the best adhesion and is preferred for even (uniform) coverage. Optimum performance of lead and other metals is achieved at approximately 1 μm thickness. Ion-plated lead films have been particularly effective in spacecraft bearings found in solar array drive mechanisms, especially in

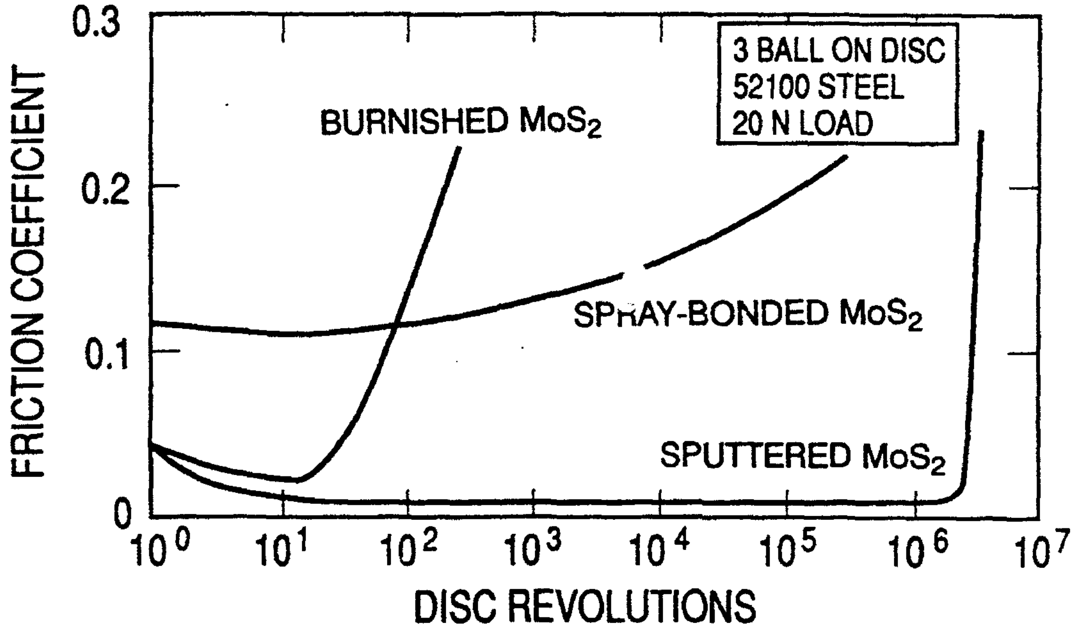


Figure 1. Friction coefficient of various types of MoS_2 as a function of cycles in pin-on-disk tests. [From E. W. Roberts and W. B. Price, Mat. Res. Soc. Symp. Proc., **140**, 251 (1989).]

European satellites. Silver and gold are useful in situations requiring electrical conductivity. However, silver is generally too hard for most applications, and gold work-hardens quite easily. Lead remains soft at room temperatures, and there is evidence which indicates that it can lubricate at 20°K.[13]

2. Lamellar Solids

Lamellar solids in relatively wide use as lubricants include the disulfides and diselenides of Mo, W, Nb, and Ta. Graphite is also a lamellar solid lubricant, but the pure material is not suitable for vacuum applications, as will be discussed shortly.[4,12] (Some other doped or intercalated layered solids--such as $Ag_xNbSe_{2-y}S_y$ [x = 0.1-1.0; y = 0.0-2.0] compounds, $Ag_{0.33}WSe_2$, $Cu_{0.33}WS_2$, $Cu_{0.33}NbSe_2$, and $Cu_{0.33}NbSSe$--have been investigated for their lubrication properties, but they are not in wide use.[14]) The anisotropic, planar crystal structures of lamellar solids provide low-shear planes for lubrication. These solids also have high load-bearing capacity when compressed in a direction perpendicular to their low-shear planes. This load-bearing capability of the lamellar solids is an advantage over solid polymer lubricants.

Of the lamellar solids, MoS_2 films deposited by sputtering have been the most widely investigated and developed, since early in the space program[15] and especially in the last few years.[16,17] MoS_2 films have a lower friction coefficient than Pb films ($\leq$ 0.01 vs 0.1 in vacuum, respectively), which lowers mechanism torque and power consumption (always a concern on spacecraft). MoS_2 films are also superior to Pb films in pure sliding applications. Sputter-deposited MoS_2 has superior endurance and a lower running friction than either burnished or bonded MoS_2, as shown in Figure 1.

The performance of sputter-deposited MoS_2 is critically dependent upon film microstructure, which includes composition, morphology, crystallinity, and preferred orientation.[15,18] These properties, in turn, are very dependent upon deposition conditions; the presence of water vapor during deposition is a particularly insidious variable.[19] The general trend in film development in recent years has been the production of dense films with low porosity, because porosity leads to large-scale film debris generation early in wear.[18] Most films grow with their low-shear basal planes perpendicular to the substrate. Reorientation of the basal planes to a parallel alignment with the substrate occurs during wear. Stress-induced crystallization has also been observed after sliding wear in some dense films that were disordered as-deposited.[20] There are several deposition practices that can yield these dense films, including high growth rates,[21] low deposition pressures,[22] ion bombardment during film growth,[23,24] and the incorporation of dopants (Au, Ni, water vapor) that are either co-sputtered continuously[18,19,25] or deposited as multilayers.[26] Some of these films have an initial preferred orientation of low-shear basal planes parallel to the substrate.

MoS_2 is very sensitive to water vapor (though not as sensitive as polyimides, which will be discussed in the next section on Polymers and Polymer Composites). If MoS_2-lubricated components are stored in a humid environment, significant oxidation will occur over months, forming MoO_3, which is an inferior lubricant.[27] This storage problem is especially relevant for satellites (and vacuum mechanisms) that are assembled at least a year before launch (use). Satellites containing MoS_2 have to be stored in dry, inert-gas environments until shortly before launch. (In fact, there are often several environmentally sensitive materials on satellites that mandate controlled storage. However, recently developed MoS_2 films having dense morphologies may have better storage oxidation resistance--there is no oxidation data currently available on these films. Such storage has the added benefit of better maintenance of vehicle cleanliness, although the moisture issue can cause some contention, because electrical systems often prefer a moderate relative humidity to prevent static electrical discharges.) MoS_2 does not lubricate as well in a humid environment as in vacuum, where friction coefficients decrease and endurance increases.[12] Indeed, MoS_2 performs at its best in vacuum. (If an MoS_2-coated component rests in vacuum, water vapor will deposit and slightly oxidize the top surface over time. The extent of oxidation depends on the vacuum level. An initially higher friction will be observed. However, the oxidized layer is quickly removed by either frictional heating and volatilization or by being pushed aside. The underlying MoS_2 exhibits a lower friction coefficient than the top surfaces.[13,28])

With regard to water vapor effects, MoS_2 is a direct complement to graphite. Graphite is an excellent lubricant in atmospheric environments. However, the low-shear strength of graphite is critically dependent upon the intercalation of absorbed gases (especially water vapor).[29,30] At pressures below ~10^{-2} Pa (10^{-4} torr), such gases desorb from graphite, and its friction coefficient dramatically rises. Intercalated graphite compounds have been developed that work well in vacuum.[4] These compounds are not widely available and so far have only been applied by burnishing or in bonded films.[31]

Other disulfides and diselenides have been considered for vacuum applications; however, none of them have the endurance of MoS_2. Although MoS_2 is a semiconductor, it is routinely used for sliding electrical contacts (see Section IV). $NbSe_2$, which is a semimetal in its natural state, should, in principle, be better for this application. Unfortunately, in the semimetallic form, $NbSe_2$ is not a good lubricant. $NbSe_2$ becomes a good lubricant only when it is intercalated with electron donor atoms (which could be excess Nb atoms), whereupon it also becomes a semiconductor.[32] WS_2 is widely used as an additive for liquid lubricants in automotive applications. WS_2 also performs well at higher temperatures and is more oxidation resistant than MoS_2; WS_2 has been deposited by impact under high air pressure in one commercial process. However, experience has shown that WS_2 should be considered primarily as an antiseize compound for limited-use (low cycle) vacuum applications. Sputter-deposited films of WS_2 or WSe_2 codeposited with MoS_2 can have properties comparable to, or even better than, sputtered MoS_2 films.[33,34] However, MoS_2 is much more common and generally has superior endurance in vacuum applications.

3. Polymers and Polymer Composites

Polymers, consisting of anisotropically bonded molecules, can provide low friction surfaces in vacuum, if the molecule chains align properly at the contacting surface. However, the load-bearing capability of polymers is generally low, so additives are required to strengthen the polymer to avoid ploughing into the bulk. For vacuum applications, polymer composites rather than pure polymers are generally used.[35,36] Since these composites have structural integrity, self-lubricating composite components can be fabricated that car, in principle, provide a continual source of solid lubricant to critical components.

To date, polytetrafluoroethylene (PTFE) has been the polymer used the most in vacuum. This is because PTFE performs well in vacuum and in the presence of absorbed vapors. PTFE has a tendency to cold-flow under load, necessitating a binder to restrain the polymer bulk, i.e., to prevent ploughing. Some polyimides appear to be excellent in vacuum because they exhibit low friction coefficients without significant cold-flowing of the bulk.[37] However, polyimides are very sensitive to water vapor absorption. Water molecules appear to hydrogen bond to the polymer molecules and then inhibit molecular shear. Thermal pretreatment of polyimides appears to be essential for good performance in vacuum.

When making polymer composites, other materials are added to the polymers for several reasons: to increase load-carrying capacity, to lower the friction coefficient and to promote a low wear rate, and to increase the composite's thermal conductivity. Table 3 lists polymers and additives that can be used for self-lubricating composites. Both fibers and particulate additives can be used, although fibers are more effective for increasing composite load-carrying capacity. Studies indicate that MoS_2 in some composites facilitates polymer transfer to a critical component; the polymer is the primary lubricant, not the MoS_2.[38] Table 4 lists some self-lubricating composites that are available and their possible uses in space. When a polymer composite is selected for an application, contact stress is probably the most important property to consider. The ideal composite must support, in the bulk of the material, the dynamic stresses of the application and must allow for the formation, by local deformation, of a low-shear layer at the surface.

4. Other (nonpolymer-based) Composites

Two examples of nonpolymer-based composites are particularly worthy of attention. One example, leaded bronze composites, has been fabricated into bearing retainers.[9,13] When used in conjunction with lead-coated bearings (for example, in solar array drive mechanisms), the lead in the retainers provides an effective supplemental source of lead when the original film is worn. Another example--composite blocks of silver, MoS_2, and either graphite[39] or copper[40]--is used as brushes in sliding electrical contacts. The silver provides conductivity and structural integrity, the MoS_2 lubricates in vacuum, and the graphite or copper may lubricate in air.

Table 3. Plastics and Fillers for Self-Lubricating Composites

Material	Maximum Useful Temperature (°C)
Thermoplastics	
Polyethylene (high MW and UHMW)	80
Polyacetal (homo- and co-polymer)	125
Nylons (types 6, 6.6, 11)	130
Poly (phenylene sulphide)	~200
Poly (tetrafluoroethylene)	275
Poly (p-oxybenzoate)	300
Thermosetting	
Phenolics	~150
Cresylics	~150
Epoxies	~200
Silicones	~250
Polyimides	~300
Reinforcements	
Glass fibers	
Asbestos fibers	
Textiles (polyester, "Nomex," cotton)	
Mica	
Friction and Wear Reducing Additives	
Graphite	
Molydenum disulphide	
Polytetrafluoroethylene (PTFE)	
Metal oxides	
Silicone fluids	
Thermal Conductivity Adjunctives	
Bronze	
Graphite	
Silver	

Table 4. Some Self-Lubricating Composites and Their Possible Uses in Space

Composite Type	Use
PTFE/glass fiber	Bearing cages
PTFE/glass fiber/MoS_2	Bearing cages, gears
Polyacetal homopolymer/co-polymer	Bearing cages, gears, bushings, brakes
Reinforced phenolics	Bearing cages, gears
Polyimide/MoS_2	Bearing cages, gears
PTFE/woven glass fiber/resin	Bushings
PTFE/bronze sinter	Bushings, rotating nuts

B. LIQUID LUBRICANTS

Examination of Table 2 would suggest that the merits of solid lubricants frequently exceed those of liquid lubricants in vacuum applications. However, liquid lubricants are often used in space applications, particularly on U.S. systems. In the early years of the space program, liquid lubricants were understood better than solid lubricants, so mechanisms were engineered to make low vapor pressure liquids work in vacuum applications.[30,41] Early success with liquids slowed the incorporation of solid lubricants into U.S. space systems. In contrast, European-designed space systems have often incorporated solid lubricant technology as it has evolved.[42] The primary advantage of liquid lubricants over solid lubricants is their long life in high-cycle applications, such as in gyroscopes. Long life results because liquid lubricants can be resupplied and they have low frictional noise in bearing applications. Another advantage is that liquid lubricants have high thermal conductance, which may assist in managing thermal stability on spacecraft. For terrestrial vacuum systems, however, these advantages often do not outweigh the disadvantage of potential contamination from fluids. Therefore, in terrestrial vacuum systems, the use of modified surfaces and/or lubrication by solids or greases is the preferred approach for manipulators and other mechanisms.

A particular disadvantage of liquid lubricants for space applications is that accelerated testing, while desirable, is difficult because of the synergistic dependence of lubricant properties, such as film thickness, on operational parameters, such as contact speed, load, and temperature. It is reasonable to compare the performances of two or more different fluid lubricants in tests in which operational conditions are intentionally more severe than for the expected application. But extreme care is required in the selection of the parameters to be "accelerated", and specific acceleration factors should never be quoted for an application without complete theoretical justification. Such justification would have to involve a rigidly verified, mechano-chemical model for determining operational life of the system (or component) of interest.

For space applications, contamination and lubricant loss are minimized by proper lubricant selection and mechanism design. Low vapor pressure lubricants do exist, as shown in Table 5 and Figure 2. Their lubrication properties will be discussed in subsequent paragraphs. If a component is not totally sealed, lubricant loss by vapor transport is generally diminished by incorporating molecular seals, often of a labyrinth geometry (Figure 3), into the bearing design.[39,41] Contamination, via vapor transport, of critical surfaces away from the tribocontacts can also be avoided by the use of vents into space, pointed away from critical surfaces and away from the leading (front) edge of the vehicle. (The pumping speed of space vacuum is essentially infinite. There are no surfaces to reflect gas molecules back to the spacecraft. However, processes have been proposed involving photoelectric charging of emitted molecules and reattraction or collision with "ambient" molecules in the vicinity of a spacecraft and redirection toward critical surfaces.[43]) Lubricant migration by creep can be countered by anticreep barriers that are primarily made of ultralow surface energy (~11 dyne/cm) fluorocarbon coatings.[44]

If lubricant loss does occur, a passive or positive-feed resupply method is required. The passive method generally uses lubricant-impregnated porous solids. In this method, oil is provided to a contact region as long as there is some positive driving force (heat or centrifugal force) to overcome the capillary forces of the porous medium. Oil-soaked phenolic retainer materials were once thought to be lubricant resupply sources for bearings. However, both theoretical and experimental studies have shown that such materials actually can act as sinks, further depleting the lubricant supply unless they are fully

Table 5. Properties of Selected Fluid Lubricants

Property	PFPEs			PAOs		POEs (NPEs)		MAC	SiHCs	
	Demnum S200	Fomblin Z25	Krytox 16256	Nye 179	Nye 188B	Nye UC7	Nye UC9	Pennzane SHF X2000	SiHC1	SiHC2
Average molecular weight	8400	9500	11,000						1480	1704
Kinetic viscosity at 20°C, cS	50 ± 25	255	2,717	30 (40°C)	107 (40°C)	39 (38°C)	57 (38°C)	110 (40°C)	278 (3)	480 (3)
Viscosity index	210	355	---	139	145			137	125	128
Pour point, °C	-53	-66	-15	< -60°C	-55°C	-56°C	-53°C	< -55°C	-50	-15
Density at 20°C, g ml^{-1}	1.894	1.851	1.92			0.98 (16°C)	0.96 (16°C)	0.85	0.8 (4)	0.8 (4)
Surface tension at 20°C, dyne cm^{-1}	19	25	19							
Vapor pressure, torr:										
At 20°C	5×10^{-11}	2.9×10^{-12}	3×10^{-14}	(1)		(1)		1.04×10^{-12} (2)		
At 100°C	1.0×10^{-7}	1.0×10^{-8}	1×10^{-9}							
At 125°C								4.14×10^{-7}		

Comments

1. Note vapor pressures in Figure 2.
2. Extrapolated from data taken between 125°C and 175°C.
3. Extrapolated from measured viscosities at 40°C and 100°C.
4. Estimated based on densities of other silahydrocarbon (SiHC) samples.

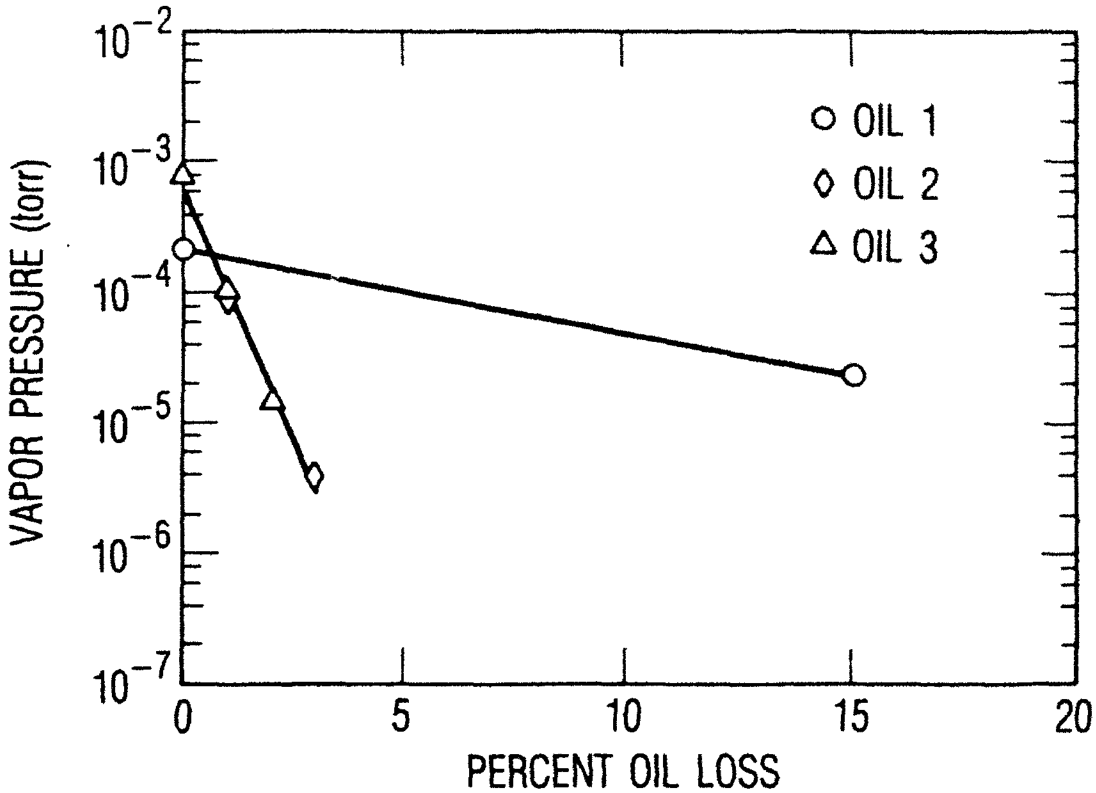


Figure 2. Reduction in vapor pressure as a function of percent oil loss for three oils: (1) mineral oil [SRG 40], (2) poly-α-olefin [Nye 179], and (3) polyolester [Nye UC7]. [From D. J. Carré, TR-0090(5945-03)-5, The Aerospace Corporation, El Segundo, CA (in press).]

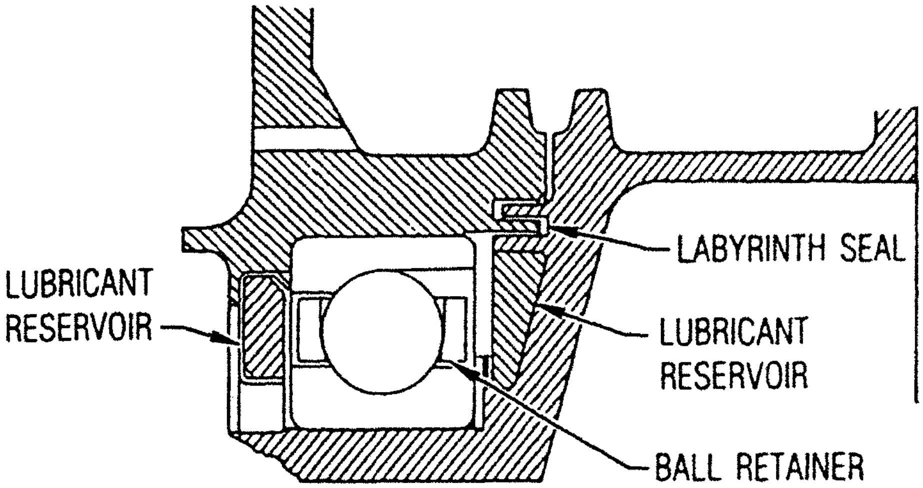


Figure 3. Schematic of a bearing configuration showing a labyrinth seal. [From M. N. Gardos, ASLE Transactions, **17(4)**, 237 (1974).]

saturated with oil.[45,46] This saturation process can take up to 2 years at ambient temperature.[39,47] Porous nylon-based materials, polyimides, and copolymer foams of acrylonitrile have been used as reseviors in several mechanisms, but they are subject to the same potential problems as phenolic retainer materials. The positive-feed method uses positive-feed suppliers with centrifugal oilers or controlled pumps. This method has been used for higher load (requiring larger bearing sizes) and/or longer life mechanisms.

There are several types or categories of liquid lubricants that have been used or could be used for vacuum/space applications. These categories include: (1) silicone oils; (2) mineral oils; (3) perfluoropolyalkylethers (PFPEs); and (4) other new synthetics (including poly-α-olephins [PAOs], polyolesters [POEs], multiply-alkylated cyclopentanes [MACs], and others). Except for gyroscope applications, these lubricants generally encounter boundary contact conditions at least at some time during their service life. Boundary lubrication additives are available for many of these lubricants and will be reviewed after lubricants are discussed.

1. Silicone Oils

The low vapor pressures and low pour points of some silicone oils led to their early use in space applications. However, these oils are only moderately effective lubricants. One problem is that some of these oils tend to form polymers on the bearing surface, which leads to torque noise. Another problem is that these oils creep readily on metal surfaces. Because of these problems and the availability of better alternatives, silicone oils would not be used on contemporary spacecraft. However, these oils are used as damper fluids and as thermal conduction media in some instances.

2. Mineral Oils

Highly refined mineral oils have been a popular choice for sealed mechanisms, such as momentum wheels, reaction wheels, and despin mechanisms. Mineral oils from manufacturers, including Shell Oil Company, Bray Products Division of Burmah Castrol Inc., Nuodix Inc. of Texaco Chemicals, Royal Lubricants, and others have been used successfully.[10] Specific examples include those of the Aeroshell and Apiezon series. (Another oil, developed by British Petroleum, BP 110, is no longer marketed.) A series of super-refined gyroscope lubricants (SRG and KG-80 [Originally manufactured by Kendall Oil Company and now available through W. F. Nye Company]) is also available which comprises a homologous group of natural polymers that allows the designer to choose a fluid having particular viscosity characteristics for a specific application (Figure 4).[48] Mineral oils also can be formulated with antiwear and other additives.

3. Perfluoropolyalkylethers (PFPEs)

PFPE lubricants have lower vapor pressures, lower pour points, and higher viscosity indexes than mineral oils (see Table 5). Thus, they are useful in space mechanisms that are not completely sealed or that are somewhat cooler (>200 K) than would be acceptable for mineral oils. In particular, one of the PFPEs (Fomblin Z25) has a very high viscosity index and is exceptionally useful over a wide temperature range.

PFPEs perform reasonably well under nonboundary contact conditions. However, these lubricants have definite limitations when used for applications involving boundary contact, particularly on steel surfaces (see Table 6). Conventional antiwear additives do not dissolve into the PFPE fluids, although a new class of compatible additives has been reported.[49] During boundary contact in the absence of additives, fluorine from the

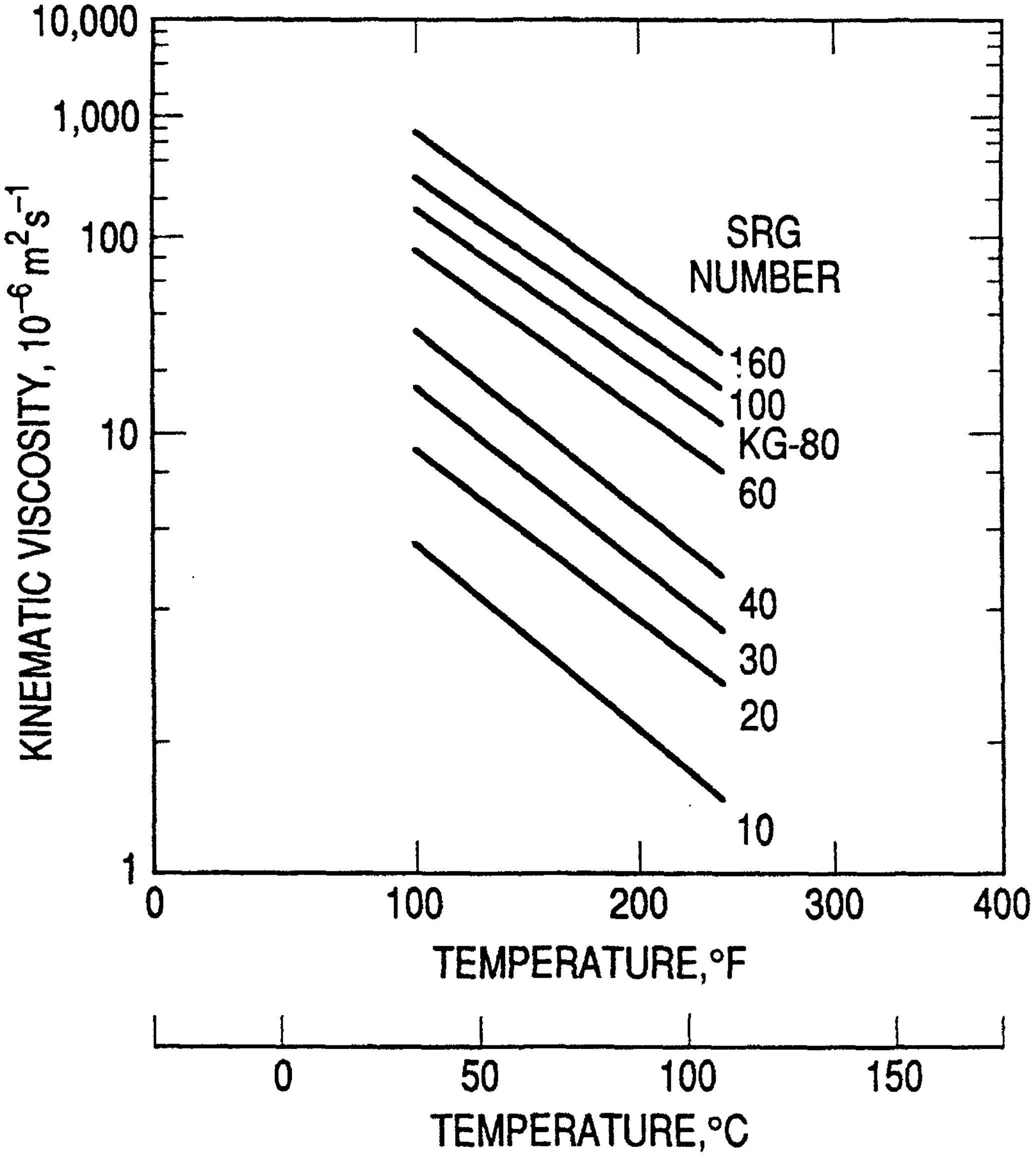


Figure 4. Viscosity versus temperature for a homologous series of super-refined mineral oils. [From J. W. Kannel and K. F. Dufrane, Twentieth Aerospace Mechanisms Symp. (1986), NASA CP-2423, 121-132.]

Table 6. Factors That Influence the Degradation of PFPE Fluids

Promote Degradation	Retard Degradation
Starved Conditions	Fully Flooded Conditions
Low Specific Film Thickness	High Specific Film Thickness
Linear Structure (Z)	Branched Structure (Y)
Aluminum/Titanium Substrates	Hydrocarbon Contamination
52100 Bearing Steel	[illegible]0C Steel and Ceramic Coatings
Temperatures > 200°C	Low Ambient Temperatures
Sliding Surfaces (Seals, etc.)	Rolling Surfaces
Vacuum Environment	Atmospheric Conditions

PFPE can react with iron to form FeF_3, a catalyst for the further breakdown of the polymer.[50] More F is released, which sustains a chain reaction. Lubricant degradation by polymerization leads to high bearing torque noise and excessive wear. The substrate-induced degradation can be retarded by substituting one or both of the steel surfaces with either ceramic components or ceramic-coated steel (or presumably by using the new additives). TiC- and TiN-coated steel and Si_3N_4 components have shown improved performance, as will be discussed in the section on surface modification.[51]

PFPEs have extremely low surface tensions (~18 dyne/cm) and, therefore, creep very readily over metal and other surfaces. Because of their similar chemical structures, the lubricants also dissolve fluorocarbon coatings that are used as antimigration barriers. The available commercial PFPEs and their properties are listed in Table 5. Their molecular structures are shown in Figure 5. The acetal groups present on the Fomblin Z25 or Braycoat 815Z polymers are particularly reactive under boundary conditions.

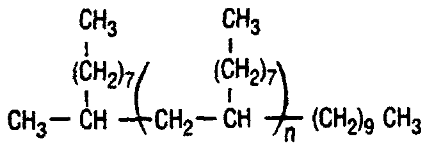
4. Other Synthetic Lubricants

Poly-α-olefin (PAO), polyolester (POE), multiply-alkylated cyclopentane (MAC), and other hydrocarbon polymer (HP) oils can be synthesized and blended to produce viscosity, vapor pressure, pour point, and other properties in a controlled way that will suit various needs.[39,52,53] Vapor pressures that are as low as those of linear PFPEs have not been obtained for the PAOs and POEs, but they can be lower than those of conventional mineral oils. Vapor pressure studies of the MAC oils are currently underway--extrapolations based on measurements at higher temperatures (125-175°C) suggest that room temperature vapor pressure of at least one MAC oil should be low, as listed in Table 5.[54] Outgassing studies of selected PAOs and POEs

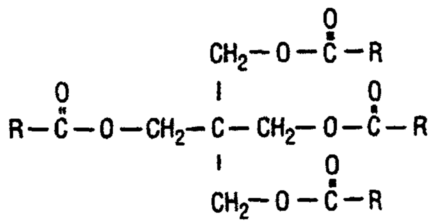
1. $R_f - (CF_2\text{-}CF_2\text{-}O)_x - (CF_2\text{-}O)_y - R_f'$ — PFPE (Fomblin Z, Braycote 815Z)

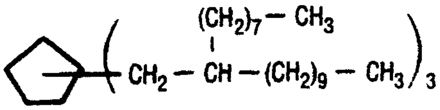
2. $R_f - (\underset{\displaystyle CF_3}{CF}\text{-}CF_2\text{-}O)_n - R_f'$ — PFPE (Krytox) [Y-structure]

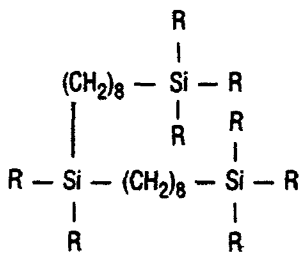
3. $R_f - (CF_2\text{-}CF_2\text{-}CF_2\text{-}O)_n - R_f'$ — PFPE (Demnum)

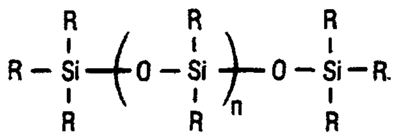
4.  PAO

n = 1 – 10

5.  R = C5 – C20 — POE (NPE)

6.  MAC

7.  R = C8 – C10 — SiHC

8.  SILICONES (not recommended)

n = 0 – 5, R = CH_3, – 

Figure 5. Nominal molecular structure of selected fluid lubricants for space/vacuum applications.

(specifically a neopentyl ester [NPE]) show that removal of relatively high-vapor-pressure light fractions, which account for ≤3% of the as-received lubricant, reduces the vapor pressure by several orders of magnitude without affecting viscosity at room temperature (see Figure 2).[5]

These synthetic hydrocarbons can be blended with conventional additive packages to provide the same type of protection against wear, oxidation, and corrosion as achieved by natural hydrocarbons. However, for vacuum applications, the low vapor pressures of the base stocks make the additives the most volatile constituents of blended lubricants. Therefore, new additives are being developed that will be compatible with the base stocks and that will have the desired low volatilities. Laboratory screening tests have shown that synthetic hydrocarbons give the longest wear lifetimes in a simulated boundary-lubrication test facility. Bearing tests with a fixture designed to simulate the oscillatory motion of a weather scanner have shown that a PAO provides near freezing (0°C) temperature capability and significantly outlasts both a silicone oil and a PFPE (Figure 6).[52,55] PAO oils have given very good performance in lightly loaded, high speed gyroscope bearings. Tests are presently aimed at determining the utility of these synthetic oils in more demanding applications, such as in the spin bearings of momentum and reaction wheels.

Another, relatively new class of synthetic lubricants with vapor pressures acceptable for vacuum applications and the capability to be compounded with additives is known by the term "silahydrocarbons."[6] Their tribological performance has not been thoroughly tested in specific applications, but the results of conventional four-ball and traction tests are very encouraging.[56]

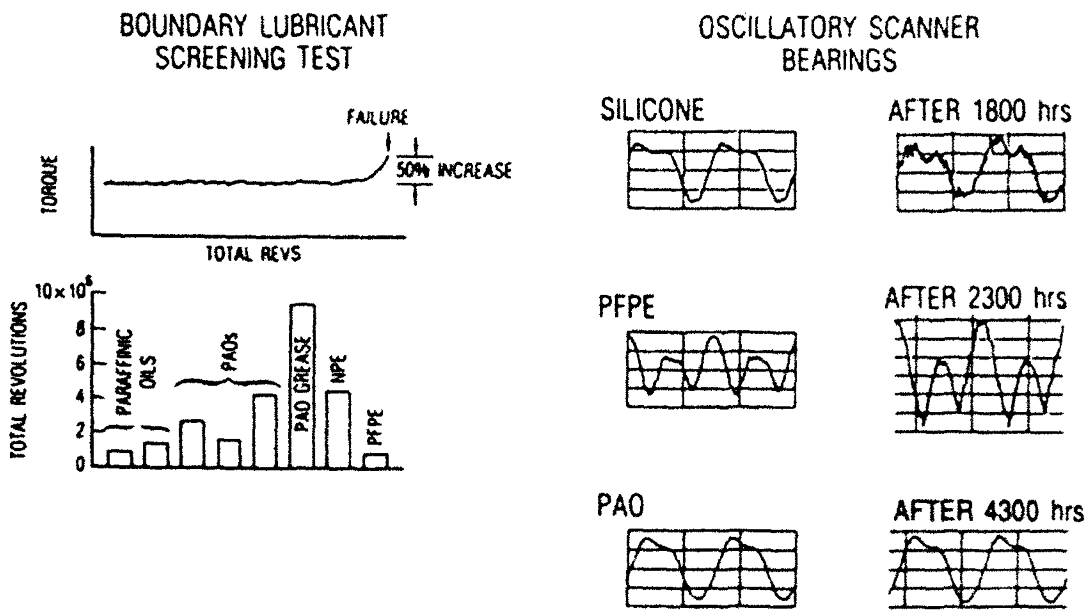


Figure 6. Life-test results for various lubricants investigated with a boundary lubricant screening test (left) and oscillatory scanner-bearing test (right). Silicone and PFPE failed after the indicated times, while the PAO test is still running. [From P. D. Fleischauer and M. R. Hilton, Mat. Res. Soc. Symp. Proc., **140**, 9 (1989).]

5. Additives

Liquid lubricants are formulated with additive packages in order to provide, for example, low friction and antiwear protection in elastohydrodynamic (EHD) or extreme pressure conditions, and to retard lubricant oxidation or substrate corrosion during atmospheric storage. Most of these additives were developed for use under atmospheric conditions, with oxygen and water vapor, and were compounded with base stocks on a highly empirical basis. In vacuum, once water vapor and reactive gases are removed, it is doubtful that most additives work in an identical chemical-mechanistic manner as they operate at atmospheric pressures. Furthermore, the nature of the interactions of these additives--that were developed for steel substrate surfaces--with newly emerging ceramic components (e.g., SiC,, Si_3N_4, TiC, TiN) is unknown. Additive surface chemistry is currently an active topic of study by many tribologists and surface scientists.

Antiwear or extreme pressure (EP) additives are often required when liquid lubricants are used in mixed or boundary regime applications in vacuum. Numerous examples exist where antiwear additives, such as tricresol phosphate, improve the operation of bearings and provide longer life. In boundary-lubrication situations, the modern designer must carefully consider the relative merits of liquid and solid lubricants. Liquid lubricants have long life and low torque but require additives and possibly, reservoirs and molecular vapor seals in the design; solid lubricants operate well in boundary conditions without reservoirs or seals but have a finite life. Another option, surface modification, is also worthy of consideration. Common EP additives include naphthenates of lead and other metals and dialkyldithiophosphates of zinc or antimony.

The role of anti-oxidation additives in vacuum lubricants is to prevent degradation of lubricants during storage. Common types of such additives include hindered phenols, and amines, such as polyphenyl α-napthylamine.

Antirust additives can be particularly important for components stored in air that are coated with the PFPE oils, because these oils do not offer the same oxidation protection to the substrate as do other oils. Unfortunately, common antirust additives do not dissolve in the fluorocarbons any better than antiwear materials. For one of the PFPE greases (see next section), $NaNO_2$ is added by first being adsorbed onto bentonite clay and then being suspended, together with the clay, to form the grease.

C. GREASE LUBRICANTS

Greases are comprised of oils compounded with a pore-network-forming thickener, such as a soap or a fine particle suspension. For thorough descriptions of greases and their properties, the reader is referred to literature references.[57,58] For results of an extensive testing program of greases in vacuum, see the reference written by McMurtrey.[59] A very brief overview of grease lubricants is provided here for reader convenience.

Depending on the type of oil and the nature of the thickener, greases can be formulated for various applications involving a variety of components with different types of contact (e.g., slow or high speed angular contact ball bearings, journals, gears). Oils in greases can be from any of the categories discussed in previous sections. However, the solubility properties (i.e., chemical compatibility) of the oil will determine the selection of thickener and, hence, the grease properties. Mineral oils and certain synthetics have good solvent properties, so they can be formulated with soaps of different cations to make what are known as channeling greases. Such greases are pushed out of the way and form a path (channel) when the balls of a bearing pass through the grease. When working properly, oil will continually diffuse out of the mounds of grease on the edges of the ball path to supply lubricant to the contacting surfaces. If a grease is fluid enough that it tends to fill the spaces between balls, it is a "slumping" (non-channeling) grease. The consistency of a grease depends on the type of thickener used and the relative amounts of oil vs thickener.

PAO and PFPE oils are poor solvents for soaps, so greases of these oils are made by suspending fine particles of inert materials in the oils until their consistency becomes thick like a grease. Two common thickeners of this type are Cab-o-sil (finely ground amorphous silica) by Cabot Corporation and another powder that is simply designated as a fluorocarbon telomer by Burmah-Castrol. This manufacturer also produces widely used PFPE greases, Braycoat 600, 601 (also contains a rust inhibitor), and 602 (also contains MoS_2). One drawback to this type of grease is that the thickener can get into the ball path of a precision bearing and, being solid, can cause noisy operation.

The primary purpose for using grease in a vacuum application is that the grease can act as a reservoir for supplying oil to contacting surfaces. A bearing properly packed with grease will also suffer less oil loss by creep or physical spattering because of the physical barrier the grease can provide. However, the lubrication properties of any grease can be only as good as those of the base oil, so care must be exercised in selection of the base oil. For example, formulation of a volatile oil into a grease cannot prevent the oil from contaminating a vacuum system; a low volatility oil must be used.

D. SURFACE MODIFICATION WITH AND WITHOUT LUBRICATION

The fourth approach for providing low friction and limited wear in vacuum is to use no lubricant all. Instead, the low reactivity of the substrate surface can be relied upon to prevent cold-welding. For lightly loaded applications that have low duty cycles, this option can work very well. For mechanisms in terrestrial vacuum systems, this approach is often a tempting first choice. Then if the component fails to operate properly, vacuum can be broken and a lubricant can be applied and tested for the application. On the contrary, spacecraft-mechanism performance cannot be left to chance, and most mechanisms that experience more than light loads and/or have frequent use will require tribological modification in the contact zone. The modification approaches in this section do not have the same historical degree of proven success as the lubricants mentioned in the previous sections; the modifications are simply too new. Nonetheless, the authors believe that these emerging technologies will be used increasingly in the future, either alone or in conjunction with lubricants.

Since metals generally do not have unreactive surfaces once their passive layers are worn away, chemical modification of the surface region or complete materials substitution is required. The basic idea is to avoid metal-to-metal contact that might cause cold-welding or adhesive wear. Ceramics often are covalently bonded materials and generally have a lower reactivity than metals (one exceptionally inert metal being gold). In particular, the carbides and nitrides of silicon and titanium (SiC, Si_3N_4, TiC, TiN) have excellent attributes: they are hard (resist plastic deformation), chemically inert (resist cold-welding/adhesive wear), and have high melting temperatures (resist chemical interdiffusion between contacting surfaces). They are also commercially available, either as ceramic components or as ceramic coatings on bearing steels. A possible alternative is to ion implant C, N, or metals into steel surfaces to create a hard, unreactive surface region. Studies have shown that ion implantation can improve the corrosion and wear resistance of steel operating in ambient environments.[60] Data of performance in vacuum applications is needed. Another future alternative may be polycrystalline diamond coatings. However, although hard carbon films are used for some computer disk drive applications, diamond films cannot yet be applied to metals without overtempering and distortions, and their tribological properties still need extensive investigation.

TiC coatings formed by chemical vapor deposition (CVD) onto steel have been used for over a decade in the tool industry to prolong tool life. CVD TiC coatings are also commercially available on 440C balls for bearing applications.[61] The high temperatures (>1000°C) used in the CVD process, in which $TiCl_4$, and H_2 and N_2 gases react on the hot steel substrate to form TiC, soften the steel. Consequently, the balls have to be heat treated again to regain hardness after deposition, and anisotropic phase transformations during the second heat treatment distort the balls into egg-shaped structures. The balls are then repolished to regain sphericity. Balls are available with a 0.375 inch diameter or less. Larger sizes distort to tolerances greater than the allowable coating thickness, resulting in "bald spots" after polishing. TiC-coated balls have been used without additional lubricant in the primary deployment mechanism of the Space Telescope solar array. These balls have also been used with PFPE oil (Fomblin Z25) for the Spacelab Instrument Pointing System.[62]

TiN and TiC coatings produced by sputtering also have been used for years in the tool industry. The lower operating temperatures of the sputtering process, particularly some high-rate variations,[63,64] can, in principle, avoid the second heat treatment problems associated with CVD. There have been very limited studies of sputtered TiN in bearing or gear applications in vacuum. Eccentric bearing tests in vacuum showed an order of magnitude increase in life when TiN-coated components were compared to uncoated 440C steel. In both cases, the bearings were lubricated with a PFPE oil (Krytox).[51]

Solid ceramic parts, such as Si_3N_4 balls formed by hot isostatic pressing, are commercially available with diameters up to 2.5 inch.[65] Appropriate polishing can produce balls down to Grade 3 finish. Grades 3, 5, and 10 are usually produced. Such balls have been used in hybrid bearings (ceramic balls and steel races) operated in ultrahigh-vacuum, either unlubricated or with solid or liquid lubricants. Eccentric bearing tests of PFPE-lubricated hybrid bearings in vacuum (Si_3N_4 balls against 440C steel races) again showed an order of magnitude increase in life over an all-steel configuration. The gains observed with the Si_3N_4/steel hybrid were identical, within experimental error, to gains obtained with all TiN-coated components.[51] The results emphasize the improvements that can be obtained when metal-to-metal contact is avoided, even by the elimination of only one metal surface from the contact. When used with PFPE oils, the ceramics appear to retard chemical degradation of the lubricant by Fe in the steel substrate.

Although the tribological improvements of using bulk ceramics or ceramic coatings on steel appear similar--basically because metal-to-metal contact is eliminated--there are important differences in bulk properties that must be considered. The ceramic coatings are thin enough (<3 μm) that the majority of the load is carried by the steel substrate. Therefore, the modulus of the steel determines the stress levels generated. Si_3N_4 has a Young's modulus (310 GPa or 45 x 10^3 Ksi) that is 50% higher than that of steel. Thus, higher contact stresses are generated in the ceramic than in the steel at any particular load. In addition, the thermal coefficient of expansion (3.5 x 10^{-6}) and the Poisson's ratio (0.28) must be taken into account when ceramics are combined with steel races in a given application. Tighter race conformance to the ball relative to steel bearings is sometimes required to reduce stresses, but the result can be increasing operating friction or torque.

A potential alternative to coatings or bulk ceramics is ion implantation of steel surfaces.[66,67,68] Energetic (100 KeV) ion beams of various species (e.g., B, C, N, Ti) are directed towards the substrate. Such species can form compounds in the near-surface region (<0.1 μm) or simply disrupt the surface structure (render amorphous) so that wear resistance can increase. This approach does not change the dimensions of the component. Sometimes, substrate cooling is necessary when high flux beams are used. The process, as originally developed, was line-of-sight, but isotropic plasma implantation techniques have become available.[69] Ion implantation has been used in many different terrestrial applications. In a vacuum application, ion implantation is being tested for possible use in the main-engine bearings of the space shuttle to provide improved corrosion and wear resistance. (During use, these bearings get very hot so that lubricants do not survive; also, stored bearings rust in condensed moisture.) A terrestrial bearing study of balls made of TiC-coated 440C, of Si_3N_4, or of ion-implanted (Ti, C) 52100 showed comparable improvements in performance for each modified material over 52100 balls in fretting tests.[70] In gyroscope spin tests, the implanted balls showed slight evidence of wear relative to the ceramic or ceramic-coated balls, but all three types performed better than the standard 52100 balls.

IV. SPECIFIC APPLICATIONS

A. SPACE ENVIRONMENTS

Although the functions or missions of different spacecraft systems vary widely, there are many similarities in their mechanical requirements. There is a large body of literature on the design and applications experience of spacecraft mechanisms, including discussion of tribology issues.[71] Table 7 is a list of mechanical components often found on spacecraft and is arranged according to the type of mechanical contact. The list is not meant to be exhaustive but is typical of components that have exhibited specific problems.[72] Articles in a recent volume of Tribology International[73] are all devoted to various aspects of tribology of space systems throughout the world. Each country's space program is treated individually, and there are some general articles on different technologies.

It is important for the reader to understand that the field of space tribology is undergoing major advances in lubricant technology. Such advances are being driven by two trends: (1) the required lifetimes of spacecraft are increasing, making some of the past lubricant practices inadequate; and (2) mechanical component failures are starting to become the life-limiting systems on spacecraft, because the traditional failure points (power systems, electronics, and contamination problems) are using newer technologies that exceed the lifetimes of the tribosystems.[40,43] The tribology advances include new or improved tribomaterials and the generation of more extensive test data to qualify these tribomaterials for various applications. Table 7 is a list of materials technologies either in use or available for implementation on various spacecraft components. The different symbols in the table correspond to a critical or less stringent requirement or to a preferred or alternative

Table 7. Tribology Components: Requirements and Technology "Solutions" for Space Applications

Mechanical components	Requirements								
	Low friction	Low wear rate	Extreme environment	Elec./therm conductivity	Periodic motion	Gas/vacuum compatibility	Storage	Non-contaminating	Controlled backlash
Sliding contact									
Clamps/latches	×		×			×	×	×	×
Slip rings	×	○	○	×			×		
Potentiometers	×	×	×	×	×				×
Seals	×	×	×		×	×		×	
Bearing retainers	×	×			×		×		
Telescoping joints	×	○	×	×	×		×	×	
Gas/magnetic bearings	×		×		×	×			
Rolling contact									
Spin bearings	×	×		×			×		
Gimbal bearings	×	○	×		×		×	×	
Sensor support bearings	×	×	×	×	×		×	×	
Motor, synchronous	×	×	×	×			×	×	×
Solar array bearings	×		×	×	×		×	×	
Mixed regime									
Gears	×	×	×	×		×		×	×
Harmonic drives	×	×	×						×

Mechanical components	Technology 'solutions'					
	Fluid lubes	Solid lubes	Hard coats	Composite materials	Additives	Ceramic bulk materials
Sliding contact						
Clamps/latches		■				
Slip rings	□	■				
Potentiometers		■		■		
Seals		□		■		
Bearing retainers	■	□		■		
Telescoping joints		■	■	■		■
Gas/magnetic bearings		■	■			
Rolling contact						
Spin bearings	■		■	■		■
Gimbal bearings	□	■	■	■	□	■
Sensor support bearings	■	■	■	■	■	■
Motor, synchronous	□	■				
Solar array bearings		■	□	■		□
Mixed regime						
Gears	■	■	■		■	□
Harmonic drives	■	□	■		■	□

Legend: × critical requirement, ○ Less stringent requirements, □ Technology that would probably improve performance, ■ Technology that would improve performance technology. The reader is referred to the references for more details concerning vacuum applications.

B. TERRESTRIAL UHV ENVIRONMENTS

UHV chambers are used primarily by three groups of people: (1) surface scientists conducting chemical experiments or analytical measurements (such as spectroscopy, diffraction, or microscopy), or both, on the first few atomic surface layers of materials; (2) scientists and engineers synthesizing or fabricating materials with features or structures of micrometer to nanometer scale; and (3) engineers testing hardware intended for vacuum applications. All three groups require extremely clean, stable environments to obtain reproducible results. Contamination from lubricants in the form of vapors, migrating liquid lubricant molecules, or particulate debris is not acceptable. Designers try, as much as possible, to keep mechanical components of such systems external to the vacuum and rely on feed-throughs, magnetic couplings, or bellows to transmit or facilitate component motion. However, UHV systems often contain manipulators to move materials within the chamber or between chambers. Rotatable fixtures are also required in line-of-sight deposition processes to adequately expose nonplanar substrates to the deposition flux. If the manipulators are used frequently, undergo moderate to heavy stresses, or have tight-tolerance components, some lubrication is generally required to avoid frequent mechanism repair (which necessitates breaking vacuum). Lubricants for pumps are not covered in this report because that technology is well developed, and the pump manufacturers are quite capable and flexible in meeting customer requirements for specific applications.

The general strategy that has been used is to avoid metal-to-metal contact and to have minimum lubrication. For example, PTFE and polyimide polymers (pure or composites) have been used to make bearing bushings for UHV manipulators. Recently, Si_3N_4 balls have been used to make hybrid bearings for UHV mechanisms. (Presumably TiC- or TiN-coated materials would also work.) The Si_3N_4 has been used without lubricant or with spray-deposited WS_2 (Dichronite) for more demanding applications.[74] WS_2 has also been used on steel. Sputter-deposited MoS_2 has been used on deposition fixtures and on a cryogenic (helium) manipulator for an acoustic microscope (made of steel), resulting in lower operating torque of these mechanisms.

Grease (Castrol [Braycoat] 600) has also been used in a "robot" manipulator operated in a molecular beam epitaxy (MBE) system.[75] The MBE robot has many gears, bearings, and lead screws. Over 20 robots have been built, and some have operated over 5 years without maintenance. The grease was selected instead of solid lubricants, in part, because of a desire to avoid particulate generation. Micrometer-sized particles have unusual migration tendencies in vacuum (they are easily propelled by electrostatic charges) and are devastating to the fabrication of submicrometer devices. The particulate generation properties of solid lubricants as a function of film properties (for example, porosity) have not been systematically studied. Further work is needed and is in progress.[76] The designer should place mechanisms below critical surfaces in vacuum, so that gravity will move away debris from the sites of inevitable wear. Containment barriers should also be considered that are interposed in the line of sight between critical surfaces and the lubricated sections of mechanisms.

Greases (e.g., Castrol Braycoat 600) are also used to lubricate Viton seals between UHV and air on sliding manipulators. Such seals are usually in multiple series, with differential pumping between each seal.

When selecting tribomaterials, the designer should review their temperature stabilities, load-bearing capabilities, moisture sensitivities, and achievable tolerances. Obviously, the vapor pressure of the tribomaterial must be below desired system operating pressure. Since UHV systems are routinely baked out, the vapor pressure and load-carrying capacities of the tribomaterials must not degrade by such heating. Moisture sensitivity is important if the mechanism is routinely stored and/or operated in air. Polyimides are extremely sensitive to water vapor (these polymers absorb as much as 2% moisture and minutes or hours of moisture exposure will require subsequent bake-out), while PTFE is not, yet polyimides have load-bearing capabilities superior to those of PTFE. MoS_2 is more sensitive to water vapor exposure than WS_2 (MoS_2 will significantly oxidize over a period of months to a year), yet MoS_2 has better sliding wear endurance in vacuum. (MoS_2 oxidation can be effectively avoided at atmospheric pressure by storage of the lubricated component in a dry or inert gas, desiccated environment.) Sputter deposition can yield solid lubricant coatings to better tolerance than burnishing or spray methods. Sputter-deposited films can also be prepared that will resist oxidation upon standing (not operating) in air for many months, and such films should be considered for conventional uses. Bonded films, though subject to greater debris formation, are generally much more resistant to oxidation. A typical procedure for applying bonded films is to run the film in (burnish) after the normal application and then remove any debris (with a vacuum brush) before using.

V. SUMMARY

When selecting a lubricant for use in vacuum, the spacecraft or vacuum system designer has many more options available today than were available 30 years ago. Lubricants selected in that era have been used until proven completely inadequate with regard to newer, more demanding system requirements. Changes have not necessarily been made when better alternatives to the original choices become available. All potential lubricant candidates that can meet various system requirements should be considered in the design phase. The lubricant(s) ultimately chosen for the system should optimally address all system requirements in proportion to the importance of the requirements. The tendency to pre-select one lubricant based on its superior performance in satisfying one aspect of the system requirements should be avoided. In accordance with concurrent engineering principles, tribology should be given sufficient and timely consideration early in the vacuum/spacecraft system design phase, prior to component fabrication. Such early attention can avoid the conversion of an expensively fabricated mechanism into scrap material, which increases system cost and causes delays in schedule (which are also costly).

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